Scopus®

JOURNAL OF HUMAN SPORT AND EXERCISE

Volume 21, Issue 4 – October 2026

EDITED & PUBLISHED BY

ASOCIACIÓN ESPAÑOLA DE ANÁLISIS DEL RENDIMIENTO DEPORTIVO

ISSN 1988-5202

ORIGINAL ARTICLE

Leadership under pressure in elite tennis: Real-time coaching communication at the United Cup

Claudio Hinojosa-Torres . *Faculty of Education and Humanities. Andres Bello University. Viña del Mar, Chile.*
Paula Ortiz-Marholz. *Institute of Sport and Well-Being. Andres Bello University. Santiago, Chile.*
Juan Pablo Zavala-Crichton. *Faculty of Education and Humanities. Andres Bello University. Viña del Mar, Chile.*
Dilan Galeano-Rojas. *Faculty of Education. University of Granada. Granada, Spain.*
Rodrigo Yáñez-Sepulveda. *Faculty of Education and Humanities. Andres Bello University. Viña del Mar, Chile.*

ABSTRACT

Emotional, behavioural, and cognitive balance is critical for decision-making in elite sport, particularly during moments of maximum competitive pressure. This study examines a real-time coaching intervention delivered during the United Cup, focusing on the psychological content of a coach's message to an elite tennis player during a key stage of competition. A qualitative single-case study design was employed, supported by interpretative content analysis informed by established frameworks in sport psychology. The analytical corpus consisted of a brief in-competition verbal intervention delivered during a third-set break, which was subsequently transcribed for systematic examination. Findings suggest that the coach's message contained psychologically meaningful elements, including recognition of prior success, emotional validation, reinforcement of self-confidence, emphasis on personal agency, and encouragement of adaptive coping under pressure. These communicative elements may illustrate how coaching discourse can address psychological dimensions — such as confidence, emotional validation, and personal agency — at a critical moment in the match. However, the present design cannot establish whether they influenced the athlete's emotional state or performance. The case illustrates how coaching communication may function as a situated psychological resource in real time, extending beyond technical instruction by potentially addressing motivation, emotional regulation, and attentional refocusing. The study underscores the importance of leadership grounded in composure, strategic communication, and emotional intelligence, while suggesting that these competencies should be considered relevant components in the preparation and education of elite-level coaches.
Keywords: Coaching communication, Elite tennis, Emotional regulation, Sport leadership, Performance readiness.

Cite this article as:
Hinojosa-Torres, C., Ortiz-Marholz, P., Zavala-Crichton, J. P., Galeano-Rojas, D., & Yáñez-Sepulveda, R. (2026). Leadership under pressure in elite tennis: Real-time coaching communication at the United Cup. *Journal of Human Sport and Exercise, 21*(4), 1181-1194. https://doi.org/10.55860/8rpxb580

Corresponding author. *Faculty of Education and Humanities. Andres Bello University. Viña del Mar, Chile.*
E-mail: claudio.hinojosa@unab.cl
Submitted for publication April 29, 2026.
Accepted for publication June 08, 2026.
Published June 23, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/8rpxb580

INTRODUCTION

In elite sport, the relationship between coach and athlete constitutes a determining factor for competitive success. While an athlete's technical and physical capacities are fundamental, the coach's ability to lead and communicate effectively under high pressure can decisively influence competitive outcomes (Davis et al., 2019). Empirical evidence indicates that coaches' communication plays a significant role in emotional regulation and in the development of athletes' resilience, particularly during critical moments of competition (Davis & Davis, 2016; Fletcher & Sarkar, 2012). Within this framework, effective communication and strategic leadership have become established as central pillars of optimal sporting performance (Coker et al., 2022). The coach's capacity to convey clear, motivating, and situation-appropriate messages directly affects athletes' mindset and performance, especially under conditions of elevated pressure (Kim & Park, 2020). From this perspective, sporting success does not depend exclusively on athletes' individual abilities, but also on the quality of the interactions established between coaches and athletes (Côté & Gilbert, 2009; Jowett, 2024).

Communication in sport extends beyond the mere transmission of technical instructions. It also involves the ability to influence athletes' emotional and motivational states (Yang et al., 2024). Clear, empathetic, and coherent communication can strengthen confidence, foster cohesion, and create an environment conducive to learning and personal development. Conversely, poor communication may lead to misunderstandings, reduce motivation, and negatively affect sporting performance (Bedir et al., 2023). Consequently, the study of coaches' communicative interventions aimed at strengthening confidence and resilience has gained increasing relevance in recent scientific literature (Karayel et al., 2024; Kim & Park, 2020; Zulham et al., 2024).

Despite this growing interest, most evidence derives from retrospective sources—questionnaires, interviews, or post-hoc perceptions—rather than from coaches' communication as it unfolds during competition. Analyses of real-time coaching discourse delivered in live elite competition, and particularly in individual open-skill sports such as tennis, remain scarce, leaving the in-competition message itself largely unexamined as an object of study.

Within this context, achievement orientation emerges as a central construct, influenced by variables such as self-efficacy, goal valuation, and perceptions of the environment (Siegle et al., 2017a; Siegle et al., 2017b). The interaction between athletes' personal goals, their perceived self-efficacy, and coaches' communicative strategies can significantly shape achievement orientation, particularly in scenarios characterized by highly competitive demands (Isoard-Gautheur et al., 2016).

From a sport leadership perspective, leadership is expressed in the coach's ability to guide athletes towards shared goals, maintain cohesion, and promote a positive psychological environment. Research has shown that effective leadership is characterized by adaptability, empathy, and the capacity to inspire athletes to reach their full potential. According to Self-Determination Theory (Ryan & Deci, 2000), coaches who foster autonomy and strengthen perceptions of competence contribute not only to increased intrinsic motivation but also to the development of a growth-oriented mindset. These approaches are particularly relevant in critical contexts, where performance may be constrained by adverse factors (Liu et al., 2025). In this regard, the desire to demonstrate competence and the willingness to overcome obstacles, core elements of achievement orientation (Lee et al., 2021; Taşdemir, 2022), acquire particular importance in high-pressure sporting situations (Oudejans et al., 2010).

 © 2026 ARD Asociación Española

Recent literature supports the impact of coaches' communicative skills and leadership on sporting performance. Soto et al. (2021) showed that leadership training programmes for coaches enhance athletes' perceptions of competence. Complementarily, Jin et al. (2022) found that democratic leadership, based on shared decision-making and autonomy support, promotes athletes' psychological well-being. Similarly, Mach et al. (2022) demonstrated that, in team sports, transformational leadership enhances performance through the strengthening of cohesion. Along the same lines, Oh (2023) reported that coaches with precise and positive communication skills exert a favourable influence on performance, while Schei et al. (2023) highlighted that identity-based leadership strengthens group dynamics. Although these findings stem primarily from team sports, several of their underlying principles apply to the coach–athlete relationship in individual, open-skill disciplines.

While the literature on coach–athlete relationships continues to grow, the specific impact of the coach–athlete relationship remains an area requiring further exploration, particularly regarding its effects on motivation, athlete commitment, and competitive performance (Pan & Sui, 2025). Accordingly, the challenge of optimizing coach–athlete communication across diverse cultural and sporting contexts persists, as recent evidence indicates that the quality, symmetry, and functions of communication directly influence athletes' satisfaction, motivation, and cooperation (Hoffmann, 2025; Purnomo et al., 2025). Moreover, individual differences among athletes require coaches to adapt their communication and leadership strategies to foster closer, more meaningful relationships (Baumgärtner & Ohlert, 2025; Landman et al., 2024). Complementarily, interpersonal support styles such as autonomy-supportive coaching (Mageau & Vallerand, 2003) are associated with higher levels of resilience, adherence, and long-term development in young athletes (Llanos-Muñoz et al., 2023; Zhang et al., 2024). Finally, organizational structures within elite sport shape the context in which communicative practices unfold, exerting significant effects on team climate and sporting performance (Bjørnstad et al., 2024).

In elite sport, the ability to lead and communicate under pressure assumes critical relevance (Ortez et al., 2025). In elite competitions, high-tension moments demand not only solid technical and tactical preparation but also effective emotional management by both coaches and athletes. Sarkar and Fletcher (2014) argue that resilience in elite sporting contexts is mediated by the quality of social interactions, with the coach representing a central source of emotional and strategic support. In individual sports, where the coach–athlete relationship is more direct and personalized, this proximity intensifies both the benefits and the potential limitations of the communicative strategies employed (Kuruzović & Đorić, 2023).

Recent studies have shown that coaches who use positive, specific messages at key moments achieve significant improvements in athletes' performance (Stewart et al., 2024). Similarly, Dobrescu (2014) emphasized the relevance of non-verbal language in coach–athlete communication, demonstrating that congruence between verbal messages and non-verbal cues influences how athletes interpret and internalize coaches' instructions. These findings reinforce the notion that coaches' composure and communicative mastery are expressed not only through message content but also through tone, posture, and facial expressions.

In light of the above, the present study examines the psychological content of a real-time coaching intervention delivered by a tennis coach during an elite-level match under conditions of maximum competitive pressure. Its contribution is primarily methodological: rather than relying on athletes' or coaches' retrospective perceptions, it analyses an actual in-competition message — captured verbatim and publicly verifiable — as a situated object of study in an individual, open-skill sport. Through an interpretative single-case approach, the analysis explores how strategic communication, emotional validation, and leadership are expressed in

the message, and how this content may be read in relation to established psychological processes, while remaining within the limits of an interpretative rather than causal account.

MATERIALS AND METHODS

The present study was framed within a single-case study design (Roth, 2022; Yin, 2018), a methodological approach that allows for an in-depth examination of a specific phenomenon within its real-life context, providing detailed insights and a level of understanding that would be difficult to achieve through more generalizable methods. An interpretative approach was adopted to ensure a reflective and rigorous engagement with the data corpus, with consideration of its theoretical and practical implications. The study employed interpretative content analysis (Bardin, 1996) through a psychological lens, supported by the qualitative data analysis software MAXQDA 26 (VERBI Software, 2026).

Case selection followed a purposive, instrumental rationale: the episode was chosen not because it is statistically representative, but because it offers a rare opportunity to examine the phenomenon of interest —real-time coaching communication under maximum competitive pressure— in a naturally occurring elite setting. Three criteria guided this choice. First, the episode constitutes a critical and revelatory case (Yin, 2018): verbatim coaching discourse delivered during live elite competition is seldom accessible to researchers, and this intervention was captured in full at a decisive stage of the match (a third-set break with the outcome still undecided). Second, it occurred under conditions of maximum competitive pressure, the very context in which communicative leadership is theoretically most consequential. Third, the material is publicly available and verifiable through an official source, which allows the analytical corpus to be transparently constructed and independently consulted. Consistent with the logic of single-case research (Roth, 2022; Yin, 2018), the case is therefore treated as instrumental and illustrative rather than typical or generalizable: its value lies in the depth of understanding it affords regarding a specific, hard-to-observe phenomenon, not in its representativeness.

The analytical corpus consisted of a real-time coaching intervention delivered verbally by the captain and coach of the Chilean team (J.F.D.) to the player (N.J.F.) during a match at the United Cup in Sydney (December 2023). The material was retrieved from the official video published on the @ATPTour_ES account on the social media platform X (https://x.com/ATPTour_ES/status/1792034948397822136). Through audio transcription, a textual corpus of 79 words was constructed, distributed across six sentences (consecutively numbered from 1 to 6):

> *"The answer is within yourself. You demonstrated it in this game (1). You played this game by yourself. And all the time you're playing it alone (2). It's you who has to fight this. We can't do more than what we are doing here (3). You did well in what you did there. You took the initiative (4). You have more than enough talent. So, trust, trust (5). This is not easy. It's difficult. But you have to trust yourself (6)"*

The intervention under analysis was delivered during a third-set break at a psychologically critical stage of the match, at which point the Chilean player went to the bench to hydrate and change his shirt. During this interval, the coach (J.F.D.) addressed the player (N.J.F. ATP ranking 19), who had won the first set (6–3), lost the second set (3–6), and was leading 5–4 in the third set against a Greek opponent (S.S. ATP ranking 416). Following this break, the opponent (who was serving) held his service game, levelling the set at 5–5. Subsequently, the Chilean player won the next two games, securing the third set 7–5 and ultimately winning the match 6–3, 3–6, 7–5. This match outcome is reported solely to contextualize the episode; the temporal

 © 2026 ARD Asociación Española

sequence between the intervention and the subsequent games does not imply any causal relationship, and the result is not treated as evidence of the message's effectiveness.

Consistent with this interpretative orientation, the study relied on a single publicly available data source (the audiovisual record of the intervention and its verbatim transcription) and did not incorporate additional sources such as athlete or coach interviews, physiological indicators, or performance metrics. This single-source design was deliberate: the aim was to analyse the message as naturally occurring discourse, as it was actually delivered in competition, rather than to reconstruct its experienced effects. Accordingly, the analysis is confined to the psychological content expressed in the message. It does not seek to triangulate or to infer its impact on the athlete's emotional state or performance.

INTERPRETATIVE PSYCHOLOGICAL ANALYSIS

The analysis examined the six communicative units comprising the intervention across three central psychological dimensions: self-efficacy and perceived competence; emotion regulation and coping under pressure; and motivational climate/autonomy-supportive communication. These dimensions were selected because they align directly with the content of the coach's message and established constructs in sport psychology. The purpose of the analysis was not to infer the coach's intentional use of formal psychological theories, but to interpret how naturally occurring communicative content may align with evidence-based psychological processes relevant to elite performance. Other theoretical references were used only as complementary interpretative support when they helped clarify specific nuances of the discourse. This analytical decision was intended to avoid over-fragmentation and to maintain coherence between the brief nature of the communicative episode and the theoretical scope of the interpretation. The psychological frameworks were therefore applied post hoc, as heuristic interpretative lenses rather than as constructs the coach deliberately operationalized. Consequently, the analysis is exploratory rather than confirmatory: the correspondences identified between the message and established constructs represent one plausible reading of the discourse, not evidence that these theories were enacted or that the proposed alignment is the only possible interpretation.

Given that the analytical corpus comprises a single in-competition episode, this analysis is intended as an interpretative illustration rather than as an analytically generalizable account: it aims to characterize the psychological content of the message as discourse, not to establish its effects on the athlete.

The verbal intervention was first segmented into six communicative units corresponding to the six consecutive sentences of the transcript, each treated as a meaning unit suitable for interpretative coding. A coding frame was defined a priori from the sport-psychology literature, comprising the three dimensions described above. Each dimension was given a working definition derived from its source constructs (Bandura, 1997; Gross, 2014; Ryan & Deci, 2000), and a communicative unit was assigned to a dimension when its content was judged to express the corresponding psychological process; a unit could be associated with more than one dimension when its content warranted it. The corpus was coded by one of the co-authors, who has academic training and expertise in sport psychology; the resulting coding and interpretations were subsequently reviewed independently by the co-authors, and any divergences were discussed until consensus was reached. Given the interpretative nature of the analysis, analytical memos were kept throughout coding to make interpretative decisions explicit and to reduce confirmation bias; interpretations are accordingly reported in tentative terms.

(1) ***"The answer is within yourself. You demonstrated it in this game".***

This segment of the intervention appears to strengthen the athlete's self-efficacy, consistent with Self-Efficacy Theory (Bandura, 1997), which proposes that confidence in one's own capabilities is a key determinant of performance under pressure. By directing attention to previous successful actions within the same match, the coach's message could be read as reinforcing perceptions of competence and personal control. Such references to recent mastery experiences may be particularly relevant in elite competition, where confidence can fluctuate rapidly across critical moments.

(2) ***"You played this game by yourself. And all the time you're playing it alone".***

This segment of the intervention may be interpreted as emphasizing personal agency and responsibility within performance. From the perspective of Self-Determination Theory (Ryan & Deci, 2000), the message may be read as reinforcing autonomy by reminding the athlete that decisive actions remain under personal control. In high-pressure moments, such cues help redirect attention toward controllable aspects of performance, strengthening commitment and task-focused engagement. At the same time, the same wording ("*you're playing it alone*") could be read less as autonomy support than as a reminder of the athlete's isolation under pressure; this ambiguity underscores the interpretative — rather than definitive — nature of the present reading.

(3) ***"It's you who has to fight this. We can't do more than what we are doing here".***

This segment of the intervention can be read as emphasizing personal responsibility in confronting the immediate competitive challenge. Rather than offering technical instruction, the coach appears to redirect the athlete toward active engagement, which may reinforce the idea that the decisive response must come from within performance itself. In psychological terms, such communication may support coping under pressure by promoting agency, persistence, and readiness to act during a critical moment of the match. Alternatively, the statement that the coaching staff "*can't do more*" could be interpreted as a withdrawal of support, or as added pressure, rather than as an invitation to agency; the present reading is therefore one plausible interpretation among others.

 © 2026 ARD Asociación Española

(4) *"You did well in what you did there. You took the initiative".*

This segment of the intervention provides immediate positive feedback regarding the athlete's recent actions. By validating proactive behavior, the coach appears to reinforce perceptions of competence and to encourage continued assertiveness in play. In high-pressure situations, brief affirmations of effective decisions may help stabilize confidence in the moment, without this implying a measurable effect on subsequent play.

(5) "*You have more than enough talent. So, trust, trust*".

This segment of the intervention appears oriented toward restoring confidence at a decisive stage of the match. By affirming the athlete's existing capabilities, the coach could be read as reinforcing perceived competence and encouraging trust in the skills that have been developed. In high-pressure moments, reminders of one's readiness and ability may help counter self-doubt and foster a more confident stance.

(6) *"This is not easy. It's difficult. But you have to trust yourself".*

This segment of the intervention may be interpreted as combining emotional validation with confidence restoration. By openly acknowledging the difficulty of the situation, the coach appears to normalize competitive stress rather than deny it. At the same time, the invitation to trust oneself can be read as pointing the athlete toward coping resources already available. From a psychological perspective, such communication may support emotional regulation and resilient functioning during moments of heightened pressure.

DISCUSSION

The findings of this study contribute to a more situated understanding of coaches' communication under highly competitive pressure, particularly in elite individual sports. Because these findings derive from a single brief intervention (79 words across six units), they should be read as an interpretative illustration of the message's psychological content rather than as evidence of its effects on the athlete's emotional state or performance.

In line with the literature on competitive stress, performance-related pressure may generate emotional disturbances that compromise athletes' functioning, reinforcing the potential value of timely communicative interventions that promote psychological balance (Lopes, 2024). Within this context, the present case illustrates how the content of a brief real-time coaching message delivered at a critical stage of competition

can be interpreted as psychologically supportive —addressing emotional regulation, attentional refocusing, and confidence restoration—while the design does not allow any claim that these functions were actually produced in the athlete.

From a sport psychology perspective, the findings align with Self-Efficacy Theory, suggesting that validation of effort and emphasis on prior achievements may reinforce athletes' beliefs in their own capabilities, which could facilitate adaptive responses under pressure (Bandura, 1997; Beattie et al., 2015). Emotional regulation also emerges as a central component of this process and may facilitate cognitive reappraisal of the competitive situation, reducing the negative emotional load associated with decisive moments (Biggin et al., 2017; Gross, 2014). Consistent with Lazarus and Folkman's (1986) transactional model, the way athletes cognitively appraise the situation is key to modulating their emotional responses, positioning coaches' communication as a strategic resource for mitigating anxiety and fostering resilience (Smith et al., 2022).

A relevant contribution of this study lies in illustrating how the coach–athlete relationship manifests not merely as a general source of support, but as a form of situated psychological intervention that may be interpreted as oriented toward athletes' motivation and emotional control in real time. As noted by Jowett and Shanmugam (2016), the quality of this relationship affects motivational and emotional processes, an assertion illustrated by the present analysis, which suggests how a strategically framed message could orient the motivational climate toward task involvement while maintaining awareness of competitive outcomes (Knight et al., 2017). In this way, the analysed case illustrates how coaches' communicative leadership may operate as a regulator of attentional focus and psychological arousal in high-demand scenarios. In addition, the content of the intervention was oriented toward narrowing attentional focus toward controllable actions; whether it actually reduced distraction associated with score pressure cannot be determined from the present data.

This discussion also engages with recent literature highlighting emotional regulation as a cornerstone of psychological preparation in elite sport. Evidence suggests that athletes with stronger emotional competencies display a greater capacity to cope with competitive challenges and to sustain an achievement-oriented mindset (Montenegro-Bonilla et al., 2024). Within this context, the message analysed may be interpreted as oriented toward emotional stability and confidence; whether it facilitated a resilient stance in the athlete remains beyond the scope of this interpretative analysis. This interpretation is consistent with studies emphasizing cognitive reappraisal as an effective strategy for optimizing performance in high-demand situations (Aiba et al., 2023), as well as with research underscoring the importance of flexibility in emotional regulation to respond to changing competitive scenarios (Kucharski et al., 2018).

From the coach's perspective, the case points to the potential relevance of communicative styles that foster athlete autonomy and intrinsic motivation. In line with Ortega and Montero (2021), coaches' support not only contributes to more effective adversity management but also strengthens long-term commitment and performance. Moreover, satisfaction of basic psychological needs (autonomy, competence, and relatedness) is associated with more effective emotional regulation and greater well-being in competitive contexts (Robazza et al., 2023). The present case illustrates how these needs can be implicitly addressed through a brief yet strategically structured message.

Furthermore, the existing literature indicates that the use of adaptive emotional regulation strategies is associated with more positive cognitive appraisals and favourable emotional experiences throughout the competitive season (Cece et al., 2021). In this regard, the present analysis suggests that the content of coaches' communication may be relevant to such processes; the data, however, do not permit claims about

 © 2026 ARD Asociación Española

anxiety reduction, intrinsic motivation, or adherence to the training process (Leñador-Albano et al., 2023). The framing of the competitive challenge in terms of an internal locus of control, present in the analysed message, aligns with evidence highlighting the importance of setting clear and challenging goals to enhance self-regulation and athlete commitment (Pop et al., 2021).

Taken together, this study offers a situated and contextualized perspective on coaches' communicative leadership in elite sport, highlighting its potential relevance for emotional regulation, motivation, and performance readiness under pressure. Rather than seeking a causal explanation, the present analysis provides an in-depth illustration of how psychologically meaningful communication may emerge in real time during competition. Accordingly, the psychological functions attributed to the message should be read as interpretative hypotheses to be tested in future research, rather than as established effects. This perspective contributes to broader discussions on psychological preparation in sport by underscoring the value of integrating communicative and emotional competencies into coach education and athlete support, particularly within the temporal and psychological demands of elite tennis.

A specific interpretative caution concerns the risk of outcome bias. Because the athlete ultimately won the match, the coaching intervention could be read retrospectively as effective. The present analysis explicitly avoids this inference: knowing the final result may colour the interpretation of the message, but a favourable outcome cannot be used as evidence that the communication caused, or even contributed to, the athlete's performance. The interpretation offered here pertains exclusively to the psychological content of the message as discourse and is deliberately decoupled from the competitive result.

Limitations and future directions

This study should be interpreted in light of several limitations. First, the analysis focused on a single communicative episode in a single elite tennis match, limiting transferability beyond this specific competitive context. Second, the analytical corpus consisted of a brief naturally occurring verbal intervention, meaning that interpretations were necessarily based on bounded discursive material rather than on extended interactional data. Third, and most critically, the study relied on a single data source and therefore lacks triangulation: no athlete or coach interviews, physiological indicators, or performance measures were available to corroborate the interpretation. As a result, the psychological functions attributed to the message remain interpretative, and the study cannot establish how the message was subjectively experienced or whether it produced measurable changes in emotional state or performance.

Fourth, the analysis is inherently interpretative and therefore shaped by the researcher's subjectivity. The psychological frameworks adopted as interpretative lenses inevitably directed attention toward certain features of the message and away from others, and the authors' prior knowledge of the match outcome may have predisposed them to read the intervention as effective (an outcome-bias concern addressed in the Discussion). To mitigate these influences, the coding and interpretations were cross-reviewed among the authors until consensus, analytical memos were used to make interpretative decisions explicit, and the findings are reported in deliberately tentative terms; nonetheless, alternative interpretations of the same material remain possible.

In addition, the intervention was examined retrospectively through publicly available audiovisual material, which may omit contextual elements not visible during broadcast coverage. Accordingly, the findings should be understood as interpretative rather than causal. Future research may build on this work by combining real-time coaching discourse analysis with athlete interviews, psychophysiological indicators, observational

designs, or longitudinal approaches examining how communication influences coping and performance readiness across repeated competitive situations.

CONCLUSIONS

This study offers a situated, interpretative reading of coaches' communicative leadership under highly competitive pressure. Drawing on a single, publicly documented real-time intervention in elite tennis, treated as an instrumental and illustrative case, the analysis characterizes the psychological content of the message as discourse —encompassing confidence support, emotional validation, personal agency, and coping under pressure— without inferring its effects on the athlete's emotional state or performance. Its main contribution is to show how, even within a brief in-competition exchange, coaching communication can be read as a situated psychological resource that extends beyond technical instruction; the psychological functions identified should be understood as interpretative hypotheses rather than as established outcomes.

Read in this light, the case underscores the potential relevance of communicative competence — alongside technical and tactical expertise — in the preparation and education of elite-level coaches, particularly the capacity to frame messages that acknowledge athletes' experience and orient attention toward controllable actions under pressure. Because these conclusions rest on a single interpretative episode, they are offered as a contribution to be tested rather than generalized, inviting future work that links real-time coaching discourse to athletes' and coaches' own accounts and to performance-related measures across repeated competitive situations.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Claudio Hinojosa-Torres. Methodology: Juan Pablo Zavala-Crichton. Formal analysis: Claudio Hinojosa-Torres. Data curation: Dilan Galeano-Rojas. Writing – original draft: Paula Ortiz-Marholz, Juan Pablo Zavala-Crichton. Writing – review & editing: Paula Ortiz-Marholz, Juan Pablo Zavala-Crichton. Supervision: Rodrigo Yáñez-Sepúlveda. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data

 © 2026 ARD Asociación Española

collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

ACKNOWLEDGMENTS

We want to thank the Chilean Observatory of Physical Education and School Sport (OCHEFID) at Universidad Andrés Bello (Chile) for its support during the development of this research.

REFERENCES

Aiba, E., Matsuda, K., & Sugiyama, Y. (2023). Emotion regulation strategies during competitive games: Examination of the relationship between reappraisal/expressive suppression and psychological competitive ability. International Journal of Sport and Health Science, 21(0), 96-105. https://doi.org/10.5432/ijshs.202303

Bandura, A. (1997). Self-efficacy: The exercise of control. Freeman.

Bardin, L. (1996). El análisis de contenido. Segunda edición. Ediciones Akal.

Baumgärtner, S., & Ohlert, J. (2025). The Coach-Athlete relationship. Journal of Applied Sport and Exercise Psychology, 32(3), 91-94. https://doi.org/10.1026/2941-7597/a000055

Beattie, S., Hardy, L., & Woodman, T. (2015). A longitudinal examination of the interactive effects of goal importance and self-efficacy upon multiple life goal progress. Canadian Journal of Behavioural Science / Revue canadienne des Sciences du Comportement, 47(3), 201-206. https://doi.org/10.1037/a0039022

Bedir, D., Agduman, F., Bedir, F., & Erhan, S. (2023). The mediator role of communication skill in the relationship between empathy, team cohesion, and competition performance in curlers. Frontiers in Psychology, 14, 1115402. https://doi.org/10.3389/fpsyg.2023.1115402

Biggin, I., Burns, J., & Uphill, M. (2017). An investigation of athletes' and coaches' perceptions of mental ill-health in elite athletes. Journal of Clinical Sport Psychology, 11(2), 126-147. https://doi.org/10.1123/jcsp.2016-0017

Bjørnstad, M., Tam, A., McDougall, M., & Feddersen, N. (2024). Relationships influencing organisational culture in men's elite football clubs in Norway. Psychology of Sport and Exercise, 72(102604), 102604. https://doi.org/10.1016/j.psychsport.2024.102604

Cece, V., Guillet-Descas, E., Brenas, M., & Martinent, G. (2021). The role of dispositional emotion regulation strategies on the longitudinal emotional process and subjective performance during a competitive season. European Journal of Sport Science: EJSS: Official Journal of the European College of Sport Science, 21(10), 1448-1458. https://doi.org/10.1080/17461391.2020.1862304

Côté, J., & Gilbert, W. (2009). An integrative definition of coaching effectiveness and expertise. International Journal of Sports Science & Coaching, 4(3), 307-323. https://doi.org/10.1260/174795409789623892

Coker, I., Cotterill, S., & Griffin, J. (2022). Player perceptions of athlete leadership and leadership development in an English Premier League football academy. Asian Journal of Sport and Exercise Psychology, 2(3), 182-189. https://doi.org/10.1016/j.ajsep.2021.12.001

Davis, L., Jowett, S., & Tafvelin, S. (2019). Communication strategies: The fuel for quality coach-athlete relationships and athlete satisfaction. Frontiers in Psychology, 10, 2156. https://doi.org/10.3389/fpsyg.2019.02156

Davis, P., & Davis, L. (2016). Emotions and emotion regulation in coaching. In P. A. Davis (Ed.). The psychology of effective coaching and management (pp. 285-306). Nova Science Publishers.

Dobrescu, T. (2014). The role of non-verbal communication in the coach-athlete relationship. Procedia, Social and Behavioral Sciences, 149, 286-291. https://doi.org/10.1016/j.sbspro.2014.08.231

Fletcher, D., & Sarkar, M. (2012). A grounded theory of psychological resilience in Olympic champions. Psychology of Sport and Exercise, 13(5), 669-678. https://doi.org/10.1016/j.psychsport.2012.04.007

Gross, J. J. (2014). Emotion Regulation: Conceptual and Empirical Foundations. In J. J. Gross (Ed.), Handbook of Emotion Regulation (2nd Edition). Guilford.

Hoffmann, A. (2025). Athletes' participation in communication with coaches: functions and preconditions in elite sports using the example of three film sessions. Communication & Sport, 0(0), 1-29. https://doi.org/10.1177/21674795251363419

Isoard-Gautheur, S., Trouilloud, D., Gustafsson, H., & Guillet-Descas, E. (2016). Associations between the perceived quality of the coach-athlete relationship and athlete burnout: An examination of the mediating role of achievement goals. Psychology of Sport and Exercise, 22, 210-217. https://doi.org/10.1016/j.psychsport.2015.08.003

Jin, H., Kim, S., Love, A., Jin, Y., & Zhao, J. (2022). Effects of leadership style on coach-athlete relationship, athletes' motivations, and athlete satisfaction. Frontiers in Psychology, 13. https://doi.org/10.3389/fpsyg.2022.1012953

Jowett, S. (2024). The coach-athlete relationship within a cross-boundary team of experts: a conceptual analysis. International Review of Sport and Exercise Psychology, 1(16). https://doi.org/10.1080/1750984X.2024.2416968

Jowett, S., & Shanmugam, V. (2016). Relational coaching in sport: Its psychological underpinnings and practical effectiveness. In R. Schinke, K. McGannon, & B. Smith (Eds.), The Routledge international handbook of sport psychology (pp. 471-484). Routledge.

Karayel, E., Adilogullari, I., & Senel, E. (2024). The role of transformational leadership in the associations between coach-athlete relationship and team resilience: A study on elite football players. BMC Psychology, 12(1). https://doi.org/10.1186/s40359-024-02043-7

Kim, Y., & Park, I. (2020). "Coach Really Knew What I Needed and Understood Me Well as a Person": Effective Communication Acts in Coach-Athlete Interactions among Korean Olympic Archers. International Journal of Environmental Research and Public Health, 17(9), 3101. https://doi.org/10.3390/ijerph17093101

Knight, C., Harwood, C., & Gould, D. (Eds.). (2017). Sport Psychology for Young Athletes. (1st ed.). Routledge. https://doi.org/10.4324/9781315545202

Kucharski, B., Strating, M., Ahluwalia Cameron, A., & Pascual-Leone, A. (2018). Complexity of emotion regulation strategies in changing contexts: A study of varsity athletes. Journal of Contextual Behavioral Science, 10, 85-91. https://doi.org/10.1016/j.jcbs.2018.09.002

Kuruzović, N., & Đorić, V. (2023). Relations of coach-athlete relationship' quality and athlete psychosocial functioning: A Systematic Review. Sportlogia, 19(1). https://doi.org/10.7251/SGIA2319002K

Landman, M., Grobbelaar, H., & Kraak, W. (2024). Coach perspectives on coach-athlete relationships and characteristics of Generation Z academy level rugby union players from South Africa. Frontiers in Sports and Active Living, 6, 1461951. https://doi.org/10.3389/fspor.2024.1461951

Lazarus, R., & Folkman, S. (1986). Estrés y procesos cognitivos. Editorial Martínez Roca.

Lee, S., Kwon, S., Kim, Y., & Lee, D. (2021). The effect of adolescent athletes' achievement goal orientation and perception of error on their sport-confidence. International Journal of Sports Science & Coaching, 16(3), 646-657. https://doi.org/10.1177/1747954120976248

Leñador-Albano, V. M., Gragera-López, A., Córdoba-Caro, L., & Feu-Molina, S. (2023). Práctica deportiva e Inteligencia Emocional en jóvenes. Revisión sistemática. Cuadernos de Psicología del Deporte, 23(3). https://doi.org/10.6018/cpd.536391

Liu, R., Wang, S., & Li, J. (2025). How coach leadership behavior influences athletes' performance: the chain-mediated role of the coach-athlete relationship and psychological fatigue. Frontiers in Psychology, 15, 1500867. https://doi.org/10.3389/fpsyg.2024.1500867

 © 2026 ARD Asociación Española

Llanos-Muñoz, R., Pulido, J., Nobari, H., Raya-González, J., & López-Gajardo, M. A. (2023). Effect of coaches' interpersonal style on young athletes' individual resilience and team adherence intention: a season-long investigation. BMC Psychology, 11(1), 412. https://doi.org/10.1186/s40359-023-01445-3

Lopes, G. (2024). The Influence of psychology on sports performance: emotional and cognitive factors. South Florida Journal of Development, 5(11), e4683. https://doi.org/10.46932/sfjdv5n11-038

Mach, M., Ferreira, A., & Abrantes, A. (2022). Transformational leadership and team performance in sports teams: A conditional indirect model. Applied Psychology, 71(2), 662-694. https://doi.org/10.1111/apps.12342

Mageau, G., & Vallerand, R. (2003). The coach-athlete relationship: a motivational model. Journal of Sports Sciences, 21(11), 883-904. https://doi.org/10.1080/0264041031000140374

Montenegro-Bonilla, A., Becerra-Patiño, B., Pino-Ortega, J., Hernández-Beltrán, V., & Gamonales, J. M. (2024). Influencia de la Inteligencia Emocional en el Rendimiento Deportivo: una Revisión Sistemática. Cuadernos de Psicología del Deporte, 24(3), 34-52. https://doi.org/10.6018/cpd.617181

Oh, Y. (2023). Communication and team cohesion moderate the relationship between transformational leadership and athletic performance. SAGE Open, 13(3). https://doi.org/10.1177/21582440231195196

Ortega, A., & Montero, F. (2021). Relación entre resiliencia y rendimiento en deportistas. Revisión sistemática. Revista de Psicología aplicada al Deporte y el Ejercicio Físico, 6(2). https://doi.org/10.5093/rpadef2021a16

Ortez, D., Gorman, A., & Coulter, T. (2025). Comparing elite sport coaches' pressure training practices to recommended guidelines. International Journal of Sports Science & Coaching, 20(4), 1395-1408. https://doi.org/10.1177/17479541251333935

Oudejans, R., Kuijpers, W., Kooijman, C., & Bakker, F. (2010). Thoughts and attention of athletes under pressure: skill-focus or performance worries? Anxiety, Stress, & Coping, 24(1), 59-73. https://doi.org/10.1080/10615806.2010.481331

Pan, F., & Sui, W. (2025). Research on coach-athlete relationship and team performance based on 3Cs theory: the chain mediating role of emotional intelligence and athletic engagement. Frontiers in Psychology, 16, 1587900. https://doi.org/10.3389/fpsyg.2025.1587900

Pop, R., Grosu, E., & Zadic, A. (2021). A systematic review of goal setting interventions to improve sports performance. Studia Universitatis Babeş-Bolyai Educatio Artis Gymnasticae, 66(1), 35-50. https://doi.org/10.24193/subbeag.66(1).04

Purnomo, E., Nadzalan, A., Jermaina, N., Indrayeni, W., Akbar, A., Suardika, I., Duhe, E., Parengkuan, M., Hafiar, H., & Marheni, E. (2025). Communication patterns direct demonstration and verbal instructions in the SMCR program to improve coach-athlete relationships through interpersonal communication. International Journal of Human Movement and Sports Sciences, 13(6), 1255-1265. https://doi.org/10.13189/saj.2025.130610

Robazza, C., Morano, M., Bortoli, L., & Ruiz, M. (2023). Athletes' basic psychological needs and emotions: the role of cognitive reappraisal. Frontiers in Psychology, 14. https://doi.org/10.3389/fpsyg.2023.1205102

Roth, N. (2022). Los estudios de caso único en la investigación social y organizacional. Avanzando hacia la comprensión de sus aspectos epistemológicos y metodológicos. RLE. Revista de Liderazgo Educacional, 2, 9-31. https://doi.org/10.29393/RLE2-1ECNR10001

Ryan, R., & Deci, E. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. Contemporary Educational Psychology, 25(1), 54-67. https://doi.org/10.1006/ceps.1999.1020

Sarkar, M., & Fletcher, D. (2014). Psychological resilience in sport performers: a review of stressors and protective factors. Journal of Sports Sciences, 32(15), 1419-1434. https://doi.org/10.1080/02640414.2014.901551

Schei, G., Høigaard, R., Erikstad, M., Ivarsson, A., & Haugen, T. (2023). Identity leadership and cohesion in elite sport: The mediating role of intra-team communication. Heliyon, 9(7), e17853. https://doi.org/10.1016/j.heliyon.2023.e17853

Siegle, D., McCoach, D., & Bloomfield, E. (2017a). Achievement orientation model. In M. Makel, A. Rinn, & J. Plucker (Eds.), From giftedness to gifted education: Reflecting theory in practice (pp. 301-318). Routledge. https://doi.org/10.4324/9781003235262-14

Siegle, D., McCoach, D. B., & Roberts, A. (2017b). Why I believe I achieve determines whether I achieve. High Ability Studies, 28(1), 59-72. https://doi.org/10.1080/13598139.2017.1302873

Smith, M., Runswick, O., Jewiss, M., & Birch, P. (2022). Examining the theory of challenge and threat states in athletes: do predictions extend to academic performance? Educational Psychology, 42(9), 1127-1144. https://doi.org/10.1080/01443410.2022.2069229

Soto, D., García, J. A., Carcedo, R. J., & Sánchez García, M. (2021). The impact of an authentic sports leadership program for coach. Frontiers in Psychology, 12, 701134. https://doi.org/10.3389/fpsyg.2021.701134

Stewart, P., Fletcher, D., Arnold, R., & McEwan, D. (2024). Performance support team effectiveness in elite sport: a narrative review. International Review of Sport and Exercise Psychology, 19(1), 126-149. https://doi.org/10.1080/1750984X.2024.2411215

Taşdemir, F. (2022). Examining the factors affecting the achievement orientations of university students with logistic regression analysis. European Journal of Education Studies, 9(7). https://doi.org/10.46827/ejes.v9i7.4367

VERBI Software. (2026). MAXQDA (Version 26) [Computer software]. Retrieved from [Accessed 2026, 10 June]: https://www.maxqda.com

Yang, P., Xu, R., & Le, Y. (2024). Factors influencing sports performance: A multi-dimensional analysis of coaching quality, athlete well-being, training intensity, and nutrition with self-efficacy mediation and cultural values moderation. Heliyon, 10(17), e36646. https://doi.org/10.1016/j.heliyon.2024.e36646

Yin, R. (2018). Case study research and applications. Design and methods (6th ed.). SAGE Publications.

Zhang, N., Du, G., & Tao, T. (2024). Empowering young athletes: the influence of autonomy-supportive coaching on resilience, optimism, and development. Frontiers in Psychology, 15, 1433171. https://doi.org/10.3389/fpsyg.2024.1433171

Zulham, Z., Candra, O., Hermanto, H., & Riyanto, P. (2024). Building confidence and well-being: The power of coach communication and personal connections in college basketball. Asian Journal of Engineering, Social and Health, 3(12), 2701-2715. https://doi.org/10.46799/ajesh.v3i12.480

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Injury prevention and rehabilitation gaps in low-resource football: Evidence from Ethiopian Premier League clubs

Belete Haileyesus Bazezew . *Bahir Dar University Sport Academy. Ethiopia.*

ABSTRACT

Examining the injury prevention and rehabilitation strategies employed by Ethiopian men's Premier League football clubs is the aim of this particular article. Since the Premier League was established in 1993, football has been quite popular in Ethiopia. However, because of their dread of injury, Ethiopian football players' longevity and playing ability remain a worry. The application of injury prevention methods in Ethiopian football teams with restricted resources is hampered by organizational constraints, the lack of qualified human resources, and poor infrastructure, despite conclusive evidence from all across the world regarding the efficacy of such methods. This specific study made use of a descriptive cross-sectional study design. The participants in this study included 140 respondents, athletes, coaches, and physiotherapists. The results indicate a high incidence of ankle sprains, knee injuries (particularly ACL injuries), hamstring strains, and groin injuries. Since there is very little participation in organized activities like FIFA 11+, and injury management and tracking systems, injury prevention strategies are not organized and are unstructured. Most rehabilitation practices are very simple and are based on manual therapy and physical therapy, and there is very little access to modern rehabilitation techniques. Lack of resources, lack of awareness, cultural, and other factors are some of the major challenges faced in the present scenario. To overcome these shortcomings, it is recommended that injury care procedures, capacity building, resource allocation, injury prevention strategies and regular training be integrated, and injury monitoring systems be adopted. With the implementation of these strategies, Ethiopian football is expected to develop in a sustainable manner, and injury and safety risks for the players can be reduced.

Keywords: Sport medicine, Injury prevention, Rehabilitation, Ethiopian football, Player safety, Resource constraints.

Cite this article as:
Haileyesus Bazezew, B. (2026). Injury prevention and rehabilitation gaps in low-resource football: Evidence from Ethiopian Premier League clubs. *Journal of Human Sport and Exercise, 21*(4), 1195-1212. https://doi.org/10.55860/zazc8v52

Corresponding author. *Bahir Dar University Sport Academy. Ethiopia.*
E-mail: henokbazewew5@gmail.com
Submitted for publication March 11, 2026.
Accepted for publication April 13, 2026.
Published June 23, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/zazc8v52

INTRODUCTION

With an estimated 4 billion fans and players worldwide, football is considered one of the most watched and played sports in the world (FIFA, 2023). In Ethiopia, where football is considered an integral part of the country's identity that instils pride, harmony, and progress in the people, the popularity of football can also be seen in the country. The Ethiopian Premier League (EPL), founded in 1993, is considered the top-level professional football league in Ethiopia. It showcases players from all across the country and promotes competitive sportsmanship in the game (Ethiopian Football Federation, 2022). The physical demands of the game make players vulnerable to injury, even if the Ethiopian Premier League has significantly contributed to the development of sports in the country.

The physical demands of sprinting, jumping, and quick changes in direction that occur in football make injuries range from minor muscle strains to major ligament injuries, fractures, and muscle injuries (Owoeye et al., 2021). These factors affect the performance of the team, which affects the league games, in addition to the ability of the player to play and participate.

The methods used in football injury care include both prevention and rehabilitation. It has been proven that the rate of injury can be reduced worldwide by implementing injury prevention programs. Such injury prevention programs include neuromuscular training, strength conditioning, appropriate warm-up methods, and load control (Gabbett & Domrow, 2022). It has been proven, for example, that the rate of injury associated with football players can be reduced by as much as 30% by using appropriate warm-ups like the FIFA 11+ method (FIFA, 2023). On the other hand, it is essential to implement appropriate rehabilitation methods for football injury care. Such methods include appropriate functional training methods, evaluations, and treatment methods. Such methods have been implemented by football teams around the world and have been proven by the latest research in sports medicine.

Despite all these advancements, Ethiopia and other developing countries are facing challenges in implementing injury prevention and rehabilitation activities to the maximum extent. It is difficult to implement injury management strategies to a maximum extent due to a lack of standardized procedures, sports medicine facilities, and training for medical personnel and sports coaches (Liu et al., 2022). In addition, a lack of sports medicine specialists, physiotherapy facilities, and awareness also affects injury prevention activities. Ethiopian football players are prone to injuries, which can have a devastating effect on their careers and the development of the sport in Ethiopia (Mengistu, 2019).

According to Tesfaye, (2020) previous research in Ethiopia has mainly concentrated on the assessment of the prevalence and nature of injuries that occur in football players Tesfaye, (2020). However, there seems to be an identified gap in terms of the injury prevention and rehabilitation techniques that are used in football clubs, in addition to the challenges that are experienced in implementing these techniques in the region. Most of the research conducted in the region does not extensively discuss the infrastructural, institutional, and resource-based factors that affect the injury management techniques that are used in football clubs.

Recent research emphasizes the importance of context-specific research and development of solutions in the context of Ethiopian football. For instance, Alemu et al. (2023) stressed the importance of improving the knowledge of coaches and sports health professionals to better manage injuries. In-depth research can bridge these gaps and develop sustainable injury management systems for the progress of Ethiopian football.

 © 2026 ARD Asociación Española

Statement of the problem

It is agreed that injuries have a negative impact on the health, career, and performance of football players. The trend of injuries, prevention of injuries, and rehabilitation of injuries in football players have been identified through various studies carried out worldwide. For instance, the prevention of injuries in professional football teams is very crucial in the prevention of injuries in football players, as noted in the study carried out by Gabbett and Domrow in 2022. In addition, Bishop et al. noted in their study in 2021 the significance of rehabilitation in the successful return to play among football players.

However, it should be noted that the majority of the research has been done in developed countries with advanced sports medicine services. Therefore, the research might not be applicable to the context of football clubs in Ethiopia. Currently, there has been limited research done in Ethiopia on the management of injuries in football. For example, the research done by Mengistu (2019) and Tesfaye (2020) has identified the prevalence of injuries in football in Ethiopia. However, the research did not address the prevention and rehabilitation of injuries in football clubs.

Moreover, the absence of standardized procedures for injury care, training, and medical staff, as well as resource limitations in Ethiopian clubs, may pose a possibility that the procedures for injury prevention and rehabilitation are not standardized (Lemma et al., 2021). This is because the need for empirical data that is context-specific to Ethiopia has been emphasized. Although research worldwide indicates the importance of standard injury management practices, there is limited knowledge about the type of injuries that occur in Ethiopian Premier League clubs, the prevention strategies used in these clubs, and the rehabilitation practices used in these clubs. There is also limited knowledge about the prevailing problems in these clubs in terms of adhering to injury management practices despite the resource constraints faced in these clubs.

Therefore, it is important to conduct this study to explore the current injury prevention and rehabilitation methods, the nature of injuries commonly experienced among players, and the challenges faced by Ethiopian male Premier League football clubs. This research aims to fill a significant gap in injury management practices within Ethiopian football teams and to provide practical, context-specific recommendations that can enhance player safety and performance.

Moreover, this study is highly relevant to low-resource football environments globally, as many regions face similar systemic challenges such as limited access to specialized sports medicine personnel, inadequate facilities, and inconsistent injury prevention and rehabilitation practices. Whether in Africa, Asia, Latin America, or other developing regions, football programs often operate under resource constraints that adversely affect athlete health and long-term development (Owoeye et al., 2021). By examining the Ethiopian context, this research offers insights and evidence applicable to a broad spectrum of low-resource settings, highlighting the need for scalable, contextually appropriate strategies to improve sports medicine infrastructure, build capacity, and optimize injury management worldwide. Consequently, the findings contribute to an expanding body of knowledge aimed at supporting sustainable football development and athlete well-being in resource-limited environments.

Research objectives

1. To identify the common types of injuries among players in Ethiopian male Premier League football clubs.
2. To explore the injury prevention strategies currently employed by these clubs.
3. To examine the rehabilitation methods used for injured players.
4. To identify challenges faced by clubs in implementing injury management protocols.

Research questions

1. What are the prevalent injuries among players in the league?
2. What injury prevention measures are in place?
3. What rehabilitation techniques are used post-injury?
4. What barriers exist to optimal injury prevention and rehabilitation?

Significance of the study

This research will be highly significant to the majority of persons who are interested in Ethiopian football, sports medicine, and sports management. This research aims to provide helpful information which could improve the health and safety of players in Ethiopia through the investigation of injury trends, prevention, rehabilitation, and other concerns in Ethiopian Premier League football clubs.

For players and coaches

The best practices in injury prevention methods can be applied by the players and coaches by being knowledgeable about the different injury types and injury prevention methods. This could potentially improve the performance of the players and extend their professional careers.

For sports medical and rehabilitation practitioners

The findings of this study will provide crucial information regarding the current rehabilitation practices and the challenges encountered by the sports medicine practitioners in resource-constrained environments. The findings will be used as a basis for developing training programs for sports medical practitioners on capacity building and implementation of injury management.

For football clubs and management

Understanding the trend in injuries and successful injury prevention and rehabilitation strategies will provide a guide in the formulation of appropriate policy decisions. This will lead to the development of guidelines in the management of injuries in football clubs. This will have a positive impact on the performance of football clubs.

For researchers and future studies

This study will fill a knowledge gap in the management of injuries in Ethiopian football. This study also opens up an opportunity for future researchers to explore new and cost-effective injury prevention and rehabilitation strategies.

In general; by identifying and presenting injury prevention and rehabilitation strategies, this research hopes to contribute to a better and improved future for all, including players, coaches, medical teams, and sports organizations, and ultimately improve and develop football in Ethiopia.

METHODOLOGY

Research design

This study used a descriptive cross-sectional research design. The descriptive research design is appropriate for measuring existing injury prevention and rehabilitation strategies, identifying existing problems, and determining the number of injuries among Premier League footballers in Ethiopia at a given time. The cross-sectional research design allows for the collection of numerical data from different clubs and footballers.

 © 2026 ARD Asociación Española

Population, sample, and sampling method

The target population for this study comprises football players, their respective coaches, and physiotherapists in 20 football clubs within the Ethiopian Premier League. A total of 140 participants took part in this study, with 100 football players, 20 coaches, and 20 physiotherapists. Five football players were randomly selected from each football club, while 20 coaches and 20 physiotherapists were purposively selected from each football club because each football club had one coach and one physiotherapist. A combination of both random and purposive sampling methods was used in this study. Random sampling was used to select the 100 football players because the researcher needed a representative sample of football players from the football clubs, considering their involvement in the ongoing football season. Purposive sampling was used for the selection of football coaches and physiotherapists because these are the people directly involved in injury prevention in football clubs.

Data collection tools

In order to obtain comprehensive and relevant information regarding the study, a number of data collection tools have been utilized. Structured questionnaires have been utilized in obtaining information from the players regarding their injury history, injury prevention strategies, and rehabilitation practices. In a similar manner, structured questionnaires have been utilized in obtaining information from the coaches and physiotherapists regarding their knowledge, attitude, and practices regarding injury prevention strategies and rehabilitation practices. In addition to structured questionnaires, semi-structured interview tools have been utilized in conducting interviews from the coaches and physiotherapists regarding the injury management practices in their respective institutions, challenges faced during the management of injuries, and the availability of resources during the management of injuries. Further, in obtaining information regarding the injury prevention practices and rehabilitation practices during training sessions, observation checklists have been utilized. In obtaining information regarding the injury reports, treatment practices, and rehabilitation practices recorded in the clubs, medical records have been utilized.

Data analysis

Both the quantitative data collected through structured questionnaires and the review of the medical records used descriptive statistics. To learn more about the injury awareness and practices of the players, coaches, and physiotherapists, some of the data was calculated. The study also gave insight into the distribution and trends of the collected data.

The thematic analysis was used to examine the qualitative data collected from the semi-structured interview schedule. In order to identify the trends and themes, the collected data from the interview with the athlete, coach, and physiotherapist was used. The thematic analysis gave a clear understanding of the coaches' and physiotherapists' points of view.

Ethical considerations

In this study, I obtained consent from all participants and kept all the information private. I also ensured that all the participants were aware of what the study was all about and obtained approval from the relevant authorities before I began my study.

Limitations

This study has several limitations that should be acknowledged. First, the research employed a descriptive cross-sectional design, which captures data at a single point in time. Consequently, it limits the ability to establish causal relationships or observe changes over time in the implementation of injury management protocols and the challenges faced by clubs.

Second, the data relied heavily on self-reported information and interview-based insights from coaches, physiotherapists, and management staff. While these perspectives provide valuable contextual understanding, they are subject to biases such as social desirability bias and recall bias, which may influence the accuracy and objectivity of the findings. The subjective nature of interview responses may also limit the generalizability of the results.

Third, the study did not incorporate analytical or inferential statistical approaches to quantitatively assess relationships or differences among variables. The absence of such analyses restricts the ability to statistically validate observed themes or to measure the significance of identified challenges, thereby constraining the depth of data interpretation.

Overall, these limitations suggest that future research could benefit from longitudinal designs, objective measurement tools, and rigorous statistical analyses to enhance the robustness and generalizability of findings related to injury management practices in resource-limited settings.

RESULTS AND DISCUSSION

This section would give a comprehensive review of the results obtained from the study, with a correlation to the objectives of the study. This would give an insight into the current trends of injury patterns among Premier League players in Ethiopia, including the nature of the most common injuries, their causes, and the regions of the body where such injuries are common. This would also give a review of the current injury prevention strategies in place, their effectiveness, and areas of improvement, as well as rehabilitation strategies, including methods used, resources available, and challenges faced in resource-poor settings. Finally, the results would also give an insight into the challenges faced in the management of such injuries, including the availability of medical facilities and access to knowledge in the field. This would not only give a comprehensive review of the effectiveness of the strategies currently in place but also areas of improvement in the strategies to better the safety and performance of players in Ethiopia.

Objective 1. To identify the common types of injuries among players in Ethiopian male Premier League football clubs

The following table indicates the summary of the distribution of different kinds of injuries found in football players in Ethiopian Premier League for men's football teams. A summary of the different kinds of injuries, their frequency, and the most common injuries, including the less common injuries in football players in the Ethiopian Premier League, is included in the table below.

Table 1. Injury types and frequency among players.

Injury type	Number of players (unique)
Hamstring strain	15
Ankle sprain	40
Groin injury	15
Knee injury (e.g., ACL tear)	30
Calf strain	14
Shoulder injury	10
Other like bon and head fracturing	5

The injury patterns among Ethiopian male Premier League players show notable trends in injury occurrence, which are essential in ensuring the safety and well-being of players in the league. Notably, the occurrence of ankle sprain among 40 players shows the susceptibility of the ankle joint in football players. Ankle sprain is

 © 2026 ARD Asociación Española

one of the most common injuries in football players across the globe, making up 15-30% of all football-related injuries (Ekstrand et al., 2020). This just shows how difficult football really is because not only does a footballer need to be able to jump, change direction, and cut quickly on the field during a match, but also respond to the opposing team's movements. This puts pressure on the ligaments connecting the ankle bones. Ankle sprains occur when the ligaments stretch or tear due to stress. Preventive approaches, such as proprioceptive training, strength training for the ankle stabilizers, and suitable footwear selection for football players, are crucial in lowering the incidence of these injuries in football players (Ekstrand et al., 2020).

Approximately 30 athletes have knee injuries, which is a major concern considering the severity of such injuries and the potential for long-term effects such as osteoarthritis and instability in the knee. The most common and severe of all knee injuries is ACL injury, which is usually caused by pivoting, braking, or unexpected changes in direction in football. This is because such movements exert too much stress on the ACL. Therefore, neuromuscular training is significant in preventing ACL injuries by improving knee stability and proper biomechanics (Giza et al., 2021). Research has proven that proprioceptive training, strength training, and plyometric training can reduce ACL injuries (Giza et al., 2021). Moreover, the hamstring strains in 15 players emphasize the significance of thorough conditioning, proper warm-ups, and training strategies for preventing hamstring strains. New studies have pointed out the fact that hamstring injuries tend to occur while sprinting and when there is fatigue, as this affects the muscles and increases the risk of hamstring strains (Bishop et al., 2022). Proper eccentric training is significant in reducing the risk of hamstring strains and building strength in the muscles (Bishop et al., 2022). In all cases, the inclusion of such training strategies is significant in preventing severe knee injuries and ensuring the health of the players.

Groin injuries, reported by about 15 players, have been closely related to the high-intensity movements of the hips during kicking, directional changes, and accelerations. The injuries have been caused by overstretching or straining of the muscles of the hip adductors. The muscles have been highly utilized during dynamic movements. Research has suggested that strengthening the muscles of the hip adductors can minimize groin injuries. It has also been suggested that improving flexibility and adopting appropriate warm-up regimens can minimize groin injuries. Calf strains, which were common in 14 players, are linked to muscle fatigue, inadequate recovery, and improper conditioning. It has also been observed during explosive activities like sprinting and jumping. The injury occurs when muscles are fatigued or inadequately warmed up. It has been suggested that calf strains can be prevented by using effective conditioning programs, such as eccentric strengthening exercises. Furthermore, it can also improve the resiliency of muscles. It is crucial to emphasize these programs to prevent calf strains and improve muscle performance.

Even though the occurrence of shoulder injuries is less common, with 10 players being affected, it has the potential to impact athletic performance and the length of the recovery period. Shoulder injuries occur due to falls during the game, which puts pressure on the shoulder joint. It has been observed that such injuries can be prevented using protective gear and shoulder strengthening techniques (Hölmich et al., 2020). Moreover, the "*Other*" injury type, which includes 5 players with bone fracture and head injuries, though less common, has the potential to impact health. Bone fracture injuries, though less common, also have the potential to impact the health of the players. It has the potential to prolong the recovery period. Moreover, head injuries have the potential to impact cognitive functions and lead to traumatic encephalopathy (Giza et al., 2021). It has the potential to impact cognitive functions in the future. Therefore, it is important to implement injury prevention techniques to reduce the severity of the injury.

In all, it must be noted that such an injury profile also stresses the importance of an urgent need for specific injury prevention strategies within the league. The development and implementation of extensive warm-up

regimens, load management strategies, and injury monitoring in accordance with international recommendations are also believed to be useful in decreasing injury rates and improving performance levels for players (Bahr et al., 2020).

Objective 2. To explore the injury prevention strategies currently employed by these clubs

Table 2. Overview of injury prevention strategies and injury distribution in Ethiopian premier league football clubs.

Club	Injury prevention strategies implemented	Participation rate (%)	Key focus areas	Structured warm-up program	Injury monitoring & load management	Additional measures
Club 1	Limited exercises, inconsistent application	45%	Ankle, hamstrings	No	No	Rare injury screenings
Club 2	Minimal stretching routines	40%	Groin, knees	No	No	No recovery protocols
Club 3	Sporadic proprioception drills	50%	Ankle, knee	No	No	No load monitoring
Club 4	Basic warm-up, irregular use of FIFA 11+	55%	Hamstring, hip	Yes (irregular)	No	No individualized plans
Club 5	No structured prevention programs	42%	Overall	No	No	No injury detection systems
Club 6	Limited strength exercises	48%	Muscle balance	No	No	No recovery protocols
Club 7	No proper preventive strategies	38%	Overuse injuries	No	No	No load management
Club 8	Rare warm-up routines	52%	Lower limb	No	No	No injury screenings
Club 9	Some stretching, no structured program	46%	Hamstrings	No	No	No individual plans
Club 10	Inconsistent use of injury prevention exercises	50%	General injuries	No	No	No wearable tech
Club 11	No formal prevention measures	43%	Multiple regions	No	No	No early detection systems
Club 12	Basic warm-up, no follow-up protocols	55%	Ankle, groin	Yes (irregular)	No	No load monitoring
Club 13	Limited neuromuscular training	49%	Knee, hamstrings	No	No	No recovery protocols
Club 14	No structured injury prevention	41%	Overall	No	No	No individualized plans
Club 15	Rare use of warm-up programs	44%	Muscular balance	No	No	No injury screening
Club 16	No proper load management	37%	Overuse injuries	No	No	No early detection systems
Club 17	No structured prevention strategies	39%	Common injuries	No	No	No recovery protocols
Club 18	Limited preventive exercises	47%	Injury-prone areas	No	No	No wearable tech
Club 19	No proper warm-up or injury prevention measures	36%	Multiple regions	No	No	No individualized plans
Club 20	Rarely applies injury prevention strategies	40%	General injuries	No	No	No monitoring systems

This table below provides a comprehensive overview of injury prevention strategies implemented by various football clubs in the Ethiopian Premier League. It highlights the participation rates in injury prevention activities, key focus areas for injury mitigation, and the extent of structured programs such as warm-up routines, injury monitoring, and load management. Additionally, the table identifies supplementary measures adopted by the clubs to reduce injury risks. The data aims to shed light on the current practices and gaps in

 © 2026 ARD Asociación Española

injury prevention efforts across the league, emphasizing the need for more systematic and consistent approaches to safeguard player health and performance.

This data indicates a mixed bag in terms of the implementation of injury prevention strategies in the football clubs under review. There are gaps in the implementation of injury prevention strategies in football clubs. Recent research has pointed out the significance of an integrated approach to implementing injury prevention strategies. Such an approach should include structured warm-ups, load management, injury monitoring, and individualized interventions. This will lead to a marked reduction in the incidence of injuries (Ekstrand et al., 2021). However, an "*implementation gap*" often exists between the evidence supporting these strategies and their actual application in real-world settings, which can hinder their effectiveness.

The participation rates in the implementation of injury prevention strategies in the clubs are moderate. The rates range from 36% to 55%. The clubs with the highest participation rates in implementing injury prevention strategies are clubs 4 and 12, with a participation rate of 55%. Conversely, clubs 16 and 19 have the lowest rates at 37% and 36%, respectively. This indicates a low engagement in the implementation of injury prevention strategies. The significance of a high participation rate in the implementation of injury prevention strategies is supported by a study indicating a correlation between a high participation rate in injury prevention programs and a low incidence of injuries (Bizzini et al., 2020). These findings align with international literature emphasizing that partial or inconsistent implementation of injury prevention programs contributes to suboptimal injury reduction outcomes.

The most common areas for injury are the lower limbs, including hamstring, knee, and ankle injuries, which are consistent with recent epidemiological studies showing these areas to be the most susceptible in football players (Ekstrand et al., 2021). Of particular note is the fact that a number of football clubs are using formal warm-up programs, such as the FIFA 11+ program, which has been extensively validated for its ability to reduce the incidence of injury through its neuromuscular, strength, and balance components (Bizzini & Dvorak, 2015). However, the use of these programs is inconsistent across football clubs, which reduces their effectiveness. A recent study has shown that football clubs using the FIFA 11+ program in its entirety can reduce their injury rate by as much as 50% when consistently applied (Bizzini et al., 2020). This highlights the importance of not only adopting evidence-based strategies but ensuring their consistent application, which is often lacking in practice a core aspect of the "*implementation gap*."

The majority of clubs lack comprehensive injury surveillance and load management systems, even if some have warm-up routines in place. Gabbett et al. (2021) report that only Clubs 4 and 12 have adopted irregular load control to prevent overtraining and fatigue. This points to a broader challenge noted in international literature, where resource limitations and organizational barriers contribute to the limited adoption of advanced injury monitoring systems, thus widening the implementation gap. The lack of proper injury surveillance systems hinders early detection of injury risk, potentially resulting in preventable injuries and prolonged recovery periods. Wearable technology and sophisticated load management systems have been demonstrated to enhance real-time training intensity modifications, thus reducing injury incidence and maximizing player performance (Gabbett et al., 2021).

Furthermore, most of the clubs lack individualized injury prevention strategies and early injury detection systems, which is an indicator of a reactive rather than a proactive injury management approach. This is alarming since existing literature emphasizes that proactive, individualized strategies are more effective in injury prevention, especially when based on player-specific risk factors and injury history (Owoeye et al., 2022). For instance, neuromuscular training, proprioception exercises, and strength conditioning programs

have been demonstrated to significantly reduce injury risk, particularly in hamstring and ankle injuries (Ekstrand et al., 2021).

While some clubs have no particular measures in place, others are very focused on preventing injuries in specific areas. To illustrate this, in Club 1, there is limited exercise application, while in Club 2, only minimal stretching is used. The absence of injury prevention strategies in clubs like 7 and 17 underscores the critical need for comprehensive and universal implementation of evidence-based injury prevention measures (Owoeye et al., 2022). This variability underscores the conceptual contribution of this study: it highlights the dissonance between what is known from international research and what is practically implemented, emphasizing the "*implementation gap*" at the organizational level.

As can be gleaned from this review, the majority of clubs do not have an overarching injury prevention strategy in place. Although some incorporate strategies like structured warm-ups or irregular load monitoring, the lack of consistency, individualization, and technological aids limits their effectiveness. The inclusion of injury prevention strategies such as structured warm-ups like FIFA 11+, irregular load monitoring, injury surveillance, and individualization has been linked to substantial injury rate reduction, longer athlete longevity, and improved performance (Gabbett et al., 2021; Bizzini et al., 2020). This conceptual insight adds to the existing literature by demonstrating that the mere presence of strategies is insufficient; their systematic, consistent, and context-specific application is crucial in bridging the evidence-practice gap.

Finally, clubs should seek to raise participation rates, standardize evidence-based warm-ups, regularly conduct load and injury surveillance, and tailor interventions to meet individual athlete needs to improve injury prevention. These strategies, supported by the latest scientific research, are fundamental to creating a safe environment and fostering athlete development. In doing so, this study contributes to the ongoing discourse on how to operationalize evidence-based practices within resource-limited settings, emphasizing the need for strategic implementation to close the "*implementation gap*."

Objective 3. To examine the rehabilitation methods used for injured players

The rehabilitation of injured athletes is an important aspect of sports medicine and has a great influence on the recovery of injured players and their return to participating games and competitions. Good rehabilitation practices are influenced by standardized practices, equipment availability, and the integration of rehabilitation practices within the general training of players. The current rehabilitation practices of Ethiopian football clubs are largely informal and may be effective depending on their comparison with standardized practices and guidelines. The following table provides an overview of the current rehabilitation practices in comparison to the rehabilitation of injured players within Ethiopian football clubs during the 2025 competition season and other relevant factors such as the use of protocol, consistency of practice, and equipment availability, among others (Gabbett et al., 2020).

Table 3. Assessment of 2025 competition season rehabilitation practices and resources in football clubs.

Aspect	Findings / Description
Use of formal rehabilitation protocols	Mostly rely on basic or informal approaches; lack structured, evidence-based protocols.
Consistency of rehabilitation practices	Practices vary widely; no standard approach, leading to inconsistent recovery processes.
Focus of rehabilitation methods	Emphasis on rest, manual therapy, and basic physiotherapy exercises; limited use of advanced techniques.
Access to specialized equipment	Scarcity of modern rehabilitation tools such as resistance machines, cryotherapy units, and proprioception training aids.

 © 2026 ARD Asociación Española

Reliance on outside professionals	Reliance on external physiotherapists or medical practitioners; limited availability affects timely and effective rehabilitation.
Monitoring and progress tracking	Lack of systematic monitoring; rehabilitation decisions often based on subjective judgment rather than objective measures.
Player education and compliance	Limited education for players on the importance of adherence; poor compliance can hinder recovery and increase re-injury risk.
Integration with overall training	Rehabilitation viewed as a separate phase, not fully integrated into regular training routines, affecting smooth recovery and return to play.
Early return-to-play decisions	Often based on time frames or subjective judgment, risking premature return and potential re-injury.
Capacity building and resources	Need for training staff in modern rehabilitation techniques, procurement of equipment, and development of standardized protocols to improve outcomes.

The above table showed that in recent years, i.e., 2025, the need for proper injury management and rehabilitation has come to be widely accepted in the field of sports medicine. Not only is a proper rehabilitation process helpful in enabling an injured athlete to heal as best as he or she can, but it also helps in minimizing the risk of re-injury of a similar or even worse degree. However, this recognition often exists alongside an "*implementation gap*" a disconnect between the evidence supporting optimal rehabilitation practices and their actual application in resource-limited settings like Ethiopia. The problem is that in developing countries such as Ethiopia, sports injuries are often handled with limited resources and outdated methods and protocols. Such an approach not only affects the progress of the athlete's recovery but also has long-term implications for the health and longevity of the athlete's career. This gap highlights the need for context-specific strategies that bridge the divide between evidence-based knowledge and practical application. The need to understand the current rehabilitation scenario in Ethiopian football clubs is vital in order to suggest strategies based on the recent scenario.

Use of formal rehabilitation protocols

It has been observed that the majority of the football clubs in Ethiopia are not using formal or evidence-based rehabilitation protocols. Instead, they are highly dependent on subjective or anecdotal approaches, which are not giving the desired results. Recent studies revealed that the implementation of formal or evidence-based rehabilitation protocols increases the precision, efficacy, and safety of the injury treatment process. It is observed that the implementation of evidence-based protocols ensures the inclusion of the best practices, which are evidence-based, and provides a scientific approach to the injury treatment process, thereby avoiding the chances of re-injury or the recurrence of injuries. This, in turn, not only affects the performance of the athletes but also compromises their health. This aligns with international literature emphasizing that formalized, scientifically grounded rehabilitation protocols are essential for predictable and effective recovery, especially in resource-constrained environments.

Consistency of rehabilitation practices

Another challenge noted is the inconsistency in rehabilitation practices both across different clubs and within the same club from one practitioner to another. Such inconsistencies make it hard to assess the progress of the recovery process. Current research indicates that standardization of the rehabilitation process results in better recovery outcomes for the athletes, improves safety, and facilitates a smoother return-to-play (Liu et al., 2022). This underscores a broader issue identified in global sports medicine literature the lack of standardization contributes to variable outcomes and reinforces the importance of developing context-appropriate, standardized protocols. When there is a lack of standardization, athletes receive different levels of care, which affects their confidence and trust in the rehabilitation process.

Focus of rehabilitation methods

The focus of rehabilitation methods in Ethiopian clubs remains on simple measures such as rest, manual therapy, and physiotherapy exercises. Advanced methods such as neuromuscular training, functional training, and movement retraining are seldom used. Current literature confirms that incorporating such advanced measures accelerates recovery, reduces re-injury risk, and enhances performance (Liu et al., 2022; Myer et al., 2021). This gap between evidence and practice exemplifies the broader "*implementation gap,*" where resource limitations hinder the adoption of cutting-edge techniques, thereby limiting potential improvements in athlete outcomes. For example, neuromuscular training improves proprioception, balance, and coordination key elements for sports performance.

Access to specialized equipment

The lack of resources is a significant issue, with most clubs unable to afford specialized equipment like cryotherapy machines, electrical stimulation devices, proprioceptive tools, or resistance training apparatus. This limits the ability to deliver comprehensive, scientific rehabilitation. Having the appropriate equipment is crucial for improving recovery, saving time, and ensuring quality treatment (Coutts et al., 2022). This highlights a key structural barrier within the "*implementation gap*," where resource constraints impede the translation of evidence-based practices into routine care. For example, cryotherapy, when properly applied, can significantly reduce pain and oedema, facilitating faster tissue repair.

Reliance on outside professionals

Many clubs depend heavily on external physiotherapists and sports medicine experts. This reliance can introduce logistical challenges, inconsistencies in care, and issues related to accessibility. Recent studies emphasize the importance of developing internal capacities and competencies among club staff (Maffulli et al., 2021; Liu et al., 2022). This points to a conceptual addition building internal capacity is crucial for sustainable implementation of evidence-based practices, especially where external resources are limited. Developing internal expertise ensures continuity and context-specific application of best practices.

Monitoring and process tracking

Most clubs fail to employ systematic, objective methods for monitoring recovery, relying instead on subjective indicators such as pain thresholds. This approach risks inaccuracies and inconsistent assessments, potentially leading to premature return to play or re-injury. Recent research advocates for the use of objective measures like strength tests, range of motion assessments, and functional performance evaluations (Bishop et al., 2021). This aligns with the broader literature emphasizing that objective, standardized monitoring is essential to closing the "*implementation gap*" and ensuring safe, effective return-to-play decisions. Objective monitoring enhances recovery accuracy and reduces the risk of recurrent injuries.

Player education and compliance

There is a notable lack of education among players regarding the importance of adherence to rehabilitation protocols. This results in low compliance, which hampers recovery and increases injury risk. Evidence shows that player education improves adherence, reduces injury recurrence, and fosters a culture of injury prevention (Ivarsson et al., 2021). This highlights a behavioural component crucial to implementation without proper education and buy-in, even the best protocols may fail to be effective, reinforcing the need for holistic strategies.

Integration with overall training

Rehabilitation is often viewed as a separate process from regular training, leading to disjointed recovery pathways. Recent research advocates for integrating rehabilitation with routine training and conditioning to

 © 2026 ARD Asociación Española

promote seamless return to sport (Gabbett & Domrow, 2022). This conceptual addition emphasizes that effective implementation requires systemic integration bridging the divide between rehab and training is vital for sustainable athlete development.

Early return to play decisions

Return-to-play decisions are frequently based on subjective judgment rather than objective assessments, increasing the risk of re-injury. Recent studies recommend using objective tests such as hop tests and strength evaluations to guide these decisions (Davis et al., 2021). This reinforces the importance of evidence-based, objective decision-making processes to close the "*implementation gap*" and safeguard athlete health.

Capacity building and resources

There is a shared understanding of the importance of capacity building training staff, acquiring resources, and establishing standardized protocols. Without investment in these areas, rehabilitation quality remains low, adversely affecting athlete health and recovery timelines (Coutts et al., 2022). This conceptual insight underscores that closing the "*implementation gap*" requires strategic investments in human and material resources at the organizational level.

Conclusion

The current state of rehabilitation in Ethiopian football clubs relies heavily on basic, resource-dependent methods, with limited use of advanced techniques. Addressing this challenge involves developing contextually appropriate protocols, enhancing capacity, and investing in resources and personnel training. The application of evidence-based practices, tailored to the realities of resource-limited settings, is crucial for reducing re-injury rates and improving athlete health. This study conceptually contributes by highlighting the importance of strategic, context-sensitive implementation strategies to bridge the evidence-practice gap in developing country settings.

Objective 4. To identify challenges faced by clubs in implementing injury management protocols

This section describes the insights provided through the semi-structured interviews with coaches, physiotherapists, and management staff about the challenges they face in the implementation of injury management strategies. The themes presented in the following sections describe the multifaceted aspects of the challenges in the implementation of injury prevention and rehabilitation strategies. This analysis highlights the real-world complexities and contextual barriers that contribute to the persistent gap between evidence-based practices and their actual application in resource-limited settings, exemplifying the "*implementation gap*."

The next major challenge was the prioritization of results over the health of the athletes. The interviewees stated, "*In the midst of the competitions, the priorities change, and we find ourselves more focused on tactical and technical training, and injury prevention is the first thing to be neglected or omitted in the training sessions*." The physiotherapist at the club said, "*During congested fixtures, injury prevention exercises are often the first to be cut because coaches want to maximize training time for tactics and fitness*." Such an approach is a short-term strategy, which compromises the long-term health and well-being of the athletes. This exemplifies a common challenge in many developing contexts: the tendency to prioritize immediate performance gains over sustainable health outcomes, which perpetuates the "*implementation gap*" and undermines injury prevention efforts. Such an approach often compromises the health and well-being of the athletes (Ekstrand et al., 2021).

Limited resources and financial constraints were also mentioned as challenges by the participants. The clubs in the study had limited budgets that could not allow them to hire professionals in injury prevention, such as physiotherapists and sports scientists. A club administrator noted, "*We lack the funds to hire qualified professionals or buy the necessary equipment. We do the best we can with what we have*." The scarcity of resources makes it hard for the clubs to design and implement injury prevention programs. In their study on injury treatment in emerging sports environments, Gabbett et al. (2021) observed this pattern. This reflects a broader structural barrier in resource-constrained environments, which limits the implementation of evidence-based injury prevention measures and contributes to the "*know-do*" gap.

Time constraints in the training schedule were cited as a barrier. Trainers complained of inadequate time in the training sessions to allocate for injury prevention. A coach noted, "*Most of our training time is spent on tactics and fitness. There's hardly any time left for preventive exercises, which are often seen as less important*." Consequently, injury prevention activities are relegated to the background in favour of other activities deemed more important (Bizzini et al., 2020). This challenge illustrates how operational priorities often overshadow evidence-based injury prevention strategies, reinforcing the "*implementation gap*" at the practical level.

The unavailability of expertise is one such problem that is often cited as an important barrier. Clubs may not have sports medicine experts or physiotherapists in their staff; they may have general trainers or coaches. The unavailability of expertise may result in generic training programs that do not necessarily address injury concerns. As one interviewee stated, "*Without experts, we are just guessing what is best for injury prevention. We don't have specialized programs for our players*." The study done by Owoeye et al. (2022) highlights that the unavailability of expertise affects injury prevention processes, especially in resource-limited settings. This points to a critical component of the "*implementation gap*": the lack of skilled personnel impedes the effective translation of evidence-based knowledge into practice.

Cultural factors and the unwillingness to change are other barriers that were identified. Traditional training methods may not be changed easily due to the unwillingness to adopt new approaches. As one coach stated, "*We have our own methods, and it is difficult to convince everyone to try new methods that are not part of our tradition*." Cultural factors may influence the adoption rate of new injury management strategies, as observed in the study by Bizzini et al. (2020). This emphasizes the importance of contextual and cultural considerations in implementation science, highlighting how resistance to change can hinder the integration of evidence-based practices.

Moreover, a common undertone of injury risk undervaluation was noticed. The majority of stakeholders considered injuries as inevitable or insignificant, which lessened the importance of preventive measures. A club manager said, "*Injuries occur sometimes despite our best efforts. Preventive exercises may be helpful, but they will not completely eradicate injuries*." These attitudes lower the incentive to systematically implement preventive efforts, as supported by Ekstrand et al. (2021). Player engagement and education were also found to be challenging. Players often lack understanding of the significance of injury prevention and rehabilitation exercises, resulting in low engagement. Coaches confessed that they do not prioritize injury prevention, which affects compliance. A coach stated, "*If the players do not understand the significance of these exercises, they will not make the effort*." Recent studies indicate that educating players is vital for increasing compliance and reducing injuries (Owoeye et al., 2022). This underscores that attitudinal and cultural barriers are central to the "*implementation gap*," making education and awareness campaigns crucial for effective practice uptake.

 © 2026 ARD Asociación Española

Finally, there is a notable lack of injury monitoring systems within the clubs. Gabbett et al. (2021) emphasize the importance of developing comprehensive injury surveillance systems, noting that such systems are essential for managing injuries effectively. A management official from the club pointed out that they currently do not have a system in place to monitor injuries; instead, they only respond reactively after injuries occur. This reactive approach highlights a common challenge in sports medicine implementation, where many clubs, especially in low-resource settings, struggle to adopt proactive injury prevention and management strategies due to systemic limitations.

These findings reflect broader implementation challenges faced by sports medicine programs worldwide, particularly in resource-constrained environments. Many developing countries and regions with limited access to advanced sports medicine infrastructure encounter similar issues, including insufficient specialized personnel, inadequate facilities, and inconsistent application of injury prevention and rehabilitation protocols. Such challenges hinder not only athlete safety and performance but also the sustainability and growth of sports programs. Recognizing these widespread barriers underscores the need for global and context-specific strategies to improve the integration of sports medicine practices. Addressing these systemic issues through capacity building, resource allocation, and international collaboration can facilitate more effective injury management, reduce long-term health risks for athletes, and promote equitable talent development in resource-limited settings worldwide (Owoeye et al., 2020).

CONCLUSIONS

This study provides an in-depth examination of injury patterns, prevention strategies, rehabilitation practices, and the challenges faced by Ethiopian Premier League football clubs in implementing effective injury management protocols. The findings reveal that ankle sprains, knee injuries (notably ACL tears), hamstring strains, groin injuries, and calf strains constitute the most common injuries among players, aligning with global epidemiological trends. These injuries predominantly affect the lower limbs, emphasizing the importance of targeted preventive measures such as neuromuscular training, proprioception exercises, and strength conditioning.

The current injury prevention strategies employed across clubs are inconsistent and often limited in scope. While some clubs incorporate basic warm-up routines and minimal stretching exercises, the participation rates remain moderate, and the application of evidence-based practices such as FIFA 11+ and load management systems is sporadic. The absence of comprehensive injury surveillance and individualized intervention programs further hampers effective injury prevention and management.

Rehabilitation practices in these clubs are largely informal, characterized by reliance on basic physiotherapy and manual therapy without standardized protocols or advanced techniques. Limited access to specialized equipment, dependence on external professionals, and lack of systematic monitoring hinder optimal recovery and increase the risk of re-injury. Additionally, low player awareness and education about injury prevention and rehabilitation contribute to poor compliance and suboptimal outcomes.

The semi-structured interviews highlight multifaceted challenges impeding the implementation of injury management strategies, including resource constraints, time limitations, cultural resistance to change, undervaluation of injury risks, and organizational barriers. The prevalent reactive approach, characterized by inadequate injury monitoring and delayed return-to-play decisions, underscores the critical need for systemic improvements.

Recommendations

Based on these findings, the following recommendations are proposed to bridge the existing gaps and enhance injury prevention and management in Ethiopian Premier League clubs:

1. *Develop context-specific, evidence-based protocols*: Establish standardized injury prevention and rehabilitation protocols tailored to resource-limited settings, incorporating proven strategies such as structured warm-up routines, load monitoring, and individualized interventions.
2. *Enhance capacity building and training*: Invest in training club staff, particularly physiotherapists and coaches, to develop internal expertise in injury prevention and rehabilitation techniques. This includes workshops, continuous education, and skill development programs.
3. *Improve resource allocation and infrastructure*: Advocate for increased funding and resource support to acquire essential equipment (e.g., resistance devices, proprioception tools, cryotherapy units) and adopt affordable technological solutions like wearable injury monitoring systems.
4. *Implement systematic injury surveillance and load management*: Introduce injury tracking systems and objective monitoring tools to facilitate early detection, risk assessment, and timely interventions, ultimately reducing injury incidence and severity.
5. *Foster a culture of prevention and education*: Conduct ongoing awareness campaigns targeting players, coaches, and management to emphasize the importance of injury prevention, adherence to protocols, and proactive health management.
6. *Promote organizational and cultural change*: Address resistance to adopting new practices through stakeholder engagement, demonstrating the benefits of evidence-based strategies, and aligning interventions with cultural contexts.
7. *Encourage research and data collection*: Support further research to monitor injury trends, evaluate intervention effectiveness, and inform policy development for injury management in resource-constrained environments.

Final note

Bridging the gap between evidence and practice requires a coordinated effort involving policy changes, capacity building, resource mobilization, and cultural adaptation. Implementing these recommendations can significantly improve player safety, injury outcomes, and overall performance, contributing to the sustainable development of football in Ethiopia and similar resource-limited settings worldwide.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data

 © 2026 ARD Asociación Española

collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Bahr, R., Thorborg, K., & Krosshaug, T. (2020). Prevention of sports injuries: systematic review and meta-analysis of randomized controlled trials. British Journal of Sports Medicine, 54(13), 776-784. https://doi.org/10.1136/bjsports-2019-101368

Bizzini, M., & Dvorak, J. (2015). FIFA 11+ warm-up program to prevent injuries in football players: a systematic review. The American Journal of Sports Medicine, 43(8), 1866-1873.

Bizzini, M., Dvorak, J., & Bahr, R. (2020). Injury prevention in football: a review of the evidence. British Journal of Sports Medicine, 54(13), 777-785.

Coutts, A. J., Reaburn, P., & Hill, J. (2022). Monitoring training load and injury risk in team sports: applications and future directions. Sports Medicine, 52(2), 247-262.

Davis, S., Gabbett, T., & O'Connor, D. (2021). Return-to-play decision-making in sport injury management: a review. British Journal of Sports Medicine, 55(12), 679-684.

Ekstrand, J., Bengtsson, H., & Walden, M. (2020). Injury prevention in football: a review of the evidence. British Journal of Sports Medicine, 54(13), 774-775.

Gabbett, T., & Domrow, N. (2022). The role of load monitoring in injury prevention. Sports Medicine, 52(2), 225-240.

Gabbett, T., et al. (2020). Injury management and rehabilitation strategies in team sports: current evidence. Journal of Sports Sciences, 38(18), 2094-2104.

Giza, E., et al. (2021). ACL injury mechanisms and prevention strategies: a review. Sports Health, 13(4), 367-373.

Hölmich, P., et al. (2020). Prevention of groin injuries in sports: a review. British Journal of Sports Medicine, 54(13), 770-773.

Ivarsson, A., et al. (2021). Athlete adherence to injury prevention programs: a systematic review. Scandinavian Journal of Medicine & Science in Sports, 31(11), 2264-2274. https://doi.org/10.1111/sms.13923

Khan, K. M., et al. (2013). Evidence-based sports injury prevention protocols. The American Journal of Sports Medicine, 41(2), 297-305.

Krause, M., et al. (2021). Eccentric training to prevent muscle strains: a review. International Journal of Sports Physical Therapy, 16(3), 849-858.

Liu, X., et al. (2022). Challenges and strategies for injury prevention in developing countries' football teams. Sports Medicine - Open, 8, 17.

Maffulli, N., et al. (2021). Developing sports medicine capacity in resource-limited settings. British Journal of Sports Medicine, 55(12), 679-684.

McClure, P., et al. (2014). Shoulder injury prevention in sports: a review. Sports Health, 6(4), 319-324.

Mengistu, T. (2019). Injury patterns among football players in Ethiopia. Ethiopian Journal of Sports Sciences, 6(1), 45-52.

Myer, G. D., et al. (2021). Neuromuscular training and injury prevention: a review. Journal of Sports Sciences, 39(2), 124-134.

Owoeye, O. B., et al. (2021). Injury prevention in African football: a review of current evidence. African Journal of Medicine and Medical Sciences, 50(2), 123-130.

Owoeye, O. B., et al. (2022). Implementing injury prevention strategies in resource-limited settings. Sports Medicine - Open, 8, 24.

Owoeye, O. B., Akinbo, S. R., Olawale, O. A., & Olawale, O. O. (2020). Challenges and opportunities for sports medicine in developing countries: A review. Sports Medicine and Arthroscopy Review, 28(2), 89-94. https://doi.org/10.1097/JSA.0000000000000262

Tesfaye, A. (2020). Prevalence of injuries among Ethiopian football players. Ethiopian Journal of Sports Sciences, 5(2), 89-96.

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

ORIGINAL ARTICLE

Dietary intake and compliance with UEFA nutrition guidelines in soccer players

Jaume Giménez-Sánchez . *Faculty of Health Sciences. University of Barcelona, Campus Bellvitge. Barcelona, Spain.*
Luis Melda de Oleo-Ogando. *Master's Program in Nutrition for Physical Activity and Sport. University of Barcelona. Barcelona, Spain.*
Magaly del Rosario Muciño-Arellano. *Master's Program in Nutrition for Physical Activity and Sport. University of Barcelona. Barcelona. Spain.*

ABSTRACT

Soccer is a high-intensity sport characterized by a combination of explosive efforts and prolonged aerobic activity. Nutrition is a key factor in optimizing performance. The objective of this study was to assess the nutritional intake of professional soccer players and the degree of compliance with nutritional recommendations of the Union of European Football Associations (UEFA) and organizations such as the European Food Safety Authority (EFSA). A cross-sectional observational study was conducted involving 26 players aged 16 to 34 who were in training. Dietary analysis was performed using EasyDiet® software, and data were processed with the Statistical Package for the Social Sciences (IBM SPSS Statistics). The normality of the variables was assessed, and means, standard deviations, and ranges were determined; a frequency analysis was conducted to establish the proportion of compliance with certain macronutrients. The results showed that the players evaluated had an energy intake below the recommended level, accompanied by an insufficient intake of carbohydrates; protein intake was generally adequate or above established recommendations, while fat intake remained within acceptable ranges, even exceeding the recommended value. An imbalance in micronutrients was observed, with low intakes of vitamin A and D, and high consumption of calcium, iron, sodium, and other micronutrients.

Keywords: Sport medicine, Performance analysis, Dietary requirements UEFA, Macronutrients, Micronutrients, Athletic performance.

Cite this article as:
Giménez-Sánchez, J., Melda de Oleo-Ogando, L., & Muciño-Arellano, M. R. (2026). Dietary intake and compliance with UEFA utrition guidelines in soccer players. *Journal of Human Sport and Exercise, 21*(4), 1213-1227. https://doi.org/10.55860/net7d643

Corresponding author. *Faculty of Health Sciences. University of Barcelona, Campus Bellvitge. Barcelona, Spain.*
E-mail: jaumegimenez@ub.edu
Submitted for publication April 23, 2026.
Accepted for publication June 11, 2026.
Published June 23, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/net7d643

INTRODUCTION

Soccer is a sport played by both men and women and is considered a high-intensity activity that combines explosive movements such as sprints, jumps, and changes of direction with long periods of moderate-intensity aerobic activity. Increasingly, the sport faces greater physical and technical demands, coupled with the growing economic implications of winning or losing a match (Amawi et al., 2024; Mohr et al., 2022; Sebastiá-Rico et al., 2023). Due to the high-intensity physical exertion of this sport and the goal of optimizing the quality of play, adjusting energy and dietary intake is necessary to achieve optimal performance (Amawi et al., 2023), as adherence to recommended nutritional practices for this sport influences multiple bodily processes, from energy production to post-exercise recovery (Amawi et al., 2024).

The physiological demands placed on each player result in a high energy and metabolic load, not to mention the stress to which the musculoskeletal system is subjected; consequently, nutrition is a determining factor in in-game performance, post-game recovery, and the prevention and rehabilitation of injuries that may occur in players (Amawi et al., 2024; Mohr et al., 2022). This implies high demands on both the aerobic and anaerobic systems to achieve optimal performance. During competition, anaerobic glycolysis and carbohydrate oxidation are fundamental sources of energy, and it has been observed that muscle glycogen can be depleted after matches to approximately 43% of pre-match levels, remaining significantly reduced in the hours that follow (Hulton et al., 2022). This energy depletion highlights the importance of adequate preparation for soccer players, both from a training and nutritional standpoint, to effectively meet energy requirements (Iblasi et al., 2025).

Each player's nutritional needs are determined by the intensity, volume, and objectives of training, as well as by the frequency of competition, which requires a diet balanced in both quantity and quality (Amawi et al., 2024). It has been suggested that current competition schedules increase the risk of injury. Added to this is the fact that match schedules are variable, designed to accommodate the needs of television broadcasts and an audience constantly tuned in to the TV. This means that players are subjected to constant domestic and international travel, posing an even greater challenge to the body (Collins et al., 2021).

Various studies and meta-analyses have shown that soccer players frequently fail to meet energy and carbohydrate recommendations (Amawi et al., 2024; Iblasi et al., 2025; Jenner et al., 2019; Macuh et al., 2022; Sebastiá-Rico et al., 2023; Steffl et al., 2019). Protein intake is often higher than recommended, while fat intake is generally adequate, though in some cases it may be slightly high (Iblasi et al., 2025; Sebastiá-Rico et al., 2023; Steffl et al., 2019). In addition, several micronutrients, such as vitamin D, vitamin K, and potassium, are below recommended levels, while sodium is consumed in excess (Iblasi et al., 2025). These dietary imbalances can compromise recovery, performance, and training capacity, highlighting the need for specific nutritional monitoring (Iblasi et al., 2025; Jenner et al., 2019; Steffl et al., 2019).

An energy intake that is unbalanced in macronutrients can compromise adaptations to training and recovery processes. Inadequate energy intake can decrease performance and increase the risk of changes in body composition, such as a decrease in fat-free mass, potentially compromising immune function and bone health, increasing susceptibility to injuries, and symptoms related to overtraining (Amawi et al., 2024; Jenner et al., 2019).

That is why, in 2017, the steering committee of the current UEFA Nutrition Expert Statement (JC; RM, JB, AMcC) undertook the task of compiling an expert panel statement with the aim of updating, based on evidence, all existing knowledge and research on nutrition in professional soccer. The most recent

 © 2026 ARD Asociación Española

compendium includes nine key sections covering all participants in a match: field players, goalkeepers, and referees, taking into account both men and women. The topics included are: match-day nutrition, training-day nutrition, body composition, stressful environments and travel, cultural diversity and dietary considerations, dietary supplements, rehabilitation, referees, and elite youth players (Collins et al., 2021).

Although previous studies have consistently reported inadequate energy and carbohydrate intake among soccer players, relatively few have simultaneously evaluated compliance with both football-specific macronutrient recommendations and a comprehensive micronutrient profile using the most recent UEFA and EFSA reference standards. Therefore, the objective of this study was to assess the nutritional intake of professional and semi-professional soccer players and determine the degree of compliance with current recommendations for energy, macronutrients, and micronutrients. The novelty of this work lies in its integrated evaluation of dietary adequacy using updated reference frameworks, allowing a more comprehensive characterization of nutritional practices and the identification of nutritional priorities that may support individualized dietary interventions, nutritional periodization, and performance optimization in soccer players.

MATERIAL AND METHODS

A cross-sectional observational study to assess the dietary intake of professional and semi-professional soccer players in Spain during the 2025–2026 period.

Participants

A selection of 26 active professional and semi-professional soccer players was made from the sports nutrition service. The players' ages ranged from 16 to 34 years (n = 26; age 21.5 ± 4.7 years; body weight 72.9 ± 9.4 kg; height 179.8 ± 7.1 cm; body mass index (BMI) 22.5 ± 2.3 kg/m²), and they were of Spanish or Latin American nationality. All players who, at the time of data collection, had any medical condition or were injured were excluded.

Procedures

Dietary intake was assessed using a one-hour structured interview. Each subject was asked to provide a detailed description of their food intake using a 72-hour recall. To collect data on food intake, DIN A3-sized food photographs were used, based on the Food Exchange System for Dietary Planning and Menu Design (Marques-Lopes et al., 2018), thereby ensuring greater accuracy in intake assessment.

Dietary analysis

A single researcher performed the analysis of total dietary intake, measuring variables such as energy, macronutrient, and micronutrient intakes. The data were entered and analysed using the EasyDiet® software from the Spanish Academy of Nutrition and Dietetics S.L.U. 2026.

The comparison of the data obtained during data collection was performed based on the variables to be analysed. Intake of energy, protein, carbohydrates, fat, calcium, and iron was compared with the specific recommendations for professional soccer players established by UEFA in 2021. Sugar, fibre, and other micronutrients (sodium, potassium, magnesium, phosphorus, zinc, vitamin A, vitamin D, vitamin E, thiamine, riboflavin, niacin, vitamin B6, folate, vitamin B12, and vitamin C), for which reference values are not determined by this organization, were compared with those described by the EFSA and updated in 2019 for the general population.

Statistical analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences (IBM SPSS Statistics) version 31.0.1.0 (49).

The normality of the variables was assessed using the Shapiro-Wilk test, with a *p*-value > .05 considered indicative of a normal distribution. The variables representing the sample characteristics that exhibited a normal distribution were body weight and height, while age and BMI did not meet this criterion.

Regarding energy and macronutrient values such as total protein (animal and plant protein), fats (saturated and monounsaturated fatty acids), carbohydrates, and fibre, these followed a normal distribution. Those that did not fall within this category were the values for polyunsaturated fatty acids and sugar.

As for micronutrient intake: magnesium, phosphorus, zinc, thiamine, riboflavin, niacin, and vitamin B12 showed a normal distribution, while sodium, potassium, vitamins A, D, E, B6, folate, and C did not.

Descriptive statistics were calculated: minimum (min) and maximum (max), mean (x) ± standard deviation (SD). Although some variables did not strictly meet the normality criterion, the data are presented as mean and standard deviation to facilitate interpretation and comparison with previous studies. In addition, a frequency analysis was performed for certain variables (proteins, carbohydrates, and fats) to establish the proportion (%) of values falling within the reference ranges.

RESULTS

Sample

Of the 26 male soccer players, physical characteristics such as age, weight, height, and BMI, obtained from the medical histories in the participants' clinical records, are described. The mean values, along with the minimum and maximum ranges, are presented in Table 1.

Table 1. Characteristics of the participants.

Variable (n = 26)	Mean ± SD	Range (Min-Max)
Age (years)	21.5 ± 4.7	16–34
Body weight (kg)	72.9 ± 9.4	53–92
Height (cm)	179.8 ± 7.1	165–192
BMI (kg/m²)	22.5 ± 2.3	17.3–27.2

Note. SD = Standard Deviation; Min = Minimum; Max = Maximum; BMI = Body Mass Index.

Nutrient intake according to UEFA 2021 recommendations

The average energy intake was 2,700.2 ± 520.6 kcal/day, equivalent to 77.2% compliance with the minimum recommendation established by UEFA (3,500 kcal/day). This intake corresponded to 37.6 ± 8.8 kcal/kg/day. The energy distribution showed 25.7% coming from protein, 40.4% from carbohydrates, and 33.9% from fat, with the latter falling within the upper limit established by the UEFA's (20–35% of total kcal) (Collins et al., 2021) (Table 2).

The average total protein intake was 171.4 ± 40.6 g/day, equivalent to 2.4 ± 0.6 g/kg/day, which is slightly above the range recommended by UEFA of 1.6–2.2 g/kg/day (Collins et al., 2021). Of the total protein consumed, 79.1% came from animal sources (136.3 ± 37.6 g/day), while 20.9% came from plant sources (35.1 ± 14.6 g/day) (Table 2).

 © 2026 ARD Asociación Española

An average carbohydrate intake of 274.3 ± 78.6 g/day was calculated, equivalent to 3.9 ± 1.4 g/kg/day, a value that falls at the lower limit of the range recommended by UEFA (3–8 g/kg/day) (Collins et al., 2021).

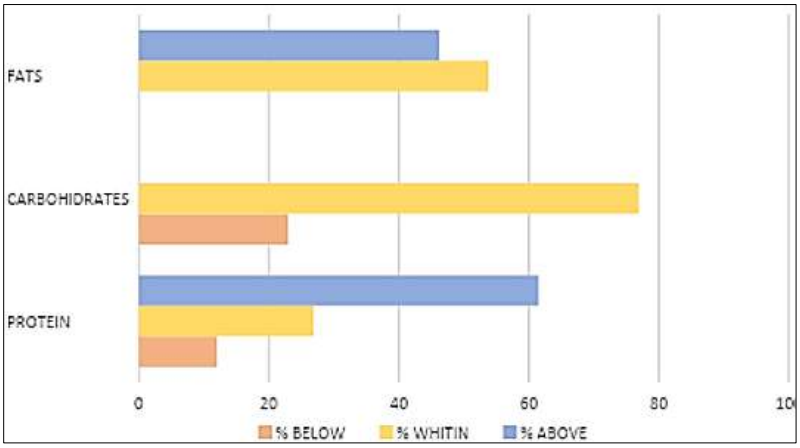
The average fat intake was 101.9 ± 27.2 g/day, equivalent to 1.4 ± 0.4 g/kg/day. The distribution of saturated, monounsaturated, and polyunsaturated fatty acids was 8.7%, 16.8%, and 5.2% of total kcal, respectively (Table 2).

Table 2. Energy and nutrient intake of soccer players (n = 26) compared with UEFA standards.

Variable	Mean ± SD	Recommendation
Energy		
kcal/day	2700.2 ± 520.6	3500 kcal/day UEFA
kcal/kg/day	37.6 ± 8.8	
% compliance	77.2 ± 14.9	
Protein		
g/day	171.4 ± 40.6	
g/kg/day	2.4 ± 0.6	1.6–2.2 g/kg/day UEFA
% of total kcal	25.7 ± 5.8	
Animal protein		
g/day	136.3 ± 37.6	
% total protein	79.1 ± 8.1	
Plant-based protein		
g/day	35.1 ± 14.6	
% total protein	20.9 ± 8.1	
Carbohydrates		
g/day	274.3 ± 78.6	
g/kg/day	3.9 ± 1.4	3–8 g/kg/day UEFA
% of total kcal	40.4 ± 7.5	
Fat		
g/day	101.9 ± 27.2	
g/kg/day	1.4 ± 0.4	
% of total kcal	33.9 ± 6.1	20–35% of total kcal UEFA
AGS		
g/day	26.5 ± 9.5	
% of total kcal	8.7 ± 2.3	
AGM		
g/day	50.5 ± 16.8	
% of total kcal	16.8 ± 4.6	
AGP		
g/day	15.5 ± 5.8	
% of total kcal	5.2 ± 1.9	

Note. Values are expressed as mean ± SD (Standard Deviation); SFA = Saturated Fatty Acids; MUFA = Monounsaturated Fatty Acids; PUFA = Polyunsaturated Fatty Acids.

Regarding the distribution of players' macronutrient intake based on UEFA's 2021 nutritional recommendations, 26.9% of them had a protein intake within the recommended range (1.6–2.2 g/kg/day), while 61.5% of the athletes exceeded that range. For carbohydrates, 76.9% of soccer players fell within the recommended range (3–8 g/kg/day), while 23.1% had a lower intake. Regarding fats, 53.8% of the players met the recommended range, and 46.2% had values above the recommended range (20–35% of total kcal) (Collins et al., 2021) (Figure 1).



Note. All data are presented as percentages (%).

Figure 1. Distribution of soccer players according to macronutrient intake relative to UEFA recommendations (n = 26).

Regarding the micronutrient profile, the athletes showed an average intake of calcium and iron above the values recommended by UEFA 2021 (Collins et al., 2021). See Table 3 for adequacy percentages.

Table 3. Micronutrient intake compared to UEFA guidelines.

Variable (n = 26)	Mean ± SD	Range (Min-Max)
Calcium (mg/day)	842.7 ± 381.7	326–1619
% Adequacy	120.4 ± 54.4	47–231
Iron (mg/day)	17.3 ± 5.7	8–30
% Adequacy	199.8 ± 65.9	91–340

Note. Values are expressed as mean ± SD and range from Min-minimum to Max-maximum.

Nutrient intake according to EFSA 2019 recommendations

As part of the carbohydrate analysis, the intake of free sugars was measured; the average intake was 94.7 ± 55.3 g/day, representing 13.9% of total kcal, exceeding the maximum value recommended by EFSA (<10% of total kcal). The average fibre intake was 25.6 ± 13.2 g/day, which corresponded to 102.6% of the EFSA recommendation (25 g/day) (Authority (EFSA), 2017) (Table 4).

Table 4. Sugar and fibre intake of the players (n = 26) according to EFSA recommendations.

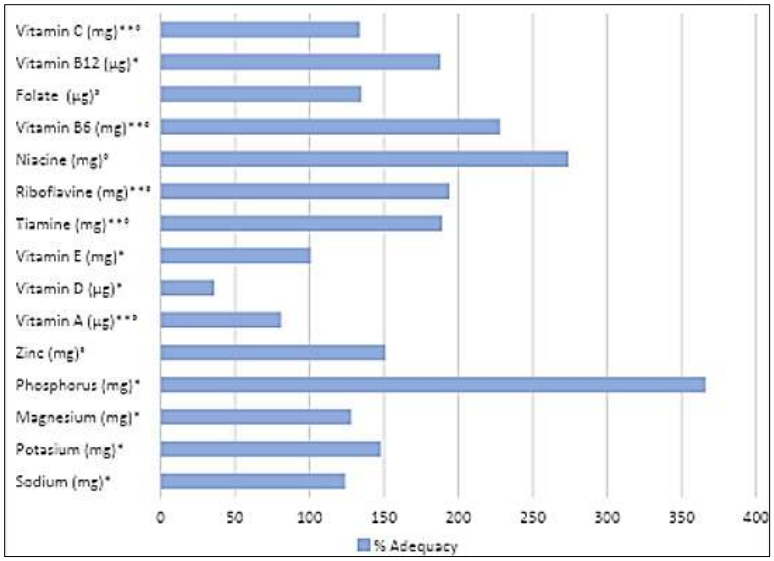
Variable	Mean ± SD	Recommendation
Sugar		
g/day	94.7 ± 55.3	
% of total kcal	13.9 ± 6.9	<10% of total kcal (EFSA)
Fiber		
g/day	25.6 ± 13.2	25 g/day (EFSA)
% compliance	102.6 ± 52.9	

Note. Values are expressed as mean ± SD (Standard Deviation).

The mean intake of vitamin A and vitamin D was found to be below the recommendations in the nutritional guidelines, while vitamin E was within the recommended value. Sodium, potassium, magnesium, zinc, folate, vitamin B12, and vitamin C were found to be slightly above the recommended value. Phosphorus, niacin,

 © 2026 ARD Asociación Española

and vitamin B6 were well above the values recommended by EFSA 2019 (Authority (EFSA), 2017). See Table 5 for mean intake, minimum, and maximum values. See Figure 2 for percentage of adequacy.



*Note. *Adequate Intake (AI), **Average Requirement (AR), or Population Reference Intake (PRI).*

Figure 2. Micronutrient intake among soccer players (n = 26), presented as a percentage of the EFSA Dietary Reference Values for Nutrients, 2019.

Table 5. Micronutrient intake compared to EFSA.

Variable (n = 26)	Mean ± SD	Range (Min-Max)
Sodium (mg)	2481.7 ± 1185.7	635.2 - 5228.5
Potassium (mg)	5178.2 ± 1828.7	2520.2–10820.4
Magnesium (mg)	449.1 ± 145.5	223.0–814.4
Phosphorus (mg)	2011.1 ± 454.5	1093.7–3274.4
Zinc (mg)	14.2 ± 3.8	5.7–21.4
Vitamin A (µg)	608.1 ± 522.4	106.5–2,241.3
Vitamin D (µg)	5.3 ± 5.5	0.0–20.5
Vitamin E (mg)	13.1 ± 5.3	7.3–32.2
Thiamine (mg)	2.0 ± 0.8	0.8–3.7
Riboflavin (mg)	3.1 ± 0.9	1.8–5.4
Niacin (mg)	45.9 ± 11.3	27.1–76.0
Vitamin B6 (mg)	3.8 ± 1.4	2.0–7.3
Folate (µg)	446.2 ± 230.7	159.1–1,139.9
Vitamin B12 (µg)	7.5 ± 2.9	2.1–13.8
Vitamin C (mg)	147.1 ± 122.4	34.0–545.4

Note. Values are expressed as mean ± SD and range (min–max).

DISCUSSION

Comparison of intake with UEFA recommendations

The main objective of this study was to assess the nutritional intake of professional soccer players and the degree of compliance with the recommendations on macronutrients and micronutrients established by UEFA and organizations such as the EFSA.

The players' mean spontaneous energy intake was 2700.2 ± 520.6 kcal/day, which is equivalent to 72.2% of UEFA's minimum recommendation of 3500 kcal/day (Collins et al., 2021). Similarly, the average intake relative to body mass was 37.6 ± 8.8 kcal/kg/day, which is below the 40–70 kcal/kg/day suggested for athletes exposed to high training volumes (Kerksick et al., 2018). These findings are consistent with previous studies reporting inadequate energy intake among soccer players (Anderson et al., 2017; Brinkmans et al., 2019; Devlin et al., 2017; Ebine et al., 2002; Iblasi et al., 2025). From a practical standpoint, this energy deficit may increase the risk of low energy availability (LEA), a condition associated with poor recovery, hormonal disturbances, reduced adaptation to training, increased risk of injury, and compromised performance throughout the season (Amawi et al., 2024; Jenner et al., 2019; Mountjoy et al., 2018; Sebastiá-Rico et al., 2023). Therefore, routine monitoring of energy intake and expenditure should be considered to identify at-risk players and implement individualized nutritional interventions.

Regarding macronutrient distribution, a high protein intake was observed, accounting for 26% of total energy intake, while carbohydrates accounted for 40% and fats for 34% of total kilocalories, with the latter falling at the upper limit of the range recommended by UEFA, which is 20–35% (Collins et al., 2021). This is a clear and common dietary pattern among soccer players, characterized by high consumption of protein—primarily of animal origin—and fat, with a relatively low intake of carbohydrates despite soccer's high energy demands during certain phases of the season (Anderson et al., 2016).

Although adequate protein intake supports muscle protein synthesis and recovery, chronically high intake can inadvertently displace carbohydrate-rich foods from the diet, especially when total energy intake is insufficient (Burke et al., 2019; Collins et al., 2021; Dobrowolski & Włodarek, 2019; Leão et al., 2022; Rocha-Rodrigues et al., 2021; Thomas et al., 2016). This finding is particularly relevant in soccer, where carbohydrates represent the primary substrate for high-intensity intermittent exercise. Consequently, nutritional advice should focus not only on achieving adequate protein intake but also on maintaining an appropriate balance between protein and carbohydrate consumption to promote both recovery and glycogen replenishment.

Animal-derived proteins accounted for 79.1% of total protein intake, confirming a dietary pattern previously described in soccer players (Mielgo-Ayuso et al., 2015). Although this pattern ensures an adequate supply of essential amino acids, it may reduce the diversity of plant-based foods and, consequently, limit the intake of dietary fibre, antioxidants, vitamins, minerals, and other bioactive compounds relevant to long-term health and recovery. From a practical standpoint, promoting a more balanced distribution between animal and plant-based protein sources could improve the overall quality of the diet, while maintaining adequate protein availability for performance and recovery.

Carbohydrate intake averaged 3.9 ± 1.4 g/kg/day, placing it at the lower limit of UEFA recommendations, although nearly a quarter of the players did not meet these values (Collins et al., 2021). Similar findings have been consistently reported in soccer players (Amawi et al., 2024; Iblasi et al., 2025; Jenner et al., 2019; Macuh et al., 2022; Sebastiá-Rico et al., 2023; Steffl et al., 2019). Given the central role of muscle glycogen in soccer performance, inadequate carbohydrate intake can lead to suboptimal glycogen stores, which could affect the ability to perform repeated sprints, performance in high-intensity runs, and recovery between training sessions and matches. These findings support the implementation of nutritional periodization strategies, with carbohydrate intake adjusted according to training and competition demands and increased around match days to optimize glycogen availability and recovery (Collins et al., 2021; Mohr et al., 2022, 2022; Pueyo et al., 2024).

 © 2026 ARD Asociación Española

Regarding fats, the average intake was 1.4 ± 0.4 g/kg/day, representing an average of 33.9% of total calories, with a fatty acid distribution showing that 8.7% of total calories came from saturated fats, 16.8% from monounsaturated fatty acids, and 5.2% from polyunsaturated fatty acids. Although the proportion of monounsaturated fatty acids was adequate, nearly half of the players (46.2%) exceeded the recommended range for total fat; it should be noted that no player fell below the range recommended by UEFA. Other studies have reported that, although the average total fat intake approaches the recommended upper limit, there is considerable individual variability, with some players exceeding the recommendations and others falling within the appropriate range (Macuh et al., 2022). Although fat is essential for the absorption of fat-soluble vitamins and the supply of essential fatty acids, excessive fat intake can contribute to a lower relative intake of carbohydrates when total energy intake is limited. Therefore, dietary planning should prioritize not only total fat intake but also its balance with carbohydrate needs according to training demands.

Comparison of micronutrients with UEFA recommendations

The results of this study on micronutrient intake confirm the importance of including them in the diet, as established by the UEFA statement and other studies in the scientific literature. Although this organization does not establish precise intake figures—and, in this regard, we must reiterate the importance of personalizing dietary intake—it does highlight certain vitamins and minerals as essential for soccer players: calcium and iron. A varied, healthy, and balanced diet should be sufficient to meet these needs before resorting to supplements, which aligns with the "*food first*" philosophy (Collins et al., 2021).

The mean calcium intake was 842.7 ± 381.7 mg/day, with a compliance rate of 120.4%. This result suggests adequate intake based on the reference value used, previous studies indicate that many athletes may still fall short of the optimal calcium intake for bone health and recovery. This is particularly relevant for athletes at risk of relative energy deficiency in sport (RED-S), in whom calcium requirements may increase to 1500 mg/day (Collins et al., 2021; Macuh et al., 2022). Therefore, calcium intake should be interpreted not only in relation to general reference values but also according to individual risk factors, energy availability, and training load.

The mean iron intake was 17.3 ± 5.7 mg/day, with a percentage of adequacy close to 200%, indicating that the players met and even exceeded established recommendations (Collins et al., 2021). This high iron intake can be partly explained by the predominance of animal protein sources, which provide heme iron. However, sufficient dietary intake does not always guarantee adequate iron status, as exercise-induced inflammation, sweating, gastrointestinal microbleeds, and other factors can negatively affect iron bioavailability (Ghazzawi et al., 2023; Turchaninov et al., 2015). Given that iron deficiency, even in the absence of anaemia, can limit aerobic capacity, recovery from fatigue, and performance—and considering its higher prevalence among female athletes—dietary assessment should be supplemented with periodic haematological monitoring, especially during periods of high training load or in players at higher risk.

Comparison with EFSA recommendations

Compared to EFSA recommendations, the average intake of free sugars accounted for 14% of total energy intake, exceeding the recommendation that sets a lower limit of 10% of total energy intake—a recommendation that the World Health Organization also classifies as evidence-based (Authority (EFSA), 2017; *Guideline*, 2015). This finding suggests a high presence of sugary foods in the players' diet, which could have negative implications for the nutritional quality of the diet; reducing free sugar intake should not necessarily involve reducing total carbohydrate intake but rather replacing low-quality sugar sources with carbohydrate-rich, nutrient-dense foods that promote glycogen availability and recovery.

The mean dietary fibre intake was 25.6 ± 13.2 g/day, representing approximately 102.6% of the EFSA recommendation of 25 g/day (Authority (EFSA), 2017). Although this indicates that the players met the minimum recommendation, intakes exceeding 30 g/day may provide additional benefits, especially in populations with higher energy demands (Mancin et al., 2025; Sommer et al., 2024). In sports contexts, adequate fibre intake can support gastrointestinal function, gut microbiota modulation, short-chain fatty acid production, immune function, and metabolic health, and may reduce perceived fatigue during training (Mancin et al., 2025; Zha et al., 2025). Therefore, fibre intake should be considered as part of overall dietary quality, while also being individually tailored to training and match schedules to prevent gastrointestinal discomfort.

Comparison of micronutrients with EFSA recommendations

Although nutritional periodization typically focuses on energy and macronutrient planning, many metabolic processes involved in performance, recovery, and adaptation also depend on adequate intake of vitamins and minerals (Beck et al., 2021; Jeukendrup, 2017; Volpe, 2007). In this study, all mean micronutrient intakes were established, and adequacy percentages were calculated based on the EFSA dietary reference values (Figure 2; Table 5).

Vitamin A and vitamin D showed adequacy rates of 81.1% and 35.6%, respectively, suggesting an insufficient intake of these fat-soluble vitamins, consistent with previous reports in soccer players (Beck et al., 2021; Bezuglov et al., 2023; Collins et al., 2021; Mancin et al., 2025; Nikniaz et al., 2021). Given their role in muscle function, immune health, recovery, and injury prevention, the observed low intake could warrant routine monitoring of vitamin D status. Early identification of vitamin D deficiency could facilitate targeted nutritional interventions and, potentially, improve player availability throughout the season.

In contrast, sodium, potassium, magnesium, zinc, folate, vitamin B12, and vitamin C showed intakes slightly higher than recommended, while phosphorus, niacin, and vitamin B6 are consumed in considerably higher amounts, reaching up to twice the reference values. These findings suggest that, although recommendations are met, there is a tendency among players toward high consumption of certain nutrients, which may reflect their usual diet or result from dietary strategies for athletic preparation.

This study suggests that the soccer players evaluated had a spontaneous dietary intake that, although it largely met micronutrient requirements, showed significant deficits in total energy and carbohydrate intake, along with a high-protein pattern and a fat intake close to the recommended upper limit. Furthermore, the consistent presence of deficiencies in fat-soluble vitamins and relative excesses of certain micronutrients highlights that quantitative compliance with recommendations does not guarantee the functional adequacy of the diet when non-athlete-specific reference values are applied. These findings reinforce the need for individualized and periodized nutritional strategies, aligned with training and competition loads, as well as routine monitoring of key nutrients and biomarkers, particularly vitamin D, iron, calcium, and indicators related to low energy availability. Such strategies can help optimize players' performance, recovery, and availability throughout the competitive season.

Among the limitations of this study is the small sample size (n = 26), which may affect the external validity of the findings and their generalizability to other populations of soccer players. Furthermore, the small number of participants limits the ability to identify potential differences among subgroups of interest, such as playing position, age group, competitive level, or different phases of athletic training—factors that could significantly influence nutritional requirements and dietary patterns.

 © 2026 ARD Asociación Española

Furthermore, the cross-sectional design provides only a snapshot of dietary intake at a specific point in time, without allowing for the evaluation of changes throughout the season or the establishment of causal relationships between nutritional intake and variables related to athletic performance.

Although the 72-hour dietary recall is a widely used tool in nutritional research, it relies on participants' memory and the accuracy of their self-reports; therefore, memory errors, underreporting, or overestimation of food intake cannot be ruled out here. Although the use of standardized photographs helped improve portion size estimation, the possibility of measurement errors remains. Furthermore, the interpretation of the observed energy deficits should be analysed with caution, as direct measurements of energy expenditure, training load, or competitive exposure were not available to allow for individualized contextualization of the players' nutritional requirements. Finally, the lack of specific biomarker measurements prevents us from determining whether the reported dietary inadequacies translated into actual physiological deficiencies.

A conceptual limitation of this study is the use of EFSA reference values to assess certain nutrients, due to the absence of specific recommendations for soccer players from UEFA. Although these values constitute a widely recognized and used reference framework, they were developed for the general population and may not fully reflect the physiological demands associated with training and sports competition. Consequently, the adequacy percentages observed differ because athletes' nutritional requirements differ from those established for the general population. This highlights the need to develop specific recommendations for athletic populations to enable a more accurate assessment of nutritional education.

CONCLUSIONS

In conclusion, this study demonstrated that the players' spontaneous dietary intake did not meet the energy recommendations established by UEFA; furthermore, carbohydrate intake was insufficient to meet the minimum requirements for training, and even less so during competition. In contrast, the players' protein and fat intake levels aligned with the recommendations, even exceeding the recommended limits in some cases. The average intake of free sugars and dietary fibre exceeded the EFSA recommendation. The average intake of calcium and iron was above the values recommended by UEFA; meanwhile, vitamin A and D levels did not meet the EFSA's nutritional recommendations. The remaining micronutrients were slightly above the recommendations, and in some cases, the values were nearly double the recommended amounts.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Jaume Giménez-Sánchez: Conceptualization, methodology, study supervision, data analysis and interpretation, manuscript drafting, critical revision of the manuscript, and final approval of the submitted version. Luis Melda de Oleo-Ogando: Data collection, dietary assessment, literature review, support in data analysis, manuscript drafting, and critical revision of the manuscript. Magaly del Rosario Muciño-Arellano: Data collection, data organization, support in data analysis and interpretation, preparation of tables and figures, manuscript revision, and final approval of the submitted version. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Amawi, A., Alshuwaier, G., Alaqil, A., Alkasasbeh, W. J., Bursais, A., Al-Nuaim, A., Alhaji, J., Alibrahim, M., Alosaimi, F., Nemer, L., Gautam, Y., Al-Barha, N., & Shehadeh, J. (2023). Exploring the Impact of Dietary Factors on Body Composition in Elite Saudi Soccer Players: A Focus on Added Sugars, Salt, and Oil Consumption. International Journal of Human Movement and Sports Sciences, 11(6), 1305-1312. https://doi.org/10.13189/saj.2023.110614

Amawi, A., Khataybeh, B., Al Aqaili, R., Ababneh, N., Alnimer, L., Qoqazeh, A., Oukal, F., Jahrami, H., Mousa Ay, K., Al Saoud, H., & Ghazzawi, H. (2024). Junior athletes' nutritional demands: A narrative review of consumption and prevalence of eating disorders. Frontiers in Nutrition, 11, 1390204. https://doi.org/10.3389/fnut.2024.1390204

Anderson, L., Orme, P., Di Michele, R., Close, G. L., Milsom, J., Morgans, R., Drust, B., & Morton, J. P. (2016). Quantification of Seasonal-Long Physical Load in Soccer Players With Different Starting Status From the English Premier League: Implications for Maintaining Squad Physical Fitness. International Journal of Sports Physiology and Performance, 11(8), 1038-1046. https://doi.org/10.1123/ijspp.2015-0672

Anderson, L., Orme, P., Naughton, R. J., Close, G. L., Milsom, J., Rydings, D., O'Boyle, A., Di Michele, R., Louis, J., Hambly, C., Speakman, J. R., Morgans, R., Drust, B., & Morton, J. P. (2017). Energy Intake and Expenditure of Professional Soccer Players of the English Premier League: Evidence of Carbohydrate Periodization. International Journal of Sport Nutrition and Exercise Metabolism, 27(3), 228-238. https://doi.org/10.1123/ijsnem.2016-0259

Authority (EFSA), E. F. S. (2017). Dietary Reference Values for nutrients Summary report. EFSA Supporting Publications, 14(12), e15121E. https://doi.org/10.2903/sp.efsa.2017.e15121

Beck, K. L., von Hurst, P. R., O'Brien, W. J., & Badenhorst, C. E. (2021). Micronutrients and athletic performance: A review. Food and Chemical Toxicology: An International Journal Published for the British Industrial Biological Research Association, 158, 112618. https://doi.org/10.1016/j.fct.2021.112618

Bezuglov, E., Shoshorina, M., Lazarev, A., Emanov, A., Koroleva, E., Anishchenko, I., Waśkiewicz, Z., Butovskiy, M., & Morgans, R. (2023). Does vitamin D affect strength and speed characteristics and testosterone concentration in elite young track and field athletes in the North European summer? Nutrition Journal, 22(1), 16. https://doi.org/10.1186/s12937-023-00848-7

Brinkmans, N. Y. J., Iedema, N., Plasqui, G., Wouters, L., Saris, W. H. M., van Loon, L. J. C., & van Dijk, J.-W. (2019). Energy expenditure and dietary intake in professional football players in the Dutch Premier

 © 2026 ARD Asociación Española

League: Implications for nutritional counselling. Journal of Sports Sciences, 37(24), 2759-2767. https://doi.org/10.1080/02640414.2019.1576256

Burke, L. M., Castell, L. M., Casa, D. J., Close, G. L., Costa, R. J. S., Desbrow, B., Halson, S. L., Lis, D. M., Melin, A. K., Peeling, P., Saunders, P. U., Slater, G. J., Sygo, J., Witard, O. C., Bermon, S., & Stellingwerff, T. (2019). International Association of Athletics Federations Consensus Statement 2019: Nutrition for Athletics. International Journal of Sport Nutrition and Exercise Metabolism, 29(2), 73-84. https://doi.org/10.1123/ijsnem.2019-0065

Collins, J., Maughan, R. J., Gleeson, M., Bilsborough, J., Jeukendrup, A., Morton, J. P., Phillips, S. M., Armstrong, L., Burke, L. M., Close, G. L., Duffield, R., Larson-Meyer, E., Louis, J., Medina, D., Meyer, F., Rollo, I., Sundgot-Borgen, J., Wall, B. T., Boullosa, B., … McCall, A. (2021). UEFA expert group statement on nutrition in elite football. Current evidence to inform practical recommendations and guide future research. British Journal of Sports Medicine, 55(8), 416. https://doi.org/10.1136/bjsports-2019-101961

Devlin, B. L., Leveritt, M. D., Kingsley, M., & Belski, R. (2017). Dietary Intake, Body Composition, and Nutrition Knowledge of Australian Football and Soccer Players: Implications for Sports Nutrition Professionals in Practice. International Journal of Sport Nutrition and Exercise Metabolism, 27(2), 130-138. https://doi.org/10.1123/ijsnem.2016-0191

Dobrowolski, H., & Włodarek, D. (2019). Dietary Intake of Polish Female Soccer Players. International Journal of Environmental Research and Public Health, 16(7), 1134. https://doi.org/10.3390/ijerph16071134

Ebine, N., Rafamantanantsoa, H. H., Nayuki, Y., Yamanaka, K., Tashima, K., Ono, T., Saitoh, S., & Jones, P. J. H. (2002). Measurement of total energy expenditure by the doubly labelled water method in professional soccer players. Journal of Sports Sciences, 20(5), 391-397. https://doi.org/10.1080/026404102317366645

Ghazzawi, H. A., Hussain, M. A., Raziq, K. M., Alsendi, K. K., Alaamer, R. O., Jaradat, M., Alobaidi, S., Al Aqili, R., Trabelsi, K., & Jahrami, H. (2023). Exploring the Relationship between Micronutrients and Athletic Performance: A Comprehensive Scientific Systematic Review of the Literature in Sports Medicine. Sports, 11(6), 109. https://doi.org/10.3390/sports11060109

Guideline: Sugars Intake for Adults and Children. (2015). World Health Organization. Retrieved from [Accessed 2026, 12 June]: http://www.ncbi.nlm.nih.gov/books/NBK285537/

Hulton, A. T., Malone, J. J., Clarke, N. D., & MacLaren, D. P. M. (2022). Energy Requirements and Nutritional Strategies for Male Soccer Players: A Review and Suggestions for Practice. Nutrients, 14(3), 657. https://doi.org/10.3390/nu14030657

Iblasi, R., Abualsaud, M., Amawi, A. T., & Ghazzawi, H. (2025). Pre-season and in-season body composition assessment by bioimpedance in professional football athletes: Implications for sports nutrition, physical performance, and hormonal health. Frontiers in Nutrition, 12, 1657855. https://doi.org/10.3389/fnut.2025.1657855

Jenner, S. L., Buckley, G. L., Belski, R., Devlin, B. L., & Forsyth, A. K. (2019). Dietary Intakes of Professional and Semi-Professional Team Sport Athletes Do Not Meet Sport Nutrition Recommendations-A Systematic Literature Review. Nutrients, 11(5), 1160. https://doi.org/10.3390/nu11051160

Jeukendrup, A. E. (2017). Training the Gut for Athletes. Sports Medicine, 47(Suppl 1), 101-110. https://doi.org/10.1007/s40279-017-0690-6

Kerksick, C. M., Wilborn, C. D., Roberts, M. D., Smith-Ryan, A., Kleiner, S. M., Jäger, R., Collins, R., Cooke, M., Davis, J. N., Galvan, E., Greenwood, M., Lowery, L. M., Wildman, R., Antonio, J., & Kreider, R. B. (2018). ISSN exercise & sports nutrition review update: Research & recommendations. Journal of the International Society of Sports Nutrition, 15(1), 38. https://doi.org/10.1186/s12970-018-0242-y

Leão, C., Mendes, A. P., Custódio, C., Ng, M., Ribeiro, N., Loureiro, N., Araújo, J. P., Afonso, J., Rocha-Rodrigues, S., & Tavares, F. (2022). Nutritional Intake and Training Load of Professional Female

Football Players during a Mid-Season Microcycle. Nutrients, 14(10), 2149. https://doi.org/10.3390/nu14102149

Macuh, M., Levec, J., Kojić, N., & Knap, B. (2022). Dietary Intake, Body Composition and Performance of Professional Football Athletes in Slovenia. Nutrients, 15(1), 82. https://doi.org/10.3390/nu15010082

Mancin, L., Burke, L. M., & Rollo, I. (2025). Fibre: The Forgotten Carbohydrate in Sports Nutrition Recommendations. Sports Medicine, 55(5), 1067-1083. https://doi.org/10.1007/s40279-024-02167-1

Marques-Lopes, I., Menal-Puey, S., Martínez, J. A., & Russolillo, G. (2018). Development of a Spanish Food Exchange List: Application of Statistical Criteria to a Rationale Procedure. Journal of the Academy of Nutrition and Dietetics, 118(7), 1161-1169. https://doi.org/10.1016/j.jand.2017.04.010

Mielgo-Ayuso, J., Zourdos, M. C., Calleja-González, J., Urdampilleta, A., & Ostojic, S. M. (2015). Dietary intake habits and controlled training on body composition and strength in elite female volleyball players during the season. Applied Physiology, Nutrition, and Metabolism = Physiologie Appliquee, Nutrition Et Metabolisme, 40(8), 827-834. https://doi.org/10.1139/apnm-2015-0100

Mohr, M., Vigh-Larsen, J. F., & Krustrup, P. (2022). Muscle Glycogen in Elite Soccer-A Perspective on the Implication for Performance, Fatigue, and Recovery. Frontiers in Sports and Active Living, 4, 876534. https://doi.org/10.3389/fspor.2022.876534

Mountjoy, M., Sundgot-Borgen, J. K., Burke, L. M., Ackerman, K. E., Blauwet, C., Constantini, N., Lebrun, C., Lundy, B., Melin, A. K., Meyer, N. L., Sherman, R. T., Tenforde, A. S., Klungland Torstveit, M., & Budgett, R. (2018). IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. British Journal of Sports Medicine, 52(11), 687-697. https://doi.org/10.1136/bjsports-2018-099193

Nikniaz, L., Ghojazadeh, M., Nateghian, H., Nikniaz, Z., Farhangi, M. A., & Pourmanaf, H. (2021). The interaction effect of aerobic exercise and vitamin D supplementation on inflammatory factors, anti-inflammatory proteins, and lung function in male smokers: A randomized controlled trial. BMC Sports Science, Medicine & Rehabilitation, 13(1), 102. https://doi.org/10.1186/s13102-021-00333-w

Pueyo, M., Llodio, I., Cámara, J., Castillo, D., & Granados, C. (2024). Influence of Carbohydrate Intake on Different Parameters of Soccer Players' Performance: Systematic Review. Nutrients, 16(21), 3731. https://doi.org/10.3390/nu16213731

Rocha-Rodrigues, S., Sousa, M., Lourenço Reis, P., Leão, C., Cardoso-Marinho, B., Massada, M., & Afonso, J. (2021). Bidirectional Interactions between the Menstrual Cycle, Exercise Training, and Macronutrient Intake in Women: A Review. Nutrients, 13(2), 438. https://doi.org/10.3390/nu13020438

Sebastiá-Rico, J., Soriano, J. M., Sanchis-Chordà, J., Alonso-Calvar, M., López-Mateu, P., Romero-García, D., & Martínez-Sanz, J. M. (2023). Dietary Habits of Elite Soccer Players: Variations According to Competitive Level, Playing Position and Sex. Nutrients, 15(20), 4323. https://doi.org/10.3390/nu15204323

Sommer, I., Nußbaumer-Streit, B., & Gartlehner, G. (2024). [WHO guideline on carbohydrate intake for adults and children]. Gesundheitswesen (Bundesverband Der Arzte Des Offentlichen Gesundheitsdienstes (Germany)), 86(12), 798-802. https://doi.org/10.1055/a-2364-2388

Steffl, M., Kinkorova, I., Kokstejn, J., & Petr, M. (2019). Macronutrient Intake in Soccer Players-A Meta-Analysis. Nutrients, 11(6), 1305. https://doi.org/10.3390/nu11061305

Thomas, D. T., Erdman, K. A., & Burke, L. M. (2016). American College of Sports Medicine Joint Position Statement. Nutrition and Athletic Performance. Medicine and Science in Sports and Exercise, 48(3), 543-568. https://doi.org/10.1249/MSS.0000000000000852

 © 2026 ARD Asociación Española

Turchaninov, D. V., Bovarskaya, L. A., Bogdashin, I. V., Bagrova, L. V., Gotwald, A. R., & Kozubenko, O. V. (2015). Influence of the regular intake of fermented milk products enriched by micronutrients on some indices of iron metabolism in adolescents involved in sports. Gigiena I Sanitariia, 94(9), 76-79.

Volpe, S. L. (2007). Micronutrient requirements for athletes. Clinics in Sports Medicine, 26(1), 119-130. https://doi.org/10.1016/j.csm.2006.11.009

Zha, Y., Xiang, M., Zuo, Y., Liu, D., & Wang, Q. (2025). High-dose Dietary Fibre Supplementation Enhances the Gut Microbiome, Health, and Athletic Performance of College Basketball Players. International Journal for Vitamin and Nutrition Research. Internationale Zeitschrift Fur Vitamin- Und Ernahrungsforschung. Journal International De Vitaminologie Et De Nutrition, 95(5), 37069. https://doi.org/10.31083/IJVNR37069

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Speed-dependent stance time adaptations in long-distance runners with and without a history of knee injury

Carlos Alberto Mendoza-Gómez. *Faculty of Sports Organization. Autonomous University of Nuevo Leon. Nuevo León, Mexico.*
María Cristina Enríquez-Reyna . *Faculty of Sports Organization. Autonomous University of Nuevo Leon. Nuevo León, Mexico.*
Marina Medina-Corrales. *Faculty of Sports Organization. Autonomous University of Nuevo León. Nuevo Leon, Mexico.*
Pedro Gualberto Morales-Corral. *Faculty of Sports Organization. Autonomous University of Nuevo Leon. Nuevo León, Mexico.*
Perla Lizeth Hernández-Cortés. *Faculty of Sports Organization. Autonomous University of Nuevo Leon. Nuevo León, Mexico.*
Luis Enrique Carranza-García. *Faculty of Sports Organization. Autonomous University of Nuevo Leon. Nuevo León, Mexico.*

ABSTRACT

Running-related knee injuries are common in long-distance runners and may lead to persistent biomechanical adaptations even after return to sport. This study aimed to compare spatiotemporal parameters of the running gait cycle between long-distance runners with and without a history of knee injury during incremental treadmill running. Thirty male long-distance recreational runners (15 with previous knee injury and 15 controls) were assessed using three-dimensional motion capture at 9, 11, and 13 km/h. Temporal variables included stride time, stance time, swing time, phase distribution, and cadence. Mixed-model repeated measures analyses and Mann–Whitney U tests were applied ($p < .05$). No significant main effects or interactions were observed, indicating a preserved global temporal organization across speeds. However, runners with a history of injury demonstrated greater stance time at 9 km/h (right limb) and 11 km/h (left limb). These findings suggest the presence of subtle, speed-dependent adaptations in temporal running mechanics, particularly during the stance phase. Such localized adjustments may be relevant for understanding injury recurrence and guiding biomechanical assessment in running populations. injury recurrence and for guiding biomechanical assessment in running populations.

Keywords: Biomechanics, Spatiotemporal parameters, Treadmill running, Gait mechanics, Overuse injury.

Cite this article as:
Mendoza-Gómez, C. A., Enríquez-Reyna, M. C., Medina-Corrales, M., Morales-Corral, P. G., Hernández-Cortés, P. L., & Carranza-García, L. E. (2026). Speed-dependent stance time adaptations in long-distance runners with and without a history of knee injury. *Journal of Human Sport and Exercise, 21*(4), 1228-1237. https://doi.org/10.55860/h1sg2m46

Corresponding author. *Faculty of Sports Organization. Autonomous University of Nuevo León. Ciudad Universitaria, San Nicolás de los Garza, Nuevo León, Mexico.*
E-mail: maria.enriquezryn@uanl.edu.mx

Submitted for publication April 30, 2026.
Accepted for publication June 11, 2026.
Published June 23, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/h1sg2m46

© 2026 ARD Asociación Española

INTRODUCTION

Running-related injuries represent a major concern in long-distance runners due to the repetitive mechanical demands imposed on the musculoskeletal system. Among these injuries, the knee is one of the most frequently affected anatomical regions, largely as a consequence of cumulative loading during running activities. Injury incidence has been reported between 2.5 and 33 cases per 1,000 hours of running, reflecting the substantial mechanical stress associated with training and competition (Bertelsen et al., 2017; Videbaek et al., 2015). Furthermore, a history of injury has consistently been identified as one of the strongest predictors of future injury, suggesting that residual biomechanical alterations may persist even after athletes return to sport (Van Poppel et al., 2021).

From a biomechanical standpoint, running is a cyclic locomotor task characterized by alternating stance and swing phases, where movement is organized through coordinated temporal and spatial patterns. The analysis of spatiotemporal parameters provides valuable insight into the structure of the gait cycle and the distribution of mechanical demands across the lower extremities (Kapri et al., 2021; Van Oeveren et al., 2024). Variables such as stride time, stance time, swing time, and cadence are commonly used to describe running mechanics and have been associated with performance, efficiency, and injury risk.

Among these variables, stance time is of particular interest, as it represents the period during which the foot remains in contact with the ground, and external forces are transmitted through the lower limb. Changes in stance duration may influence the temporal distribution of mechanical demands and reflect adjustments in motor control strategies during running. Previous studies have shown that alterations in the stance phase are associated with modifications in joint kinematics, impact attenuation, and neuromuscular coordination, particularly in populations with musculoskeletal impairments (Esculier et al., 2015; Neal et al., 2019; Yang et al., 2022).

Despite the growing body of literature on running biomechanics, most studies examining knee-related conditions have focused on symptomatic individuals or clinical populations. In contrast, less attention has been given to runners who have returned to sport and are currently asymptomatic but present a history of injury. This distinction is particularly relevant, as these individuals may exhibit subtle biomechanical adaptations that are not readily observable through global measures but could still influence injury recurrence risk.

In addition to injury history, running mechanics are influenced by external demands such as speed. Incremental treadmill protocols have been widely used to evaluate how biomechanical variables respond to increasing running intensity under controlled conditions. Evidence suggests that higher running speeds are associated with reductions in stance time, increases in cadence, and changes in stride characteristics, reflecting the adaptive behaviour of the locomotor system in response to greater mechanical demands (van Oeveren et al., 2024; Wang et al., 2025). However, it remains unclear whether these speed-dependent adaptations are consistent across individuals with different injury backgrounds.

Understanding how runners with and without a history of knee injury respond to increasing running speeds may provide relevant insights into the persistence of biomechanical adaptations following injury. In particular, examining temporal parameters may help identify subtle differences in movement organization that are not evident through global performance measures. These differences could reflect compensatory strategies or residual adaptations that influence how mechanical demands are managed during running.

Therefore, the aim of this study was to compare spatiotemporal parameters of the running gait cycle, with a specific focus on stance time, between long-distance runners with and without a history of knee injury during an incremental treadmill protocol. It was hypothesized that runners with previous injury would exhibit speed-dependent differences in temporal parameters, particularly in stance time, reflecting subtle adaptations in running mechanics.

MATERIAL AND METHODS

Participants

Thirty male recreational long-distance runners (n = 30) participated in this study. Participants were divided into two groups: runners with a history of knee injury (n = 15) and runners without a history of injury (n = 15). A history of injury was defined as a previously clinically diagnosed knee injury, with no current pain or functional limitations at the time of testing. All participants were actively training and were able to complete the protocol without interruption. Participants completed a questionnaire on their injury history and the Spanish version of the Knee Injury and Osteoarthritis Outcome Score –KOOS- (Vaquero et al., 2014). Participants were classified with and without a history of knee injury based on the information provided in the injury history questionnaire and the KOOS results, to identify both the presence of previous injuries and the current functional status of the knee joint.

Inclusion criteria were being male, participating regularly in long-distance running training, and being free of current musculoskeletal pain. All participants were informed about the study's objectives and procedures and provided written informed consent prior to their participation. The study was conducted in accordance with the Declaration of Helsinki and approved by the institutional ethics committee (REPRIN-FOD-171).

Measures

Three-dimensional kinematic data were collected using a BTS SMART-DX Evo motion capture system (BTS Bioengineering, Italy), consisting of eight infrared cameras. Reflective markers were placed according to a modified Helen Hayes protocol to identify gait cycle events and calculate temporal parameters. The following spatiotemporal variables were analysed: Stride time (s), stance time (s), swing time (s), stance phase (%), swing phase (%), cadence (steps/min). Temporal parameters were calculated separately for the right and left limbs, except for cadence, which was considered a global parameter.

Procedures

Participants were recruited through local running clubs. After verifying eligibility criteria and obtaining informed consent, each participant completed a standardized testing session. Prior to data collection, anthropometric measurements were obtained using a measuring tape, including anterior superior iliac spine (ASIS) distance, hip depth, and lower limb length, to ensure accurate marker placement. The motion capture volume was calibrated according to the manufacturer's specifications before each testing session.

Reflective markers were placed according to the modified Helen Hayes marker set implemented in the BTS SMART-Clinic treadmill protocol, which is based on the gait analysis models described by Kadaba et al. (1990) and Davis et al. (1991). Markers were positioned on specific anatomical landmarks of the lower extremities to allow precise identification of running gait cycle events. A schematic representation of the motion capture setup and camera distribution is presented in Figure 1.

A 5-minute warm-up was performed on a treadmill at a self-selected comfortable running speed, followed by an incremental treadmill protocol at three fixed speeds (9, 11, and 13 km/h). At each speed, participants

 © 2026 ARD Asociación Española

performed a 2-minute familiarization period followed by 15 seconds of data acquisition. Participants were instructed to run naturally and to avoid consciously modifying their running technique throughout the protocol. For each running speed, gait cycle events were identified using SMARTclinic software (BTS Bioengineering, Italy). A minimum of 12 valid consecutive gait cycles were analysed for each participant. Temporal variables were calculated for each gait cycle and averaged to obtain a representative value for each participant and condition.

Note. Schematic representation of the motion capture setup, illustrating the treadmill positioned at the centre of the capture volume and the peripheral distribution of eight infrared cam eras (SMART DX Evo, B TS Bioengineering).

Figure 1. Layout of the motion capture system.

Data analysis

Kinematic data were processed using SMARTclinic software (BTS Bioengineering) and statistically analysed using SPSS (version 26.0, IBM Corp., Armonk, NY, USA). Descriptive analyses were performed, reporting median, mean, and standard deviation for each variable, differentiated by group, limb, and running speed. To evaluate the effects of speed, injury history, and their interaction on the temporal parameters of the running gait cycle, mixed-model repeated measures analyses of variance were conducted, considering speed as the within-subject factor and group as the between-subject factor and Bonferroni-corrected post hoc comparisons. Additionally, non-parametric analyses were performed for between-group comparisons in specific variables using the *Mann–Whitney U* test when appropriate. The level of statistical significance was set at $p < .05$.

RESULTS

Data from 30 runners are presented, with anthropometric characteristics reflecting a typical profile of recreational long-distance runners, within the normal weight range, with a stable and homogeneous distribution of their physical characteristics ($p > .05$), suitable for the execution of the incremental treadmill protocol (Table 1).

Spatiotemporal parameters of the running gait cycle obtained at 9, 11, and 13 km/h are presented in Table 2, differentiated by group (runners with and without a history of knee injury) and by limb (right and left). For each variable, median values as well as mean and standard deviation are reported to characterize the temporal behaviour of the running pattern in both groups. Cadence is presented as a global parameter, as it represents an integrated measure of the running cycle and is not limb-dependent.

Table 1. Characteristics of participants classified as with and without a history of knee injury.

Variable	With Injury History (n = 15)		Without Injury History (n = 15)	
	Media	SD	Media	SD
Age (years)	32.87	9.53	28.53	6.22
Height (cm)	174.87	7.54	172.07	6.38
Weight (kg)	77.20	10.46	72.47	10.47
BMI (kg/m²)	25.20	2.83	24.40	3.33
ASIS (cm)	28.20	1.57	26.87	1.19
RHD (cm)	13.01	0.91	12.83	1.03
LHP (cm)	13.00	0.93	12.86	1.04
LLR (cm)	90.80	4.72	88.90	4.61
LLL (cm	90.73	4.62	88.89	4.60

Note: Data are presented as means and SD = Standard Deviation. BMI = Body Mass Index; ASIS = Anterior Superior Iliac Spine; RHD = Right Hip Depth; LHP = Left Hip Depth; LLR = Lower Limb Right; LLL = Lower Limb Left.

Table 2. Spatiotemporal parameters of the running gait cycle at 9, 11, and 13 km/h in runners with and without a history of knee injury.

S (km/h)	Limb	Variable	With Injury History (*n* = 15)				Without Injury History (*n* = 15)			
			Mdn	M ± SD	CI 95%		Mdn	M ± SD	CI 95%	
9	Right	Stride time (s)	0.720	0.718 ± 0.036	0.697	0.739	0.710	0.682 ± 0.175	0.586	0.780
		Stance time (s)	0.370	0.364 ± 0.023	0.351	0.378	0.350	0.347 ± 0.026	0.333	0.362
		Swing time (s)	0.380	0.375 ± 0.031	0.358	0.392	0.390	0.392 ± 0.027	0.377	0.407
		Stance phase (%)	50.899	50.899 ± 4.461	48.323	53.474	47.720	47.731 ± 3.443	45.830	49.633
		Swing phase (%)	53.020	52.294 ± 3.643	50.191	54.398	54.250	54.218 ± 2.706	52.719	55.717
	Left	Stride time (s)	0.720	0.721 ± 0.035	0.701	0.742	0.710	0.681 ± 0.176	0.584	0.779
		Stance time (s)	0.370	0.366 ± 0.020	0.355	0.378	0.360	0.351 ± 0.034	0.332	0.370
		Swing time (s)	0.370	0.373 ± 0.030	0.355	0.390	0.390	0.387 ± 0.028	0.371	0.402
		Stance phase (%)	51.140	50.682 ± 4.120	48.303	53.061	49.070	48.601 ± 4.367	46.183	51.019
		Swing phase (%)	52.645	51.728 ± 3.117	49.928	53.527	53.750	53.608 ± 3.479	51.682	55.534
		Cadence (steps/min)	166.500	167.23 ± 7.910	162.662	171.795	168.600	166.20 ± 9.911	160.711	171.689
11	Right	Stride time (s)	0.710	0.705 ± 0.036	0.684	0.725	0.690	0.704 ± .059	0.672	0.736
		Stance time (s)	0.320	0.323 ± 0.021	0.311	0.334	0.320	0.318 ± 0.029	0.302	0.334
		Swing time (s)	0.410	0.403 ± 0.032	0.385	0.420	0.410	0.406 ± 0.032	0.388	0.424
		Stance phase (%)	45.840	46.089 ± 4.106	43.815	48.363	45.950	45.372 ± 3.877	43.225	47.519
		Swing phase (%)	58.270	57.140 ± 3.353	55.283	58.997	58.760	57.708 ± 2.885	56.110	59.306
	Left	Stride time (s)	0.710	0.712 ± 0.25	0.698	0.726	0.710	0.706 ± 0.054	0.676	0.736
		Stance time (s)	0.330	0.319 ± 0.030	0.303	0.336	0.320	0.319 ± 0.034	0.301	0.338
		Swing time (s)	0.410	0.407 ± 0.039	0.386	0.429	0.400	0.404 ± 0.030	0.387	0.421
		Stance phase (%)	45.470	44.723 ± 4.446	42.261	47.185	47.000	45.333 ± 3.824	43.215	47.451
		Swing phase (%)	57.300	57.267 ± 4.789	54.615	59.919	57.790	57.325 ± 3.626	55.317	59.333
		Cadence (steps/min)	169.800	169.960 ± 7.152	166.000	173.920	172.8	171.08 ± 13.308	163.710	178.450
13	Right	Stride time (s)	0.680	0.683 ± 0.033	0.665	0.701	0.680	0.692 ± 0.051	0.664	0.720
		Stance time (s)	0.310	0.301 ± 0.020	0.290	0.312	0.290	0.296 ± 0.034	0.277	0.315
		Swing time (s)	0.410	0.403 ± 0.027	0.388	0.418	0.410	0.407 ± 0.051	0.3787	0.4346
		Stance phase (%)	44.360	44.195 ± 2.915	42.581	45.810	42.460	42.830 ± 5.235	39.930	45.728
		Swing phase (%)	60.120	58.982 ± 3.830	56.861	61.103	59.450	58.971 ± 5.935	55.685	62.258
	Left	Stride time (s)	0.680	0.683 ± 0.036	0.663	0.703	0.680	0.693 ± 0.049	0.666	0.720
		Stance time (s)	0.300	0.301 ± 0.013	0.293	0.308	0.280	0.285 ± 0.030	0.268	0.301
		Swing time (s)	0.410	0.405 ± 0.031	0.388	0.422	0.410	0.418 ± 0.046	0.3928	0.4432
		Stance phase (%)	45.040	43.977 ± 2.809	42.422	45.533	41.880	41.115 ± .045	38.682	43.627
		Swing phase (%)	59.260	59.304 ± 4.044	57.064	61.544	59.030	60.170 ± 4.343	57.765	62.575
		Cadence (steps/min)	175.8	176.000 ± 8.254	171.429	180.571	177.000	174.120 ± 11.477	167.764	180.476

Note. Mdn = Median; SD = Standard Deviation; S = Speed. Cadence is expressed as a global parameter of the running cycle.

Overall, descriptive values across the three running speeds showed a consistent and stable temporal pattern of the gait cycle. Stride time remained within a narrow range (0.68–0.72 s), while stance time ranged between 0.29 and 0.37 s in both limbs. The percentages of stance and swing phases showed small variations between speeds (approximately 1–3%), and minimal differences were observed between groups. Cadence increased progressively as running speed increased but remained comparable between runners with and without a history of injury (Table 2).

A mixed-design repeated-measures ANOVA was conducted with speed (9, 11 and 13 km/h) and limb (right and left) as within-subjects factors, and injury status (injured vs. uninjured) as a between-subjects factor. No significant main effects were observed for speed ($F_{(1.05, 29.45)} = 0.66$, $p = .430$, $\eta p^2 = .023$); limb ($F_{(1, 28)} = 0.76$,

 © 2026 ARD Asociación Española

p = .392, ηp^2 = .026); nor of injury ($F_{(1, 28)}$ = 0.32, p = .578, ηp^2 = .011). Similarly, no significant interactions were found between speed and limb ($F_{(1.78, 49.87)}$ = 0.50, p = .586, ηp^2 = .018); speed and injury ($F_{(1.05, 29.45)}$ = 1.22, p = .280, ηp^2 = .042); limb and injury ($F_{(1, 28)}$ = 0.34, p = .567, ηp^2 = .012); nor for the three-way interaction speed × limb × injury ($F_{(1.78, 49.87)}$ = 0.38, p = .661, ηp^2 = .013). Stance time decreases significantly as running speed increases (very large effect: ηp^2 = .846). The response of stride time to changes in speed was comparable in both groups and in both limbs.

About stance time, the mixed ANOVA revealed a significant main effect of speed on stance time ($F_{(1.68, 46.97)}$ = 154.36, p < .001, ηp^2 = .846). *Bonferroni-corrected post hoc* comparisons showed that support time decreased significantly as running speed increased, with differences observed between 9 and 11 km/h (Δ = 3.78, p < .001), between 9 and 13 km/h (Δ = 6.20, p < .001), and between 11 and 13 km/h (Δ = 2.42, p < .001). No significant effects were found for limb ($F_{(1, 28)}$ = 0.40, p = .532, ηp^2 = .014), nor for injury condition ($F_{(1, 28)}$ = 1.49, p = .232, ηp^2 = .051). Furthermore, the interactions speed × injury, speed × limb, limb × injury and speed × limb × injury did not reach statistical significance (p > .05). The trend analysis revealed significant linear ($F_{(1,28)}$ = 278.12, p < .001, ηp^2 = .909) and quadratic ($F_{(1,28)}$ = 5.42, p = .027, ηp^2 = .162), suggesting that the reduction in stance time as speed increases follows a predominantly linear pattern, albeit with some curvature.

The swing time increased significantly when speed increased from 9 km/h to 11 km/h and remained stable between 11 km/h and 13 km/h. No differences were observed between limbs or between runners with and without a history of knee injury.

However, complementary non-parametric analyses revealed specific between-group differences in stance time. A significant difference was identified in the stance time of the right limb at 9 km/hr, which was greater in runners with a history of knee injury compared to those without (Z = -2.094, p = .037). Additionally, at a running speed of 13 km/h, the stance time of the left limb was also significantly greater in the injury group (Z = -2.361, p = .018). No statistically significant differences were observed between groups for stride time, swing time, stance phase, swing phase, or cadence at any of the evaluated speeds (p > .05), reinforcing the overall similarity in temporal running patterns between groups.

DISCUSSION

The aim of this study was to compare the temporal parameters of the running cycle between long-distance runners with and without a history of knee injury during an incremental treadmill protocol. Overall, both groups exhibited a comparable overall temporal pattern across the speeds assessed. No differences were observed in stride time, swing time, phase percentages, or cadence, indicating that a history of injury was not associated with a general reorganization of the temporal cycle under the conditions analysed.

The gradual increase in speed induced the hypothesized temporal adjustments in both groups, characterized by a reduction in stride length and ground contact time, as well as an increase in cadence. This behaviour aligns with the described relationship between running frequency and stride length, where speed results from the product of these two variables and their compensatory adjustments (Kapri, Mehta & Singh, 2021; Van Oeveren et al., 2024). The consistent response to the increase in speed suggests that the basic temporal control of the locomotor pattern remains intact in runners with a history of injury.

In the inferential analyses, the mixed models for repeated measures did not reveal any significant main effects or interactions between speed and injury history, indicating that there was no structural modification of the

temporal pattern throughout the incremental protocol. However, nonparametric analyses revealed specific differences in stance time at specific speeds. At 9 km/h, stance time on the right limb was significantly longer in runners with a history of injury, whereas at 13 km/h the difference was observed on the left limb. The emergence of these differences at different speeds and in opposite limbs suggests that the effect associated with injury history does not follow a uniform bilateral pattern, but rather localized temporal adjustments that may manifest under specific mechanical demands. The absence of global effects in the mixed model, together with the presence of specific differences detected through nonparametric analyses, indicates that the adaptations associated with a history of injury were subtle and of small magnitude. This behaviour suggests that the general locomotor pattern may remain stable while specific variations are expressed in the stance phase.

Stance time is a biomechanically significant variable, as this phase involves the greatest interaction between the lower limb and the ground and is when the primary processes of shock absorption and load transfer occur. It has been reported that during running, the patellofemoral joint can experience compressive forces of up to four times body weight, especially during initial contact and load acceptance (Esculier et al., 2015). In this context, small variations in stance duration could represent temporal adjustments associated with load modulation in subjects with a history of injury.

These findings are consistent with previous research suggesting that biomechanical adaptations may persist after musculoskeletal injury. Souza et al. (2023) reported differences in lower-limb movement patterns during running, indicating that injury-related adaptations may be expressed through subtle biomechanical adjustments rather than through global alterations in running mechanics. In the present study, these adaptations were reflected in specific differences in stance time, despite the overall similarity of the temporal running pattern between groups.

Furthermore, recent evidence has shown that specific modifications can occur without a complete reorganization of the locomotor pattern. De Souza Júnior et al. (2024) observed that, following retraining interventions in runners with patellofemoral pain, no significant changes occurred in multiple kinematic variables despite clinical improvement. Taken together, these findings reinforce the idea that the locomotor system can maintain its overall organization while exhibiting discrete adjustments.

From a clinical perspective, identifying specific increases in ground contact time can provide valuable information for runners with a history of knee injuries. Given that a history of injury is one of the most consistent risk factors for recurrence in runners (Van Poppel et al., 2021), a detailed assessment of the stance phase could contribute to biomechanical monitoring during rehabilitation and secondary prevention. However, further studies are needed to confirm these findings.

Among the study's limitations are the absence of direct measurements of ground reaction forces and the calculation of joint moments using inverse dynamics, which prevents the establishment of a quantitative relationship between the observed increase in stance time and the exact magnitude of the joint load. Furthermore, the cross-sectional design does not allow for the establishment of causal relationships between the history of injury and the observed temporal differences. Another limitation of this study was that participants were classified according to their history of knee injury based on self-report, and functional assessment was carried out using the KOOS questionnaire, without a specific clinical diagnosis to identify the type, severity or exact location of the injury. In this regard, future research should incorporate specialised clinical assessments, confirmed medical diagnoses and, where possible, imaging studies or clinical records to improve the accuracy of participant classification. Furthermore, it would be appropriate to differentiate

 © 2026 ARD Asociación Española

runners according to the type of knee injury (e.g., patellofemoral pain syndrome, meniscal injury or ligament injury), the time elapsed since the injury and their recovery status, in order to determine whether these characteristics differentially influence the functional and biomechanical variables analysed. Finally, longitudinal studies could help to clarify the relationship between the functional alterations observed and the development or recurrence of knee injuries in runners.

CONCLUSIONS

In conclusion, long-distance runners with a history of knee injury exhibited an overall temporal pattern comparable to that of runners without such a history during an incremental treadmill protocol. However, specific increases in ground contact time were identified at certain speeds, suggesting the presence of discrete temporal adjustments associated with injury history. From a practical perspective, these findings suggest that temporal analysis according to running speed and limb may provide additional information for the biomechanical assessment and monitoring of runners with a history of knee injury. Further longitudinal studies are needed to determine the clinical significance of these adaptations and their relationship with future injury risk.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Carlos Alberto Mendoza Gómez (CAMG), María Cristina Enríquez Reyna (MCER), and Marina Medina Corrales (MMC) participated in the conceptualization of the study, while the methodology and data analysis involved all authors (CAMG, MCER, MMC, Perla Lizeth Hernández Cortés (PLHC), Pedro Gualberto Morales Corral (PGMC), and Luis Enrique Carranza García (LECG). The formal analysis was conducted by CAMG, MCER, and MMC, and data curation was performed by CAMG and MMC. The original draft was written by CAMG and MCER, while the revision and editing of the manuscript, as well as the visualization of the results, involved all authors. Supervisory tasks were performed by MCER, MMC, PGMG, PLHC, and LECG, while project management was handled by CAMG, MCER, and MMC. Finally, funding acquisition was managed by CAMG and MMC. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and

readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

ACKNOWLEDGMENTS

The first author gratefully acknowledges the Secretaría de Ciencia, Humanidades, Tecnología e Innovación for the scholarship supporting doctoral studies in the PhD Program in Physical Activity and Sport Sciences, as well as Hospital Ángeles Valle Oriente for the facilities and support provided during the study. Finally, we would like to thank the UANL Secretariat for Scientific Research and Technological Development for its support in the publication of this article.

REFERENCES

Bertelsen, M. L., Hulme, A., Petersen, J., Brund, R. K., Sørensen, H., Finch, C. F., Parner, E. T., & Nielsen, R. O. (2017). A framework for the etiology of running-related injuries. British Journal of Sports Medicine, 51(8), 704-711.

Davis, R. B., Ounpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. Human Movement Science, 10(5), 575-587. https://doi.org/10.1016/0167-9457(91)90046-Z

De Souza Júnior, J. R., Rabelo, P. H. R., Lemos, T. V., Esculier, J. F., Barbosa, G. M. P., & Matheus, J. P. C. (2024). Effects of two gait retraining programs on pain, function, and lower limb kinematics in runners with patellofemoral pain: A randomized controlled trial. PLoS One, 19(1), e0295645. https://doi.org/10.1371/journal.pone.0295645

De Souza Muniz, A. M., Zeitoune, G., Alvim, F., Grassi, G. B., Britto, P. A., & Nadal, J. (2023). Do exist differences in kinematics and EMG of the hip and knee between male runners with and without patellofemoral pain in different running speeds?. Physical Therapy in Sport, 59, 122-129. https://doi.org/10.1016/j.ptsp.2022.12.006

Esculier, J. F., Roy, J. S., & Bouyer, L. J. (2015). Lower limb control and strength in runners with and without patellofemoral pain syndrome. Gait & posture, 41(3), 813-819. https://doi.org/10.1016/j.gaitpost.2015.02.020

Hernández Sampieri, R., & Mendoza Torres, C. P. (2018). Metodología de la investigación: Las rutas cuantitativa, cualitativa y mixta (6.ª ed.). McGraw-Hill Interamericana.

Kadaba, M. P., Ramakrishnan, H. K., & Wootten, M. E. (1990). Measurement of lower extremity kinematics during level walking. Journal of Orthopaedic Research, 8(3), 383-392. https://doi.org/10.1002/jor.1100080310

Kapri, S., Mehta, S., & Singh, K. P. (2021). Spatiotemporal and kinematic parameters in distance running: A biomechanical overview. Sports Biomechanics, 20(4), 345-360.

Neal, B. S., Barton, C. J., Birn-Jeffery, A., & Morrissey, D. (2019). Increased hip adduction during running is associated with patellofemoral pain: A case-control study. Journal of Biomechanics, 91, 133-139. https://doi.org/10.1016/j.jbiomech.2019.04.015

Lopes, A. D., Mascarinas, A., & Hespanhol, L. (2023). Are alterations in running biomechanics associated with running injuries? A systematic review with meta-analysis. Brazilian journal of physical therapy, 27(4), 100538. https://doi.org/10.1016/j.bjpt.2023.100538

Quan, W., Zhou, H., Ma, Y., Xu, D., Gao, Z., Wang, X., Radak, Z., & Gu, Y. (2026). Effects of running distance on per-step and cumulative lower-extremity loading during a simulated treadmill half marathon. Frontiers in Public Health, 14, 1741450. https://doi.org/10.3389/fpubh.2026.1741450

 © 2026 ARD Asociación Española

Van Oeveren, B. T., de Ruiter, C. J., Beek, P. J., & van Dieën, J. H. (2024). The biomechanics of running and running styles: a synthesis. Sports biomechanics, 23(4), 516-554. https://doi.org/10.1080/14763141.2021.1873411

Van Poppel, D., van der Worp, M., Slabbekoorn, A., van den Heuvel, S. S. P., van Middelkoop, M., Koes, B. W., Verhagen, A. P., & Scholten-Peeters, G. G. M. (2021). Risk factors for overuse injuries in short- and long-distance running: A systematic review. Journal of sport and health science, 10(1), 14-28. https://doi.org/10.1016/j.jshs.2020.06.006

Vaquero, J., Longo, U. G., Forriol, F., Martinelli, N., Vethencourt, R., & Denaro, V. (2014). Reliability, validity and responsiveness of the Spanish version of the Knee Injury and Osteoarthritis Outcome Score (KOOS) in patients with chondral lesion of the knee. Knee Surgery, Sports Traumatology, Arthroscopy, 22(1), 104-108. https://doi.org/10.1007/s00167-012-2290-1

Videbaek, S., Bueno, A. M., Nielsen, R. O., & Rasmussen, S. (2015). Incidence of running-related injuries per 1000 h of running in different types of runners: A systematic review and meta-analysis. Scandinavian Journal of Medicine & Science in Sports, 25(5), 737-746. https://doi.org/10.1111/sms.12361

Wang, W., Xu, S., Komnik, I., Viellehner, J., Zedler, M., & Potthast, W. (2025). Biomechanical changes and the time course of recovery in lower extremities of recreational runners following a simulated treadmill half-marathon. Sports Medicine - Open, 11, 22. https://doi.org/10.1186/s40798-025-00824-x

Yang, C., Best, T. M., Liu, H., & Yu, B. (2022). Knee biomechanical factors associated with patellofemoral pain in recreational runners. The Knee, 35, 87-97. https://doi.org/10.1016/j.knee.2022.02.007

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Triadic assessment of oral presentations in higher education: Convergence between self-, peer- and teacher assessment according to academic performance

Andrés Sánchez-García. *Department of Physical Education and Sport. University of Sevilla. Sevilla, Spain.*
Research Group on Management and Innovation in Sports, Leisure and Recreation Services – GISDOR (SEJ-525). University of Sevilla. Sevilla, Spain.

Moisés Grimaldi-Puyana . *Department of Physical Education and Sport. University of Sevilla. Sevilla, Spain.*
Research Group on Management and Innovation in Sports, Leisure and Recreation Services – GISDOR (SEJ-525). University of Sevilla. Sevilla, Spain.

Antonio Muñoz-Llerena. *Department of Human Movement and Sports Performance. University of Sevilla. Sevilla, Spain.*
Research Group on Social Inclusion and Innovation through Physical Activity and Sport – INEFYD (HUM-1061). University of Sevilla. Sevilla, Spain.

Antonio Jesús Sánchez-Oliver. *Department of Human Movement and Sports Performance. University of Sevilla. Sevilla, Spain.*
Studies Research Group in Neuromuscular Responses (GEPREN). University of Lavras. Lavras, Brazil.

ABSTRACT

Formative assessment in higher education requires strategies that support the development of students' evaluative judgement. Triadic assessment, which integrates self-, peer- and teacher assessment, is considered a valuable practice to promote reflection on learning quality. Aiming to analyse differences between assessment modalities in university oral presentations and to examine whether students' academic performance is associated with greater convergence between student and teacher assessments, a cross-sectional observational study was conducted. 6,191 oral presentations assessments were carried out using an 8-item rubric (1–4 scale), and overall mean scores were calculated. Non-parametric procedures were used to analyse reliability, differences between assessment modalities and convergence with teacher criterion. The rubric showed adequate internal consistency (α = .85). Significant differences were found between modalities ($p < .001$), with higher scores in self-assessment (M = 3.75), followed by peer assessment (M = 3.58) and teacher assessment (M = 3.45). Overall score was positively associated with the final course grade (ρ = .16; $p < .001$), with a stronger association in self-assessment (ρ = .32) than in peer assessment (ρ = .12). Students with higher performance tended to produce assessments closer to the teacher criterion, particularly in peer assessment ($p < .001$), although the pattern was not strictly linear. The largest discrepancies were observed in content, presentation, and time management. Findings support the value of triadic assessment as a strategy for developing students' evaluative judgement and provide empirical evidence of the role of academic performance in the progressive alignment with the teacher criterion in complex tasks.

Keywords: Physical education, Formative assessment, Rubric, Higher education, Communication skills.

Cite this article as:
Sánchez-García, A., Grimaldi-Puyana, M., Muñoz-Llerena, A., & Sánchez-Oliver, A. J. (2026). Triadic assessment of oral presentations in higher education: Convergence between self-, peer- and teacher assessment according to academic performance. *Journal of Human Sport and Exercise, 21*(4), 1238-1249. https://doi.org/10.55860/tsmqhw98

Corresponding author. *Department of Physical Education and Sport. University of Sevilla. Sevilla, Spain.*
E-mail: mgrimaldi@us.es

Submitted for publication April 23, 2026.
Accepted for publication June 08, 2026.
Published June 23, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/tsmqhw98

© 2026 ARD Asociación Española

INTRODUCTION

Assessment in higher education has undergone a substantial shift in recent decades. It has gradually moved from approaches focused almost exclusively on grading towards models that emphasise its formative function (Pascual-Arias et al., 2023). This change responds to the need to promote deep, self-regulated and transferable learning. It also reflects the need to prepare students for academic and professional contexts in which the ability to judge the quality of one's own work and that of others is essential (Olague et al., 2025). In this framework, the concept of evaluative judgement has gained increasing attention.

Evaluative judgement is defined as the capacity to judge the quality of work based on explicit criteria and shared standards. It is considered a key competence for lifelong learning (Boud et al., 2018; Tai et al., 2018). From this perspective, assessment is no longer seen as a final event. Instead, it is understood as a continuous learning process (Sánchez-Oliver et al., 2025).

Self-assessment and peer assessment play a central role in the development of evaluative judgement. Many studies have shown that these practices contribute to improvements in self-regulation, metacognition and student engagement (Basurto-Mendoza et al., 2021; Bozkurt, 2020; Kambourova et al., 2021). However, it has also been repeatedly observed that student assessments differ from those made by teachers. In general, they tend to be less demanding and more variable in the application of criteria (Sánchez-García et al., 2026; Sánchez-Oliver et al., 2026).

These discrepancies can be interpreted as a problem of reliability or validity. From a formative perspective, however, they can also be understood as a natural expression of the learning process involved in assessment. This process depends on factors such as previous experience, understanding of criteria, task complexity and the level of academic competence achieved (Sánchez-García et al., 2026; Sánchez-Oliver et al., 2025; Sánchez-Oliver et al., 2026).

In this context, triadic assessment, which integrates self-assessment, peer assessment and teacher assessment, emerges as a particularly valuable strategy (Gale et al., 2002). This approach makes it possible to compare different evaluative perspectives, identify patterns of convergence and divergence, and provide students with multiple reference points to calibrate their understanding of quality (Mendoza et al., 2021). It also offers an appropriate framework to analyse how evaluative judgement develops and which variables are associated with closer alignment with the expert judgement of teachers (Boud et al., 2018; Tai et al., 2018).

Among these variables, students' academic performance appears to be a potentially relevant factor. It is reasonable to assume that students with stronger academic and conceptual mastery may have a more accurate understanding of quality criteria and, therefore, produce assessments more closely aligned with those of teachers (Sánchez-García et al., 2026; Sánchez-Oliver et al., 2026). However, empirical evidence in this area is still limited, especially in complex tasks and in transversal competences such as oral presentations.

Oral presentations are particularly suitable for this type of analysis. They integrate conceptual, communicative, organisational and social dimensions, and require the simultaneous application of multiple quality criteria (Castejón et al., 2018; Chireac & Martín-Vegas, 2022; Fernández García et al., 2008). In addition, their assessment through analytic rubrics makes it possible to break down evaluative judgement and to examine in detail areas of agreement and disagreement between assessors (López-Pastor & Pérez-Pueyo, 2017; Velasco-Martínez & Tójar, 2017).

For the purposes of the present study, evaluative judgement is understood as the capacity to make informed decisions about the quality of work, both one's own and that of others, based on explicit criteria and evidence (Tai et al., 2018; Boud et al., 2018). This concept focuses specifically on the ability to interpret standards and apply them to concrete performances. In this context, convergence with teacher judgement is not interpreted as a direct measure of evaluative competence, but rather as an operational indicator of calibration with an institutionally legitimised reference point (McConlogue, 2020).

Based on the above, the aim of the present study is to analyse differences between self-assessment, peer assessment and teacher assessment in the evaluation of university oral presentations. More specifically, it seeks to examine whether students' academic performance is associated with greater convergence with teacher assessment, both in the overall score and in each rubric item. The main contribution of this study lies in the combined analysis of assessment modality and academic performance, and in the use of a distance-based index to estimate convergence with the teacher criterion both at overall level and item by item.

METHODS

Study design

An observational, descriptive-analytical and cross-sectional study was conducted. It was based on the secondary analysis of data derived from a triadic assessment system implemented in the context of university teaching. The ex post facto design made it possible to analyse relationships and differences between variables without any experimental manipulation. To analyse the role of academic performance, the students' final course grades were categorised into four ordered levels: pass, good, very good and excellent. This classification was used as the academic performance variable in all subsequent analyses.

Sample

The sample consisted of 6,191 assessment records corresponding to theoretical oral presentations given by university students. Each record represented a single assessment, either self-assessment, peer assessment or teacher assessment. Of the total number of assessments, 1,112 were self-assessments, 4,824 were peer assessments and 255 were teacher assessments. Consequently, 96.0% of the assessments were carried out by students and 4.1% by teachers. Among the assessors, 74.0% were men and 26.0% were women. All teacher assessments were carried out by male staff. Student assessments were linked to four levels of final academic performance in the course: pass, good, very good and excellent. Regarding academic performance, student assessments were distributed as follows: pass 2.7%, good 49.1%, very good 36.1%, and excellent 12.1%.

The lower number of assessments across modalities can be attributed to the reduced number of evaluators involved in teacher assessment compared to peer assessment, as well as in self-assessment relative to peer assessment.

Instrument

Assessment was carried out using a validated rubric composed of eight items, each rated on a scale from 1 to 4 points: content, organisation of information, presentation, oral expression, non-verbal language, time management, supporting materials and teamwork (Sánchez-Oliver et al., 2025). The final score for the oral presentation was calculated as the arithmetic mean of the eight items. The instrument showed adequate internal consistency, both overall and by assessment modality (see Results), which supports its use as a measure of oral presentation quality.

 © 2026 ARD Asociación Española

Procedure

Assessments were carried out in courses from the Degree in Physical Activity and Sport Sciences at the University of Seville during the 2024–2025 academic year. Presentations took place within the usual teaching context of the courses involved. After each presentation, students completed their self-assessment and the peer assessment of their classmates using the rubric. The presentations were delivered in small groups, and the assessment referred to the group performance as presented in class. At the same time, teachers carried out the teacher assessment using the same criteria. Teacher assessment was used as the expert reference point, not because it is assumed to be infallible, but because it represents the institutionally legitimised judgement within the context of higher education assessment.

Although teacher assessment is used here as a reference point for analytical purposes, it should not be interpreted as an absolute or infallible standard of quality. Rather, it represents a socially and institutionally legitimised benchmark within a given educational context. As such, convergence with teacher judgement should be understood as an operational indicator of alignment with shared standards, rather than as a direct measure of accuracy or evaluative competence. As previous authors have noted, no single judgement can be considered an absolute gold standard; however, teacher assessment provides a stable and socially recognised benchmark against which student judgements can be compared for analytical purposes (Boud & Falchikov, 2007; McConlogue, 2020). This approach makes it possible to examine whether students' judgements progressively align with shared standards of quality, while acknowledging that agreement with the teacher does not, by itself, guarantee high-quality evaluative judgement.

Data analysis

Given the ordinal nature of the scales and the heterogeneity of sample sizes, non-parametric procedures were used. Descriptive statistics were calculated (mean, standard deviation, median and sample size). Reliability was assessed using Cronbach's alpha. Differences between assessment modalities were analysed using the Kruskal–Wallis test, with Mann–Whitney post hoc tests and Bonferroni correction. Associations with academic performance were examined using Spearman's rho. Convergence with teacher assessment was estimated using an absolute distance index between student scores and the mean teacher score. The use of absolute distance allows a direct and comparable interpretation of the degree of convergence between assessors and facilitates the analysis of the progressive alignment of students' evaluative judgement with the expert reference.

Data was analysed using Python (version 3.11).

RESULTS

The evaluation rubric showed high internal consistency (α = .85). When broken down by assessment modality, reliability was high in peer assessment (α = .85), slightly lower in self-assessment (α = .82), and acceptable in teacher assessment (α = .75). These values indicate that the items consistently measure the overall construct of oral presentation quality across the three modalities.

Differences between assessment modalities

Statistically significant differences were found in the mean oral presentation score according to the type of assessment (H = 250.54; p < .001). Self-assessment produced the highest scores (M = 3.75, SD = 0.32), followed by peer assessment (M = 3.58, SD = 0.41) and teacher assessment (M = 3.45, SD = 0.41). Post hoc comparisons confirmed significant differences between all pairs, with small to moderate effect sizes. The largest difference was observed between self-assessment and teaching assessment (Figure 1).

A particularly relevant finding is that these differences between modalities appear in all items, although with varying intensity. Item-level analyses revealed statistically significant differences between modalities in all assessed dimensions ($p < .001$). The largest discrepancies were observed in the items content, presentation and time management, where teacher assessment was systematically more demanding than both self- and peer assessment. In contrast, items such as teamwork and organisation of information showed more moderate differences, suggesting greater convergence in dimensions that are more observable or more easily shared among assessors (Figure 1).

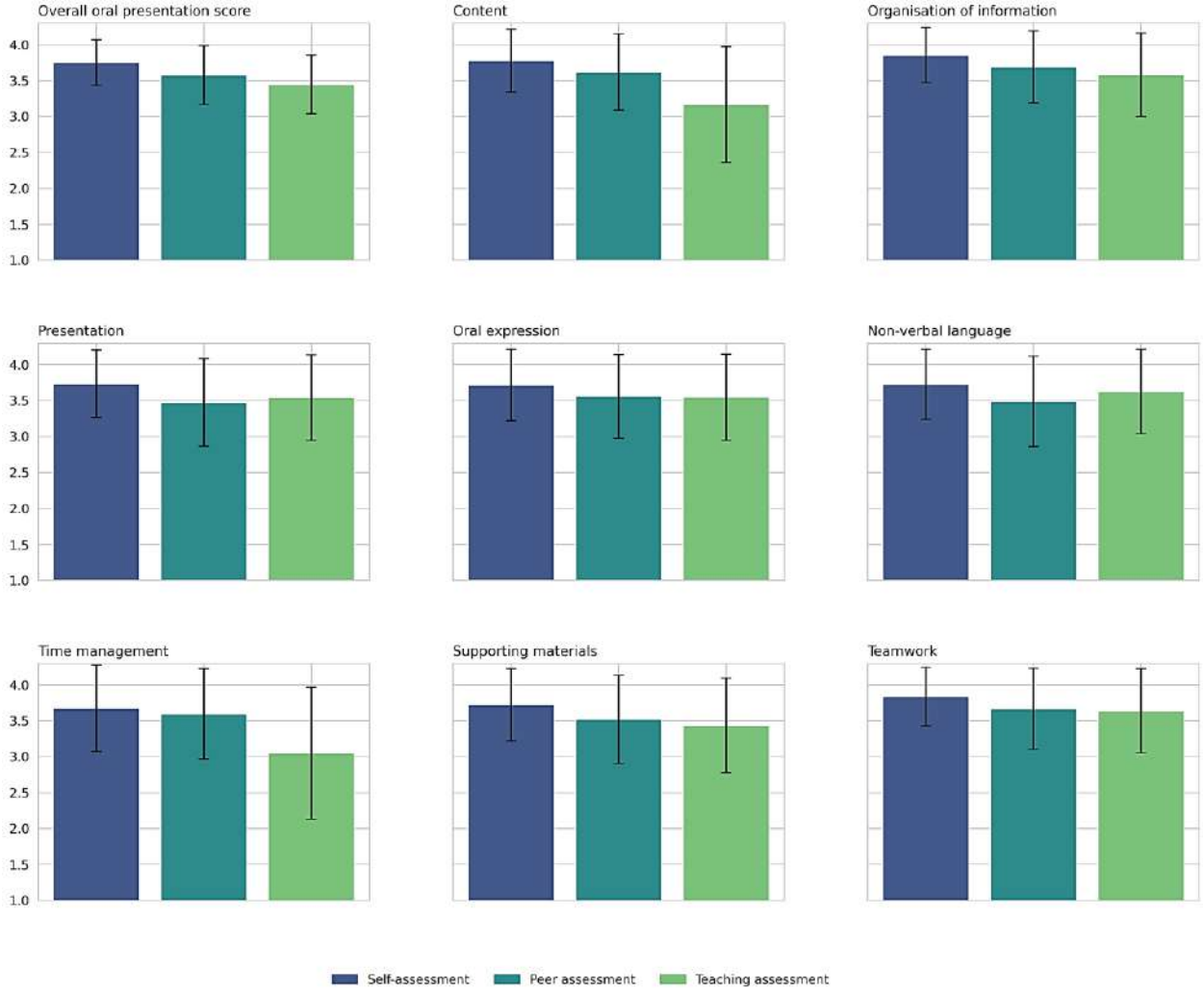


Figure 1. Overall and item-level mean scores by evaluation modality (self-assessment; peer assessment; teacher assessment) (Mean ± SD; Mean score: 1-4).

Relationship between presentation assessment and academic performance

Of particular interest is the fact that the mean presentation score was positively associated with the final course grade. This association was stronger in self-assessment than in peer assessment. The mean oral presentation score showed a positive and significant correlation with the final course grade ($\rho = .16$; $p < .001$). This pattern was maintained when analysed by modality, although with different magnitudes. The correlation was moderate for self-assessment ($\rho = .32$) and low for peer assessment ($\rho = .12$). In addition, significant differences were found in oral presentation scores according to the final course grade ($H = 195.85$;

 © 2026 ARD Asociación Española

$p < .001$). Students with very good and excellent grades generally obtained higher presentation scores than those with pass or good grades (Table 1).

Table 1. Oral presentation scores by final course grade (pass, good, very good and excellent).

Course mark	M ± SD	Median	n
Pass	3.72 ± 0.40	4.00	161
Good	3.55 ± 0.41	3.62	2.915
Very Good	3.66 ± 0.39	3.75	2.142
Excellent	3.69 ± 0.37	3.75	718

Note. M: Mean; SD: Standard Deviation.

Regarding convergence with teacher assessment, a key result is that this convergence varies according to the final course grade, with significant differences in both self- and peer assessment. Analysis of the distance between student and teacher assessments showed significant differences according to the final course grade, both for self-assessment ($H = 36.94$; $p < .001$) and for peer assessment ($H = 63.38$; $p < .001$). Overall, students with higher final course grades tended to produce assessments closer to the teacher criterion, particularly in peer assessment. However, the pattern was not strictly linear. In some cases, greater distances were observed at the highest levels of academic performance (Figure 2). It should be noted that, despite their statistical significance, these differences show small to moderate magnitudes. This is consistent with the progressive and formative nature of the development of evaluative judgement.

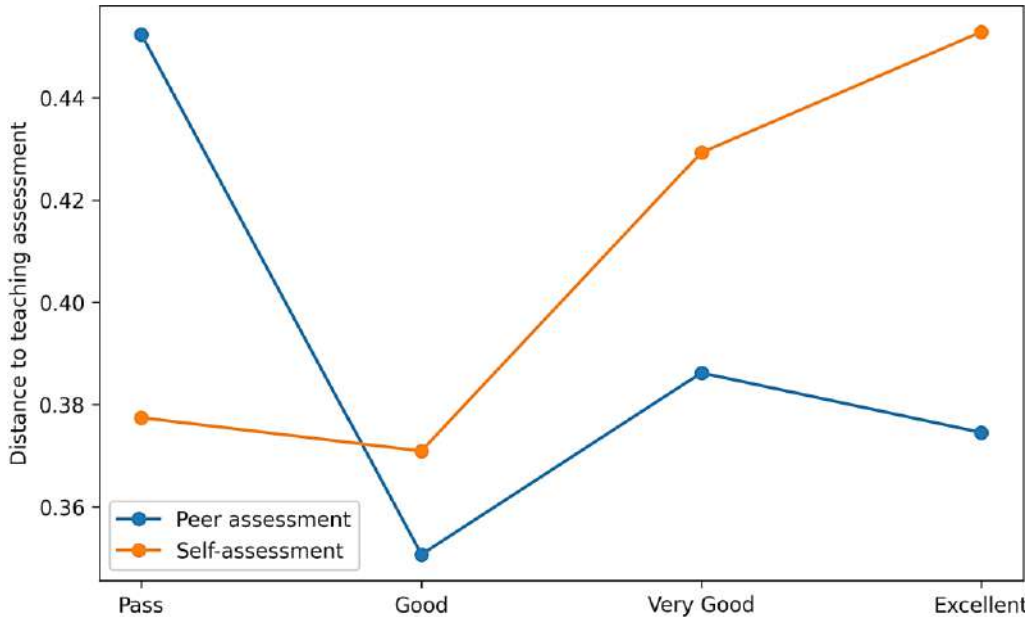


Figure 2. Convergence with teacher assessment according to final course grade (pass, good, very good and excellent).

Figure 3 shows the mean distance from the teacher assessment for each item regarding academic performance. A general trend towards greater convergence as academic performance increases can be observed, although with variations depending on the dimension assessed. The largest distances were found in the items content, presentation and time management. In contrast, organisation of information and teamwork showed closer alignment with the teacher criteria across all academic levels.

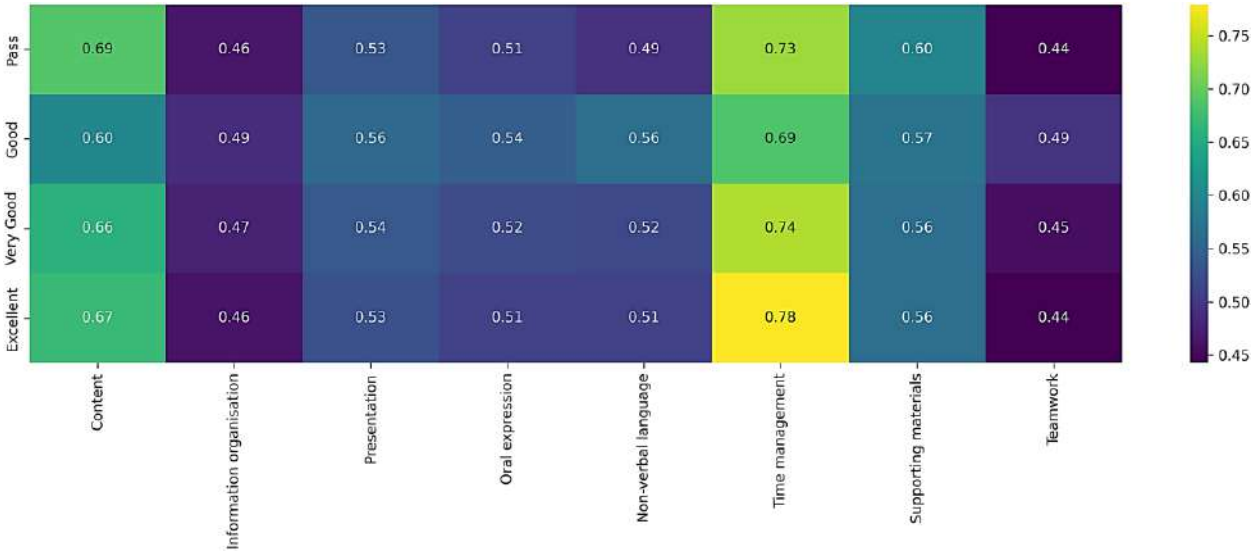


Figure 3. Distance to teacher assessment by item according to final course grade (pass, good, very good and excellent).

DISCUSSION

The findings, in this context and in similar higher education settings, confirm that the assessment of university oral presentations varies systematically according to the assessor. A clear and robust pattern shows that self-assessment produces the highest scores, peer assessment occupies an intermediate position, and teacher assessment is the most demanding. Although the observed relationships and differences are statistically significant, their magnitudes are small to moderate and should be interpreted in educational rather than deterministic terms.

Specifically, the findings show a clear gradient in triadic assessment, with higher scores in self-assessment (M = 3.75) than in peer assessment (M = 3.58), and higher scores in peer assessment than in teacher assessment (M = 3.45; H = 250.54; $p < .001$). This reproduces both the pattern observed in earlier studies and the one described in the literature on self-, peer- and teacher assessment in higher education (Topping, 1998, 2009; Falchikov & Goldfinch, 2000; Boud et al., 2018). This gradient is consistent with the idea that evaluative judgement may be associated with repeated exposure to explicit criteria, assessment practice and the use of quality evidence, rather than through grading alone (Boud & Falchikov, 2007; Boud et al., 2018).

The internal consistency of the rubric ($\alpha = .85$) supports its use to discriminate between levels of quality and suggests that the observed differences are more likely to reflect assessment processes than measurement error. This is in line with reviews showing that well-designed rubrics with clear descriptors support shared interpretations of quality (Reddy & Andrade, 2010; Panadero & Jonsson, 2013). The slightly lower alpha in teacher assessment is compatible with the application of more demanding and more differentiated criteria in dimensions with a higher conceptual load, such as content and presentation. This has also been noted in studies that point to limitations in the design and use of competence-based rubrics in higher education and to the need to improve their descriptive precision (Velasco-Martínez & Tójar, 2018; Reddy & Andrade, 2010).

From an educational validity perspective, the presentation score shows a positive association with the final course grade ($\rho = .16$; $p < .001$), with a stronger relationship in self-assessment ($\rho = .32$) than in peer

 © 2026 ARD Asociación Española

assessment (ρ = .12). This suggests that the task captures relevant transversal competences, such as communication, organisation and time management, without being reduced to a purely summative function (Sánchez-García et al., 2025). The moderate size of this association also supports the use of complementary assessment instruments to reflect the complexity of learning in academic communication tasks (Panadero & Jonsson, 2013). Although statistically significant, the magnitude of this association is modest, suggesting that academic performance explains only a limited proportion of the variance in assessment convergence.

A central contribution of this study is the finding that convergence with the teacher criterion is positively associated with academic performance, as reflected in the final course grade. Significant differences were found in the distance to teacher assessment in both self- and peer assessment, with a more consistent pattern in peer assessment (H_self = 36.94; H_peer = 63.38; $p < .001$). This pattern of alignment can be interpreted as indicative of calibration of evaluative judgement. This interpretation should be treated with caution. Convergence with teacher assessment does not necessarily reflect more accurate evaluative judgement, as teacher judgement is context-dependent and variable. Thus, alignment should be understood as calibration with an institutional reference rather than as a definitive indicator of evaluative quality, while divergence may also reflect alternative interpretations of the criteria. It is also consistent with the perspective of sustainable assessment, which aims to develop transferable evaluative capacities, and with recent proposals that integrate rubrics, exemplars, self- and peer assessment, and feedback to support the development of students' judgement (Boud & Soler, 2016; Tai et al., 2018). In this sense, the triadic structure facilitates the comparison of perspectives and the explicit discussion of criteria, as already suggested in early work on triadic assessment (Gale et al., 2002).

However, the pattern is not strictly linear. In some cases, students with excellent grades show distances similar to, or even greater than, those observed in other groups. This finding deserves a cautious and theoretically informed interpretation. Students with higher levels of mastery may tend to apply more demanding personal standards, interpret the criteria in a more critical or expert-like way, or show calibration effects associated with highly self-regulated profiles. In this sense, greater divergence from teacher judgement does not necessarily reflect poorer evaluative judgement but may be related to the adoption of stricter or more autonomous quality standards (McConlogue, 2020; Nicol & Macfarlane-Dick, 2006; Hattie & Timperley, 2007). This non-linear pattern reinforces the idea that the relationship between academic performance and evaluative alignment is complex and likely influenced by additional cognitive, motivational and contextual factors.

The item-level analysis provides useful guidance for teaching practice. The largest discrepancies are found in content, presentation and time management, whereas organisation of information and teamwork show greater convergence. This pattern is consistent with the meta-analysis by Falchikov and Goldfinch (2000), which showed that agreement between peer and teacher marks tends to decrease when assessment is multidimensional and analytic, and with reviews that stress the importance of precise descriptors to support the validity and reliability of rubrics (Reddy & Andrade, 2010). In the Spanish higher education context, limitations in the design and use of competence-based rubrics have been reported, which may partly explain item-level variability and point to the need for further teacher training in this area (Velasco-Martínez & Tójar, 2018).

Oral presentations provide a particularly suitable context for studying evaluative judgement. They integrate conceptual, communicative, organisational and social dimensions, and their assessment through analytic rubrics makes it possible to identify specific areas of agreement and disagreement that are useful for teaching (Castejón et al., 2018). In addition, Spanish research on oral communication competence has been relatively

limited in recent years, which reinforces the interest of studies such as the present one and the need for clearer pedagogical models to guide practice (Chireac & Martín-Vegas, 2022). Taken together, these results suggest that triadic assessment may support the development of students' capacity to judge quality in complex academic tasks (McConlogue, 2020).

Limitations

This study has several limitations that should be considered when interpreting the findings. First, the design is observational and cross-sectional, which allows the identification of associations but does not support causal or developmental inferences regarding the relationship between academic performance and convergence with the teacher criterion.

Second, although the dataset is large, there are important constraints related to representativeness. The distribution of assessment records is markedly unbalanced, with the vast majority of evaluations conducted by students (self- and peer-assessment) and a comparatively small proportion by teachers. This asymmetry reflects the pedagogical design but may influence variability, dispersion and comparability across assessment modalities.

Third, the teacher assessment used as the expert reference comes from a limited group of teachers within the same institutional context. In addition, the study is confined to a single university and a specific degree programme. These factors may reduce the generalisability of the findings to other institutional settings, disciplines or assessment cultures, and future research would benefit from including more diverse samples and greater inter-teacher variability.

Finally, the study focuses on theoretical oral presentations, which represent a specific type of complex task. Caution should therefore be exercised when extrapolating the results to other forms of assessment or learning outcomes. Despite these limitations, the large sample size and the adequate reliability of the rubric strengthen the internal robustness of the findings.

Implications and future research

Several lines of work appear particularly promising for further progress in this field. First, longitudinal or quasi-experimental studies are needed to examine the development of evaluative judgement over time and to test whether sustained participation in triadic assessment increases convergence with teacher assessment. Second, it would be useful to evaluate specific training interventions, such as calibration with anchored examples, commented rubrics or comparative feedback, and to analyse their impact at item level. This seems especially relevant for content, presentation and time management, where the largest discrepancies were observed. Third, future studies should include samples with greater diversity of teachers and courses, in order to estimate inter-teacher variability and improve external validity. Finally, it would be valuable to incorporate psycho-educational variables, such as self-efficacy, goal orientation, previous experience with rubrics or motivation. These variables may help to explain when and why certain profiles, including high-performing students, diverge from the teacher criterion. It would also be useful to replicate this approach in other assessable products, such as written assignments, practical tasks, projects or competence-based assessments.

CONCLUSIONS

Triadic assessment is confirmed as a valid strategy for the assessment of university oral presentations. Academic performance, operationalised here as the final course grade, is associated with closer alignment

 © 2026 ARD Asociación Española

with the teacher criterion, particularly in peer assessment. However, this convergence is neither linear nor automatic. These findings reinforce the formative value of assessment and highlight the need to design specific strategies to support the development of students' evaluative judgement. Triadic assessment makes it possible to make discrepancies visible, to promote reflection on quality, and to create learning opportunities that are unlikely to emerge in exclusively teacher-led assessment models.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualization: M.G.-P.; A.J.S.-O. Methodology: A.S.-G.; M.G.-P.; A.J.S.-O. Formal analysis: A.S.-G.; A.J.S.-O. Investigation: A.S.-G.; M.G.-P.; A.M.-L. Data curation: A.S.-G.; M.G.-P.; A.M.-L. Writing – original draft: A.S.-G.; A.J.S.-O. Writing – review & editing: A.J.S.-O.; M.G.-P.; A.M.-L. Supervision: A.J.S.-O. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This study was developed within a project funded by the IV Own Teaching Plan of the University of Seville (2023 call), under the framework of faculty activities for educational innovation (L.2.2), specifically Action 221 devoted to supporting teaching innovation. Moreover, it forms part of the doctoral dissertation of Andrés Sánchez García.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, during the preparation of this manuscript, the authors utilised Microsoft Copilot, Gemini, and Grammarly to translate and proofread the final manuscript before sending it to a native English translator, who further checked and proofread the final text. After employing these tools, the authors reviewed and edited the content as necessary. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

DATA AVAILABILITY STATEMENT

In alignment with Research Data Policies promoting open science, the dataset from this study is accessible to interested researchers via the Figshare repository: 10.6084/m9.figshare.31268428.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the collaboration of the faculty and students of the Degree in Physical Activity and Sports Sciences at the University of Seville, whose active involvement was instrumental in advancing communicative competence and enhancing formative assessment practices.

REFERENCES

Basurto-Mendoza, S. T., Moreira-Cedeño, J. A., Velásquez-Espinales, A. N., & Rodríguez-Gámez, M. (2021). Autoevaluación, Coevaluación y Heteroevaluación como enfoque innovador en la práctica pedagógica y su efecto en el proceso de enseñanza-aprendizaje. Polo del Conocimiento, 6(3), 828-845.

Boud, D., & Falchikov, N. (Eds.). (2007). Rethinking assessment in higher education: Learning for the longer term. Routledge. https://doi.org/10.4324/9780203964309

Boud, D., & Soler, R. (2016). Sustainable assessment revisited. Assessment & Evaluation in Higher Education, 41(3), 400-413. https://doi.org/10.1080/02602938.2015.1018133

Boud, D., Ajjawi, R., Dawson, P., & Tai, J. (Eds.). (2018). Developing evaluative judgement in higher education: Assessment for knowing and producing quality work. Routledge. https://doi.org/10.4324/9781315109251

Bozkurt, F. (2020). Teacher candidates' views on self and peer assessment as a tool for student development. Australian Journal of Teacher Education, 45 (1). https://doi.org/10.14221/ajte.2020v45n1.4

Castejón, F. J., Santos Pastor, M., & Cañadas, L. (2018). Desarrollo de competencias docentes en la Formación Inicial del Profesorado de Educación Física. Relación con los instrumentos de evaluación. Estudios Pedagógicos (Valdivia), 44(2), 111-126. https://doi.org/10.4067/S0718-07052018000200111

Chireac, S. M., & Martín-Vegas, R. A. (2022). A bibliometric analysis of the Spanish scientific production on teaching oral communication between 2010 and 2020. TEM Journal, 11(4), 1620-1625. https://doi.org/10.18421/TEM114-24

Falchikov, N., & Goldfinch, J. (2000). Student peer assessment in higher education: A meta-analysis comparing peer and teacher marks. Review of Educational Research, 70(3), 287-322. https://doi.org/10.3102/00346543070003287

Fernández García, C. M., Torío López, S., Viñuela Hernández, M. P., Molina Martín, S., y Bermúdez Rey, T. (2008). La comunicación oral como competencia transversal de los estudiantes de pedagogía y magisterio: Presentación del diseño metodológico de una innovación para su trabajo en el aula. Revista de Enseñanza Universitaria, 31, 26-38.

Gale, K., Martin, K., & McQueen, G. (2002). Triadic assessment. Assessment & Evaluation in Higher Education, 27(6), 557-567. https://doi.org/10.1080/0260293022000020318

Hattie, J., & Timperley, H. (2007). The power of feedback. Review of Educational Research, 77(1), 81-112. https://doi.org/10.3102/003465430298487

Kambourova, M., Gónzalez-Agudelo, E. M., & Grisales-Franco, L. M. (2021). La autoevaluación del estudiante universitario: revisión de la literatura. Teoría de la Educación: Revista Interuniversitaria: 33, 2, 2021, 217-264. https://doi.org/10.14201/teri.23672

López Pastor, V. M., & Pérez Pueyo, Á. (2017). Introducción a la creación y el uso de escalas descriptivas y rúbricas. En V. M. López Pastor & Á. Pérez Pueyo (Coords.), Evaluación formativa y compartida en educación: Experiencias de éxito en todas las etapas educativas (pp. 92-115). Universidad de León.

McConlogue, T. (2020). Assessment and feedback in higher education: A guide for teachers. UCL Press.

Mendoza, S. T. B., Cedeño, J. A. M., Espinales, A. N. V., & Gámez, M. R. (2021). Autoevaluación, Coevaluación y Heteroevaluación como enfoque innovador en la práctica pedagógica y su efecto en el proceso de enseñanza-aprendizaje. Polo del Conocimiento: Revista científico-profesional, 6(3),828-845.

 © 2026 ARD Asociación Española

Nicol, D. J., & Macfarlane Dick, D. (2006). Formative assessment and self regulated learning: A model and seven principles of good feedback practice. Studies in Higher Education, 31(2), 199-218. https://doi.org/10.1080/03075070600572090

Olague, M. Z., Cañadas, L., & Manso, J. (2025). Percepción del profesorado de educación básica sobre la participación de los diferentes agentes (profesorado y alumnado) en los procesos de evaluación. Revista Fuentes, 27(3), 289-300. https://doi.org/10.12795/revistafuentes.2025.27856

Panadero, E., & Jonsson, A. (2013). The use of scoring rubrics for formative assessment purposes revisited: A review. Educational Research Review, 9, 129-144. https://doi.org/10.1016/j.edurev.2013.01.002

Pascual-Arias, C., López-Pastór, V. M., & Hórtiguela-Alcala, D. (2023). Estudió longitudinal sobre los efectos del desarrollo de la Evaluación Formativa y Compartida en la Formación Inicial del Profesorado. Cultura, Ciencia y Deporte, 18(55), 5-31. https://doi.org/10.12800/ccd.v18i55.1904

Reddy, Y. M., & Andrade, H. (2010). A review of rubric use in higher education. Assessment & Evaluation in Higher Education, 35(4), 435-448. https://doi.org/10.1080/02602930902862859

Sánchez-García, A., Sanchez-Oliver, A. J., & Grimaldi-Puyana, M. (2026). Triadic formative assessment in higher education: interaction effects between assessment modality and evaluator sex. Retos, 77, 346-357. https://doi.org/10.47197/retos.v77.118382

Sánchez-Oliver, A. J., Carnero-Díaz, Á., Muñoz-Llerena, A., & Bianchi, P. (2025). Proyecto de innovación docente para la implementación de la evaluación formativa en la universidad. In Acciones educativas innovadoras en el ámbito universitario (pp. 85-103). Dykinson.

Sánchez-Oliver, A. J., Rodríguez Rojas, F. J., Feria-Madueño, A., Muñoz-López, A., Carnero Díaz, Ángel, Muñoz-Llerena, A., Sañudo-Corrales, B., Oviedo-Caro, M. Ángel, Grimaldi-Puyana, M., Bianchi, P., Domínguez, R., & Angosto, S. (2025). Validation of a tool to evaluate theoretical-practical presentations in Higher Education. Retos, 67, 903-916. https://doi.org/10.47197/retos.v67.112987

Sánchez-Oliver, A. J., Sánchez-García, A., Feria-Madueño, A., Muñoz-López, A., Carnero Díaz, Á., Muñoz-Llerena, A., Sañudo-Corrales, B., Oviedo-Caro, M. Á., Grimaldi-Puyana, M., Bianchi, P., & Domínguez, R. (2026). Evaluating oral presentations in university students: Self, peer, and hetero evaluation. Journal of Sport and Health Research. In press.

Tai, J., Ajjawi, R., Boud, D., Dawson, P., & Panadero, E. (2018). Developing evaluative judgement: Enabling students to make decisions about the quality of work. Higher Education, 76(3), 467-481. https://doi.org/10.1007/s10734-017-0220-3

Topping, K. J. (1998). Peer assessment between students in colleges and universities. Review of Educational Research, 68(3), 249-276. https://doi.org/10.3102/00346543068003249

Topping, K. J. (2009). Peer assessment. Theory Into Practice, 48(1), 20-27. https://doi.org/10.1080/00405840802577569

Velasco-Martínez, L. C., & Tójar Hurtado, J. C. (2018). Uso de rúbricas en educación superior y evaluación de competencias. Profesorado, Revista de Currículum y Formación del Profesorado, 22(3), 183-208. https://doi.org/10.30827/profesorado.v22i3.7998

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

How ball distribution on individual and team level affects attacking performance and team success in elite futsal

Hrvoje Sivrić. *University of Slavonski Brod. Slavonski Brod, Croatia.*
Jakov Marasović . *Faculty of Kinesiology. University of Split. Split, Croatia.*
Ante Rađa. *Faculty of Kinesiology. University of Split. Split, Croatia.*
Tomislav Lopac. *Nikola Tesla University of Applied Sciences. Gospić, Croatia.*
Marko Erceg. *Faculty of Kinesiology. University of Split. Split, Croatia.*

ABSTRACT

The study examined the impact of technical-tactical attacking indicators on futsal performance and differences between players and clubs by performance level. It included 111 elite players from the 1st Croatian Futsal League who played at least 600 seconds in the 2020–2021 season. Competitive performance was rated on a 1–5 Likert scale based on players' and clubs' competitive performance index (PCPI:1–3; CCPI:1–3). Indicators included ball receptions and ACTIVE and PASSIVE passes. Multiple regression (p < .05) and ANOVA with Bonferroni post-hoc were used for statistical analysis and group comparisons. Significant effect (b* = -0.20, p = .047) was found between PASSIVE (UN) and CCPI. On the other hand, ACTIVE (S) (b* = 0.24, p = .031) and PASSIVE (UN) (b* = -0.23, p = .016) were significantly associated with PCPI. CCPI3 significantly differed in RECEIVE (S) compared to CCPI1 / CCPI2 (20.59 vs. 16.53 / 16.40). CCPI3 performed significantly higher in PASSIVE (S) compared to CCPI1 and CCPI2 (19.33 vs. 14.25/14.32). PCPI3 also differed from PCPI1 and PCPI2 in RECEIVE (S) and PASSIVE (S). PASSIVE (UN) negatively affects both team and individual performance, while ACTIVE (S) are linked positively to competitive performance. Additionally, clubs and players with better ball distribution (RECEIVE (S) and PASSIVE (S)) are more likely to be successful.

Keywords: Performance analysis, Offense, Situational efficiency, Competitive index, Performance indicators.

Cite this article as:
Sivrić, H., Marasović, J., Rađa, A., Lopac, T., & Erceg, M. (2026). How ball distribution on individual and team level affects attacking performance and team success in elite futsal. *Journal of Human Sport and Exercise, 21*(4), 1250-1260. https://doi.org/10.55860/eef1wj67

Corresponding author. *Faculty of Kinesiology. University of Split. Split, Croatia.*
E-mail: jakov.marasovic1234@gmail.com
Submitted for publication April 29, 2026.
Accepted for publication June 16, 2026.
Published June 23, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/eef1wj67

© 2026 ARD Asociación Española

INTRODUCTION

Futsal, a smaller version of traditional football, is a standardized indoor sport recognized by both FIFA and UEFA. The term "*futsal*" is derived from the Portuguese phrase futebol de salão or the Spanish fútbol de sala, both of which translate to "*indoor football*" (Moore et al., 2014). Futsal is an intermittent sport that makes high physical, technical, and tactical demands on players (Castagna, 2009). Increasingly popular method for assessing situational efficiency is notational analysis. The primary aim of notational analysis is to optimize feedback for both players and coaches to enhance performance (Liebermann et al., 2002). Additionally, notational analysis provides opportunities to analyse the intrinsic characteristics of the teams to improve the quality of the training and quality of the opponent's observation (Clemente, 2012). According to Nemčić et al. (2016) a futsal match provides an abundance of data on various characteristic events that reflect the situational efficiency of both players and the team. By analysing these events, it becomes possible to understand how and why one player gained an advantage over another, as well as to trace the sequence of actions that ultimately determined the outcome of the game.

Finally, one of the most crucial pieces of information for coaches is understanding the differences in variables between winning and losing teams (Göral, 2018; Souza et al., 2013), as this helps identify the patterns and structures of the game that lead to the best results. However, Moore et al. (2014) stated that there is evident lack of research and understanding regarding situational efficiency, which consequently limits our understanding of the various factors influencing performance in futsal. Also, Sivrić et al. (2023) suggested that there is a limited amount of scientific research on performance indicators in futsal. According to Agras et al. (2017), most studies on futsal rely on simple descriptive analysis, the dynamics of the game, and its complexity, without investigating the differences in specific situational indicators. Guided by this context, the research conducted by Fukuda and De Santana (2012) aimed to analyse the ways in which goals are scored in futsal. Their findings revealed that 24.3% of goals were scored through organized attacks, 23.1% through counterattacks, 24.3% from set pieces, and 21.8% because of goalkeeper involvement. Chen (2011) examined attack patterns and success indicators, noting that 43% of attacks originated from individual actions, 30% from combination play, 12% from counterattacks, 5% from set pieces, 4% from steals, 3% from wing attacks, and 3% from dynamic play. Other studies have highlighted the use of break-out actions as a significant threat to the opponent's goal, with figures ranging from 37% (Irokawa et al., 2010) to 46% (Leite, 2012), although Bueno and Alves (2012) reported a slightly lower incidence of 23%.

While there is limited research examining the relationship between technical actions, such as passing, and the final outcome of a match, the work of Nemčić (2019) stands out. She categorized passes into constructive, critical, and assistive, and determined that 50% of the observed competitive performance indicators (including passes) in futsal were linked to the final result of matches in the Croatian 1st Futsal League. On the other hand, the study by Sivrić et al. (2023) focused on the connection between defensive efficiency and competitive success. The results showed a significant relationship between futsal players' defensive performance and teams' success, with a correlation of 0.40 (p = .022) between the predictor variables and the goal difference representing competitive success. Research on attacking efficiency in futsal showed notable differences between elite and semi-elite players. Better technical skills, as well as more successful passing, have been observed among elite futsal players (Mohammed et al., 2014). Additionally, Santos et al. (2020) reported that the key indicators distinguishing all-star players from others are goals scored and balls won.

Overall, the literature on situational efficiency in futsal is somewhat limited, which results in a lack of comparability between studies due to the absence of a unified methodology and the fact that many studies

lack a comprehensive overview (Sivrić et al., 2023). Given the current gaps in knowledge about futsal, further research is essential. Additionally, there is a shortage of studies addressing futsal excellence (Sekulić et al., 2021). As a result, the scientific community needs new, precise information and findings that will provide a deeper understanding of the game. Futsal has long been recognized as a sport with high technical demands; however, the number of studies focusing on detailed analyses of technical parameters, such as passing (Sivrić et al., 2021), and their impact on individual and team success remains limited. For example, existing futsal research rarely distinguishes the impact of specific ball distribution actions such as active and passive passes on individual and team situational efficiency. There is a gap in the scientific literature regarding certain parameters of situational efficiency and offensive performance in elite futsal. Furthermore, the analysis of parameters such as active and passive passing represents a valuable opportunity to advance both theoretical and practical knowledge in futsal (Setiawan et al., 2021). However, there is still limited evidence on how different functional types of passing actions, particularly active and passive passes, are related to situational efficiency and competitive success in elite futsal. Previous research has rarely distinguished between these two categories of ball distribution within performance analysis frameworks. Therefore, the primary aim of this study was to determine the influence of various technical-tactical indicators of attacking play on the performance of clubs and players with different levels of competitive efficiency in futsal. Within the main goal, the study seeks to determine how different types of passes (active and passive) and ball receptions contribute to situational efficiency (on individual and team performance). Additionally, the research aims to identify key performance indicators (KPIs) in ball distribution that can serve as predictors of offensive effectiveness and competitive success in futsal. The second goal is to examine whether there are significant differences in attacking performance indicators between groups of clubs and players categorized by competitive performance level.

METHODS

Participants

The study involved elite male futsal players (N = 111) with an average age of 25.5 years (±4.7), with 5.2 years (±4.1) of competitive playing experience. The players were from all ten clubs of the 1st Croatian Futsal league (UEFA Men's Futsal National Team Coefficients = 6) during the first part of the 2020/2021 season. Between October 2nd and December 16th, 2020, all 45 games (100%) in the 9th round of the half-season were played and recorded. The total game duration was observed, with 98.46% of the time in all 45 games being documented. The participant sample was based on players who met the criteria of at least 600 seconds of playing time during first half of a competitive season. As a result, 90.24% of the players were included in the study. On average, 11.1 players (±1.66) per club were measured.

Procedures

This study employed an observational cross-sectional design based on notational analysis of match footage.

Variables

Situational efficiency was assessed through notational analysis during all matches in the first half of the 1st Croatian Futsal league 2020/2021 season. The average value of selected performance indicators was calculated for all players, based on a minimum of 600 seconds of playing time during first half of a competitive season. A minimum inclusion threshold of 600 seconds of playing time was applied to ensure sufficient exposure to match situations and to obtain more stable estimates of performance indicators. Players with very limited playing time were excluded to reduce variability and potential bias in the analysis. Prior to data collection, all observers underwent training conducted by the principal investigator, during which the operational definitions and assessment criteria for all performance indicators were thoroughly explained and

 © 2026 ARD Asociación Española

standardized. Data coding was subsequently performed according to these predefined criteria and a standardized observation protocol, ensuring consistency throughout the analysis process. In terms of situational efficiency, the match success was represented by the club's competitive performance. This was measured by the points obtained and the table rankings. The predictor variables, were recorded during offense phase the game as performance indicators, included:

i. Successful RECEIVE (S) / unsuccessful RECEIVE (UN) - The event in the game was tested during the attacking phase, in which the player accepts and places the ball in their possession and/or control using the allowed parts of the body according to the futsal rules.
ii. Successful ACTIVE (S) / unsuccessful ACTIVE (UN) - The event in the game was tested during the attacking phase, in which the player directs the ball forward with the aim of continuing possession and / or preparing the team for an attack with the goal of activating the game and / or achieving a positive transition and/or creating a favourable opportunity to score (assist, pre-assist).
iii. Successful PASSIVE (S) / unsuccessful PASSIVE (UN) - The event in the game was tested during the attacking phase, in which the player passes the ball to a teammate with the aim of retaining possession, which does not contribute to the activation of the game.

Situational success

The competitive performance of futsal players was assessed on a Likert scale from 1 to 5 based on two parameters: the players contribution to the team's performance and the club's rank in the league. Although this approach allowed the inclusion of practical expert knowledge, the authors acknowledge that coach-based evaluations contain a subjective component that may introduce bias into the assessment of individual competitive performance.

Each coach categorized their players into three groups regarding their contribution to the team's performance: *above average* – key players, *average* – other starting players and substitutes who contribute to the team's performance, *below average* – players who rarely or never play.

Table 1. Description of situational success.

Clubs rank	Members of national team	Above average players	Average players	Below average players
CCPI3 1. – 3. place	5	5	4	3
CCPI2 4. – 6. place	5	4	3	2
CCPI1 7. – 10. place	5	3	2	1

The PCPI was developed as a composite indicator combining team competitive success and expert evaluation of individual player contribution. This approach was intended to provide a broader assessment of competitive performance than team ranking alone, taking into account both team achievement and the player's role within the team structure. Subsequently, players competitive performance index - PCPI was defined as follows: PCPI3 – players competitive performance index 3, on Likert scale 5 and 4; PCPI2 - players competitive performance index 2, on Likert scale 3; PCPI1- players competitive performance index 1, on Likert scale 2 and 1.

Club ranking: Determined by the team's performance in the first part of the 1st Croatian Futsal league 2020/2021 season. Clubs were grouped into 3 categories: 1st - 3rd places (*CCPI3* – clubs competitive performance index 3), 4th - 6th places (*CCPI2* - clubs competitive performance index 2), 7th - 10th places (*CCPI1* - clubs competitive performance index 1).

Description of the experimental procedure

In the initial phase of the study, an interview was conducted with the representatives of the 1st Croatian Futsal league, and the teams selected for testing. Concurrently, a team of three individuals responsible for conducting the measurements underwent training. Additionally, all relevant variables were determined and defined, and three independent matches were observed and measured together before the start of the measurements for the 1st Croatian Futsal league matches.

The second phase involved the collection of data through measurements. Performance indicators were obtained from the match videos, which are a requirement for every 1st Croatian Futsal league game. These videos were gathered after each match, in cooperation with the 1st Croatian Futsal league commissioner, and were randomly distributed to those performing the measurements. At the end of the first half of the 2020-2021 competitive season, for each player, total situational efficiency and playing time were summed. To obtain each players situational efficiency in 600 seconds of playing time, total values were divided by their total playing time (in seconds) and multiplied the result by 600.

Data analysis

The data processing method involved calculating descriptive statistical parameters. Means (M), standard deviations (SD), range (Min - Max) were computed after checking the normality of the distributions using the Kolmogorov-Smirnov test. A significance level of $p < .05$ was set for all statistical tests. To confirm a significant influence on criterion variable, multiple regression analysis was conducted. The data was analysed using the Statistics ver.13.0 ((Dell Inc., Round Rock, TX USA) software. To determine the differences between clubs and players with varying situational efficiency, a one-way analysis of variance (ANOVA) was used, with Bonferroni post-hoc test for significant comparisons. Magnitude-based Partial eta Squared (η^2) was also used with measures: 0.01-0.05 indicates a small effect, 0.06-0.13 indicates a medium effect and ≥ 0.14 indicates a large effect.

RESULTS

A significant influence on the criterion variable (CCPI) was found in Table 2 (R = 0.39, F = 3.06). The predictor variables explained 15% of the variation in the dependent variable. Looking at the partial results, the variable that showed a significant effect ($b^* = -0.20$) on the criterion variable was unsuccessful passive passes (PASSIVE), while the variable PASSIVE (S) was close to statistical significance ($b^* = 0.53$).

Table 2. Multiple regression for clubs of different Competitive Performance Index (CCPI).

Variable	b*	b	t	*p*
RECEIVE (S)	-0.09	-0.01	-0.38	.702
RECEIVE (UN)	0.13	0.20	1.02	.311
ACTIVE (S)	0.07	0.07	0.57	.567
ACTIVE (UN)	-0.11	-0.13	-0.94	.347
PASSIVE (S)	0.53	0.06	1.94	.055
PASSIVE (UN)	-0.20	-0.17	-2.01	.047*
R	0.39			
R^2	.15			
F (6, 104)	3.06			
p	.009*			

Note. b*: partial regression coefficient; b: regression coefficient, t: t-test value; *p:* level of significance; R: multiple correlation coefficient; R^2: coefficient of determination; F: F test result; * - statistically significant correlation at the level of $p < .05$.

 © 2026 ARD Asociación Española

In Table 3, a significant influence of independent variables on the criterion variable (PCPI) was recorded (R = 0.53, F = 6.73). The predictor variables explained 28% of the variation in the dependent variable. Successful active passes (b = 0.24) positively influenced the criterion variable, whereas unsuccessful passive passes (b = −0.23) exerted a significant negative influence.

Table 3. Multiple regression for players of different Competitive Performance Index (PCPI).

Variable	b*	b	t	*p*
RECEIVE (S)	0.25	0.03	1.12	.265
RECEIVE (UN)	-0.03	-0.01	-0.02	.977
ACTIVE (S)	0.24	0.25	2.18	.031*
ACTIVE (UN)	0.01	0.01	0.10	.920
PASSIVE (S)	0.11	0.01	0.44	.659
PASSIVE (UN)	-0.23	-0.19	-2.47	.016*
R	0.53			
R^2	.28			
F (6, 104)	6.73			
p	<.001			

Note. b: partial regression coefficient; b: regression coefficient, t: t-test value; p: level of significance; R: multiple correlation coefficient; R^2: coefficient of determination; F: F test result; * - statistically significant correlation at the level of p < .05.*

In Table 4, significant differences (ES: medium) were found in two out of the total six variables of attacking performance. The number of successful ball receptions (RECEIVE) significantly differed between CCPI3 compared to CCPI1/CCPI2 (F = 5.56, η^2 = 0.09). Furthermore, a significantly higher (ES: medium) number of successful passive passes (PASSIVE) was recorded in clubs with the highest competitive index (CCPI3) compared to CCPI1 and CCPI2 (F = 6,54, η^2 = 0.108). The other four variables unsuccessful receptions (F = 0.22, η^2 = 0.004), successful active passes (F = 2.77, η^2 = 0.05) unsuccessful active passes (F = 1.75, η^2 = 0.03), and unsuccessful passive passes (F = 1.24, η^2 = 0.022) did not show significant differences between observed clubs.

Table 4. Differences between clubs of different Competitive Performance Index (CCPI).

Variable	CCPI1 (n = 4)		CCPI2 (n = 3)		CCPI3 (n = 3)	
	M (SD)	RANGE	M (SD)	RANGE	M (SD)	RANGE
RECEIVE (S)*	16.53C (5.72)	3.41-31.65	16.40C (4.83)	5.98-26.61	20.59 (7.24)	10.25-33.01
RECEIVE (UN)	0.72 (0.60)	0.00-2.88	0.67 (0.42)	0.09-1.84	0.64 (0.47)	0.00-2.00
ACTIVE (S)	1.19 (0.66)	0.00-2.95	1.23 (0.71)	0.00-2.56	1.59 (0.99)	0.00-3.84
ACTIVE (UN)	1.14 (0.74)	0.00-3.64	0.94 (0.62)	0.00-2.53	1.20 (0.51)	0.45-2.15
PASSIVE (S)*	14.25C (6.11)	0.96-30.98	14.32C (6.04)	1.71-25.84	19.33 (7.92)	5.71-30.93
PASSIVE (UN)	2.31 (1.12)	0.00-5.34	2.36 (0.93)	0.87-4.42	2.02 (0.77)	0.65-4.19

*Note. M: arithmetic mean; SD: standard deviation; RANGE: minimum and maximum result; CCPI3: club competitive performance index 3; CCPI2: club competitive performance index 2; CCPI1: club competitive performance index 1, a: denotes significant differences from IKU1, b: denotes significant differences from CCPI2, c: denotes significant differences from CCPI3, * - statistically significant differences at the level of p < .05, F: F test result, η^2: Partial eta squared.*

In Table 5, significant differences (ES: Large) were found in the variable of successful ball reception (RECEIVE), which distinguished players with the highest competitive performance index (PCPI3) from those with PCPI1/PCPI2 (F = 14.41, η^2 = 0.199). Furthermore, the most successful players (PCPI3) had a significantly higher (ES: Large) number of successful passive passes compared to the other observed groups (F = 11.40, η^2 = 0.174). Other variables: unsuccessful receptions (F = 2.00, η^2 = 0.036), successful active

passes (F = 2.80, η^2 = 0.06) unsuccessful active passes (F = 1.80, η^2 = 0.03), and unsuccessful passive passes (F = 0.86, η^2 = 0.016) did not significantly differentiate players with varying performance levels.

Table 5. Differences between players of different Competitive Performance Index (PCPI).

Variable	PCPI1 (n = 39)		PCPI2 (n = 35)		PCPI3 (n = 37)	
	M (SD)	RANGE	M (SD)	RANGE	M (SD)	RANGE
RECEIVE (S)*	14.94C (5.88)	3.41-31.65	16.73C (4.00)	7.88-25.47	21.38 (6.41)	10.28-33.01
RECEIVE (UN)	0.80 (0.64)	0.00-2.88	0.64 (0.42)	0.00-2.00	0.59 (0.37)	0.08-1.29
ACTIVE (S)	1.01 (0.65)	0.00-2.81	1.13 (0.60)	0.00-2.25	1.82 (0.87)	0.27-3.84
ACTIVE (UN)	0.91 (0.78)	0.00-3.64	1.07 (0.51)	0.15-2.53	1.28 (0.53)	0.45-2.15
PASSIVE (S)*	12.69C (6.43)	0.96-30.98	15.05C (5.21)	4.55-25.04	19.61 (7.34)	7.12-30.93
PASSIVE (UN)	2.27 (1.21)	0.00-5.34	2.39 (0.88)	0.86-4.38	2.09 (0.72)	0.65-4.19

*Note. M: arithmetic mean; SD: standard deviation; RANGE: minimum and maximum result; PCPI3: players competitive performance index 3; PCPI2: club competitive performance index 2; PCPI1: players competitive performance index 1, a: denotes significant differences from PCPI1, b: denotes significant differences from PCPI2, c: denotes significant differences from PCPI3, * - statistically significant differences at the level of p < .05, F: F test result, η^2: Partial eta squared.*

DISCUSSION

The main objective of this study was to determine the influence of attacking performance indicators on competitive performance index at both the club and individual levels in elite futsal. A secondary objective was to examine whether differences in these indicators exist between groups with varying levels of competitive performance.

Ball distribution parameters significantly influenced both club competitive performance index (CCPI) and players competitive performance index (PCPI) with 15% and 28% of the explained variance, respectively. Within the observed variables, PASSIVE (UN) influenced negatively both the team and individual performance. Additionally, significant positive influence of ACTIVE (S) on individual player performance was obtained. Furthermore, significant differences were obtained between different ranks of CCPI and PCPI in RECEIVE (S) and PASSIVE (S), further emphasizing importance of ball distribution during futsal matches.

Club competitive performance (CCPI) was negatively influenced by unsuccessful passive passes (PASSIVE (UN)). On the other hand, CCPI was positively influenced with successful passive passes (PASSIVE (S)), however, slightly missing statistical significance (p = .055). Possible reason for these results is that a lower number of unsuccessful passes may reduce number of opportunities for opponents to regain possession and initiate counterattacks. Additionally, higher number of successful passes, even passive ones, contributes to team efficiency via ball possession and game control.

Significant influence at the individual level were found between PCPI and two parameters: successful active passes and unsuccessful passive passes. These findings are consistent with previous research and suggest that passing accuracy, especially in situations where players are under opponent pressure, is linked to individual success (Santos et al., 2020; Spyrou et al., 2023). Furthermore, mistakes in passive passes, which are most often made without substantial opponent pressure, were related to lower levels of individual performance. These results highlight the potential importance of ball-handling skills, as passing errors may negatively influence both individual and team performance.

Clubs with the highest competitive level (CCPI3) demonstrated a significantly greater number of successful ball receptions compared to clubs with lower competitive rankings (CCPI1 and CCPI2). According to

 © 2026 ARD Asociación Española

Dogramaci et al. (2015) a team's success lies in the fact that, if they manage to retain possession of the ball, they can more easily control and dictate the game. Ismael and Nunome (2020) showed that hybrid models of ball possession are effective in distinguishing more successful teams from less successful ones. Furthermore, a significantly higher success rate in passive passes (PASSIVE(S)) indicates that these clubs have better ball distribution and game control. A higher number of such passes can also be associated with a more deliberate tactical strategy by these teams, who rely less on risky passes and thus reduce the possibility of losing possession. The other variables did not prove to be significant, which may suggest that parameters such as ball reception mistakes and active passing are not critical for discriminating teams of different competitive performance levels (CCPI).

Similar to the differences in CCPI, differences were found in successful ball receptions and successful passive passes for individual PCPI. These results are supported by previous research, which also found significant differences between players of different quality in variables that assess successful passing (Mohammed et al., 2014; Santos et al., 2020; Spyrou et al., 2023). One characteristic of higher-performing players may be greater efficiency in receiving and distributing the ball. Consequently, players who perform these technical actions more effectively may be better positioned to maintain possession and support overall team performance. Certain indicators, such as active passing, are not as strongly associated with individual player success as ball reception and passive passing. The present findings indicate that ball reception and passive passing were among the variables most consistently related to individual competitive performance.

Practical implications and limitations

The results of this study provide additional insight into the influence of ball distribution on the performance at both the team and individual level. Certain technical parameters, like number of successful passive passes, appear to be related to competitive performance, which should be considered when reflecting on training process design and performance evaluation. These findings may contribute to more efficient and targeted planning and programming of the training process. Also, the number of successful passive passes and ball receptions may help distinguish more successful from less successful teams and players, which can serve as a useful tool during player selection process. This study had several limitations, primarily related to the fact that the time intervals of players on the field were summed regardless of the current score. For example, a problem may arise in situations where the team is losing, leading players to attempt riskier (active) passes, which can consequently result in a higher number of mistakes. Furthermore, tactical aspects of the matches were not controlled during this research. Another limitation of this study relates to the construction of the Player Competitive Performance Index (PCPI). Part of this index was based on coach evaluations of player contribution, which inevitably includes a subjective component. Although precise operational criteria were predefined, the lack of structured procedures and the absence inter-observer and intra-observer reliability calibration may have influenced the consistency of data coding. Consequently, some degree of classification bias cannot be excluded. Another limitation of the present study is the relatively low proportion of explained variance, particularly at the team level. This finding suggests that competitive success in futsal is influenced by numerous factors beyond the ball distribution variables included in this study. Future studies should incorporate a broader range of performance indicators to develop more comprehensive models of futsal success.

CONCLUSION

The results of this study indicate that ball distribution is related to attacking performance at both the individual and team level during professional futsal competition. Clubs and players performance index were negatively influenced by unsuccessful passive passes, while PCPI was positively influenced by successful active

passes. Furthermore, ball control obtained through passive passing and ball receiving appears to contribute to differences between more successful and less successful players and teams. Results emphasize importance of accurate ball distribution, as one of important factors for futsal success both on the individual and on the team level. As such, it should be evaluated thoroughly during players selection process and match team analysis. For future research, it would be good to explore influence of *current score* during matches on the variables of situational efficiency for both clubs and players.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Hrvoje Sivrić. Methodology: Hrvoje Sivrić. Formal analysis: Jakov Marasović. Investigation: Hrvoje Sivrić, Tomislav Lopac. Data curation: Hrvoje Sivrić, Tomislav Lopac. Writing – original draft: Hrvoje Sivrić. Writing – review & editing: Jakov Marasović, Ante Rađa, Marko Erceg. Supervision: Ante Rađa, Marko Erceg. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Agras, H., Ferragut, C., & Abraldes, J. A. (2016). Match analysis in futsal: a systematic review. International Journal of Performance Analysis in Sport, 16(2), 652-686. https://doi.org/10.1080/24748668.2016.11868915

Bueno, E. L., & Alves, I. P. (2012). Análise dos gols na primeira fase da liga de futsal 2012. RBFF-Revista Brasileira de Futsal e Futebol, 4(12), 6.

Castagna, C., D'Ottavio, S., Vera, J. G., & Álvarez, J. C. B. (2009). Match demands of professional Futsal: a case study. Journal of Science and medicine in Sport, 12(4), 490-494.3. Clemente, F. (2012). Study of successful teams on FIFA World Cup 2010 through notational analysis. Pamukkale Journal of Sport Sciences, 3(3), 90-103. https://doi.org/10.1016/j.jsams.2008.02.001

 © 2026 ARD Asociación Española

Chen, P. H. (2011, May). Analysis of attacking patterns in top level futsal. In 7th World Congress on Science and Football (pp. 26-30). https://doi.org/10.14486/IntJSCS767

Clemente, F. (2012). Study of successful teams on FIFA World Cup 2010 through notational analysis. Pamukkale Journal of Sport Sciences, 3(3), 90-103.

Dogramaci, S., Watsford, M., & Murphy, A. (2015). Activity profile differences between sub-elite futsal teams. International Journal of Exercise Science, 8(2), 2. https://doi.org/10.70252/MAYB1257

Fukuda, J. P. S., & de Santana, W. C. (2012). Analysis of goals in 2011 futsal league's games/Analises dos gols em jogos da liga futsal 2011. Revista Brasileira de futsal e futebol, 4(11), 62-67.

Göral, K. (2018). Analysis of Serbia UEFA futsal Euro 2016 competitions in terms of some variables. Journal of Education and Training Studies, 6(10), 1-6. https://doi.org/10.11114/jets.v6i10.3343

Irokawa, G. N. F., Lima, M. R. M., Soares, V. O. V., Aburachid, L. M. C., Souza, P. R. C., & Greco, P. J. (2010). Caracterização das circunstâncias e setores de finalização do jogo de futsal: Um estudo da fase final da Copa do Mundo - FIFA 2008. EFDeportes.com, Revista Digital, (144).

Ismail, S. I., & Nunome, H. (2020). The key performance indicators that discriminate winning and losing, and successful and unsuccessful teams during 2016 FIFA Futsal World Cup. Science and Medicine in Football, 4(1), 68-75. https://doi.org/10.1080/24733938.2019.1662937

Leite, W. S. S. (2012). Analysis of the offensive process of the Portuguese futsal team. Pamukkale Journal of Sport Sciences, 3(3), 78-89.

Liebermann, D. G., Katz, L., Hughes, M. D., Bartlett, R. M., McClements, J., & Franks, I. M. (2002). Advances in the application of information technology to sport performance. Journal of sports sciences, 20(10), 755-769. https://doi.org/10.1080/026404102320675611

Mohammed, A., Shafizadeh, M., & Platt, K. G. (2014). Effects of the level of expertise on the physical and technical demands in futsal. International Journal of Performance Analysis in Sport, 14(2), 473-481. https://doi.org/10.1080/24748668.2014.11868736

Moore, R., Bullough, S., Goldsmith, S., & Edmondson, L. (2014). A systematic review of futsal literature. American Journal of Sports Science and Medicine, 2(3), 108-116. https://doi.org/10.12691/ajssm-2-3-8.

Nemčić, T. (2019). Oblikovanje i vrednovanje notacijskog sustava za analizu izvedbe u futsalu (Doctoral dissertation, University of Zagreb. Faculty of Kinesiology). Retrieved from [Accessed 2026, 17 June]: https://urn.nsk.hr/urn:nbn:hr:117:420085

Nemčić, T., Sedar, M., & Tomić, M. (2016). Pokazatelji situacijske efikasnosti futsal ekipe MNK Alumnus u natjecateljskoj sezoni 2013/2014., 25. Ljetna škola kineziologa Republike Hrvatske, 370-376.

Santos, J., Mendez-Domínguez, C., Nunes, C., Gómez, M. A., & Travassos, B. (2020). Examining the key performance indicators of all-star players and winning teams in elite futsal. International Journal of Performance Analysis in Sport, 20(1),78-89. https://doi.org/10.1080/24748668.2019.1705643

Sekulic, D., Pojskic, H., Zeljko, I., Pehar, M., Modric, T., Versic, S., & Novak, D. (2021). Physiological and anthropometric determinants of performance levels in professional futsal. Frontiers in psychology, 11, 621763. https://doi.org/10.3389/fpsyg.2020.621763

Setiawan, W. A., Festiawan, R., Heza, F. N., Kusuma, I. J., Hidayat, R., & Khurrohman, M. F. (2021). Peningkatan Keterampilan Dasar Futsal Melalui Metode Latihan Passing Aktif dan Pasif. Jurnal Pendidikan Kesehatan Rekreasi, 7(2), 270-278. https://doi.org/10.5281/zenodo.4896155

Sivrić, H., Čustonja, Z., & Rukavina, D. (2021). Ball passing of futsal players with different competitive performance. In S. Šalaj & D. Škegro (Eds.), Proceedings of the 9th International Scientific Conference on Kinesiology (pp. 856-860). Faculty of Kinesiology, University of Zagreb.

Sivric, H., Milić, M., & Rađa, A. (2023). How defense performance affects the outcome of matches in elite futsal. Acta kinesiologica, 17(2), 22-28. https://doi.org/10.51371/issn.1840-2976.2023.17.2.4

Souza, P., Ribeiro, R., Rocha, R., Fernandes, B., & Moreira, E. (2013). Análise das finalizações como indicadores de rendimento em jogos de futsal [Shooting analysis as International Journal of Performance Analysis in Sport 11 performance indicators in futsal games]. Revista Mackenzie De Educação Física E Esporte, 12(2), 89-99.

Spyrou, K., Ribeiro, J. N., Ferraz, A., Alcaraz, P. E., Freitas, T. T., & Travassos, B. (2023). Interpreting match performance in elite futsal: considerations for normalizing variables using effective time. Frontiers in Sports and Active Living, 5, 1256424. https://doi.org/10.3389/fspor.2023.1256424

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

REVIEW ARTICLE

From athlete monitoring to responsible decision support in sports analytics: A bibliometric and thematic analysis of applied sport science (2015–2025)

Joseph Lobo . *College of Sports, Exercise and Recreation. Bulacan State University. Philippines*.

ABSTRACT

Sports analytics has become increasingly central to applied sport science, yet its conceptual development remains unevenly theorized. This study mapped the evolution of sports analytics research from 2015 to 2025 using a Scopus-based bibliometric analysis of 1,211 documents. Descriptive bibliometrics, co-authorship analysis, country collaboration mapping, keyword co-occurrence analysis, trend-topic analysis, bibliographic coupling, and co-citation analysis were used to examine the field's development, conceptual structure, and intellectual foundations. Findings show that sports analytics has expanded rapidly and is increasingly organized around athlete monitoring, performance analysis, machine learning, training load, artificial intelligence, and decision support. The literature reflects a shift from descriptive measurement toward predictive and computationally mediated forms of applied sport science. However, this growth also exposes unresolved tensions involving model interpretability, data quality, ethical governance, and the translation of analytics into practice. To address this, the study proposes a responsible and integrative framework that positions sports analytics as an interconnected system of data capture, computational processing, human interpretation, applied performance action, and ethical governance. The review argues that sports analytics becomes meaningful only when technological sophistication is aligned with valid, interpretable, and athlete-centred decision-making.

Keywords: Sports analytics, Applied sport science, Athlete monitoring, Performance analysis, Machine learning, Decision support systems, Bibliometric analysis, Training load.

Cite this article as:
Lobo, J. (2026). From athlete monitoring to responsible decision support in sports analytics: A bibliometric and thematic analysis of applied sport science (2015–2025). *Journal of Human Sport and Exercise, 21*(4), 1261-1282. https://doi.org/10.55860/9c1pxv60

Corresponding author. *College of Sports, Exercise and Recreation. Bulacan State University. Philippines*.
E-mail: joseph.lobo@bulsu.edu.ph
Submitted for publication May 02, 2026.
Accepted for publication June 16, 2026.
Published June 23, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/9c1pxv60

INTRODUCTION

Sports analytics has become an increasingly important part of applied sport science, not only because sport now produces more data, but because these data are being used to inform how performance, workload, fatigue, readiness, and decision-making are understood (Kang & Lee, 2025). Earlier methodological work already anticipated that large and complex datasets could reshape both the practice and knowledge base of sport science, while player-tracking scholarship showed that modern performance environments increasingly depend on the integration of multiple technologies rather than on isolated measures (Buchheit & Simpson, 2017; Passfield & Hopker, 2017). This development is consequential because analytics changes the function of data within sport settings. Data are no longer collected only to describe what happened after training or competition. They are increasingly used to support prospective judgments about adaptation, risk, tactical demands, recovery, and intervention. In this sense, sports analytics reflects a broader movement in applied sport science from fragmented measurement toward integrated, model-supported, and decision-oriented practice (Davis et al., 2024; Wilson & Kiely, 2023).

Conceptual clarity is important because sports analytics, performance analysis, and athlete monitoring are related but not identical constructs. Sports analytics is best understood as a broader analytical framework concerned with collecting, processing, modelling, interpreting, and translating sport data into actionable knowledge (Dello Iacono et al., 2026). Performance analysis is more specifically concerned with the evaluation of sport performance, often through technical, tactical, behavioural, biomechanical, or match-related indicators (Hughes & Bartlett, 2002). In contrast, athlete monitoring focuses on tracking athlete status over time, including workload, fatigue, readiness, recovery, physiological response, and adaptation (Timmerman et al., 2024). These constructs overlap in practice, but they operate at different levels of scope. Performance analysis and athlete monitoring generate important streams of evidence, while sports analytics provides the broader system through which those streams can be integrated, modelled, interpreted, and used for decision-making. This distinction is necessary because the growing visibility of sports analytics should not be reduced to either match analysis or workload tracking alone. Its significance lies in how it reorganizes multiple forms of sport evidence into a connected analytical and practical system.

This shift is especially visible in athlete monitoring, where analytics now operates as an applied decision process rather than a simple record-keeping activity. Coaches and support staff use monitoring primarily to reduce injury and illness, inform training programs, and maintain or improve performance, showing that monitoring is valued for its practical relevance to decision-making rather than for data collection alone (Timmerman et al., 2024). Recent work on athlete monitoring systems similarly shows that these platforms are increasingly designed to centralize the integration, processing, analysis, and visualization of diverse monitoring inputs (Burger et al., 2024). However, the growing availability of data does not automatically lead to better practice. Monitoring systems remain dependent on data quality, standardization, visualization, communication, and practitioner interpretation (Saw et al., 2015; Thornton et al., 2019). Therefore, the development of sports analytics should be understood not simply as a technical expansion, but as a shift toward decision architecture in applied sport science, where data become meaningful only when they support valid, interpretable, and context-sensitive action.

At the same time, the field is being reshaped by rapid computational development. Artificial intelligence is increasingly applied across biomechanics, performance enhancement, sports medicine, health monitoring, coaching, and talent identification, while deep learning has shown potential for automating performance analysis and extracting patterns from complex sport environments (Jia et al., 2025; Zhou et al., 2025). These developments indicate that many sport-performance problems are increasingly being reframed as problems

 © 2026 ARD Asociación Española

of classification, prediction, pattern recognition, optimization, and decision support. This computational turn has considerable promise, particularly for injury-risk modelling, workload interpretation, movement recognition, tactical analysis, and performance forecasting. Yet it also introduces important conceptual and practical tensions. Analytical sophistication does not guarantee interpretability, ethical acceptability, or real-world usefulness. Recent discussions of artificial intelligence and technology use in sport emphasize continuing concerns related to model validation, data heterogeneity, transparency, bias, workflow integration, privacy, and accountability (Kim et al., 2025; Naughton et al., 2024; Reis et al., 2024). Thus, the maturation of sports analytics depends not only on more powerful models, but also on stronger theoretical, ethical, and translational foundations.

Despite this momentum, the broader knowledge structure of sports analytics in applied sport science remains insufficiently synthesized. Existing mapping efforts have tended to focus on narrower subdomains, such as training-load monitoring in athletes or artificial-intelligence applications in specific sports, rather than the wider field spanning monitoring, performance analysis, coaching, computational modelling, and decision support (Hasan et al., 2024; Sampaio et al., 2024). This gap matters because without a broader bibliometric account, it remains difficult to determine whether sports analytics is merely expanding in publication volume or consolidating into a coherent conceptual and intellectual domain. More importantly, it remains unclear how the field's major strands can be integrated into a responsible framework that accounts for data capture, computational processing, human interpretation, applied performance action, and ethical governance. Accordingly, the present study maps sports analytics research in applied sport science from 2015 to 2025 through a bibliometric analysis of trends, conceptual development, and intellectual structure. Beyond mapping publication growth, collaboration patterns, keyword networks, trend topics, bibliographic coupling, and co-citation structure, the study contributes a responsible and integrative framework for sports analytics. This proposed framework positions sports analytics as an interconnected system whose value depends not only on technological sophistication, but on the valid collection, responsible processing, human interpretation, practical translation, and ethical governance of athlete and performance data.

METHODS

Research design

This study employed a bibliometric research design to map the development, collaborative structure, conceptual organization, and intellectual foundations of research (Jiang et al., 2025; Öztürk et al., 2024) on sports analytics in applied sport science. The analysis focused on literature related to athlete monitoring, workload monitoring, performance analytics, training analytics, data-driven coaching, data-informed training, and decision support systems in sport science, exercise science, and strength and conditioning. Bibliometric analysis was appropriate because it enables the systematic examination of publication patterns, citation relationships, collaboration networks, and thematic structures within a defined research field (Hoang, 2025).

Data source and search strategy

Table 1 summarizes the search strategy and inclusion parameters of the study. The bibliographic data were retrieved from the Scopus database, which was selected because it provides structured and comprehensive metadata suitable for bibliometric analysis. The search was performed using the TITLE-ABS-KEY field to capture records whose titles, abstracts, or keywords directly aligned with the focus of the study. Boolean operators, phrase searching, truncation, and exclusion terms were used to maximize topical relevance while minimizing unrelated records. The search was restricted to English-language publications and to the document types of article, review, and conference paper. The final corpus covered publications from 2015 to 2025.

Table 1. Search strategy and inclusion parameters.

Parameter	Description
Database & indexes	Scopus
Search field	TITLE-ABS-KEY
Search string	TITLE-ABS-KEY (("*sport analytics" OR "sports analytics" OR "performance analytics" OR "training analytics" OR "data-driven training" OR "data driven training" OR "data-informed training" OR "data informed training" OR "data-driven coaching" OR "data driven coaching" OR "data-informed coaching" OR "data informed coaching" OR "athlete monitoring" OR "workload monitoring" OR "decision support system*") AND (athlete* OR coach* OR coaching OR "sport science" OR "sports science" OR "exercise science" OR "strength and conditioning") AND (analytic* OR monitor* OR predict* OR model* OR workload OR performance OR decision*)) AND NOT TITLE-ABS-KEY (marketing OR sponsorship OR consumer* OR gambling OR betting OR "fantasy sport*" OR finance OR economic*) AND (LIMIT-TO LANGUAGE , "English)) AND LIMIT-TO DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "cp"))*
Language	English
Document types	Article, review, conference paper
Excluded themes	Marketing, sponsorship, consumer behaviour, gambling, betting, fantasy sports, finance, and economics
Final timespan of corpus	2015-2025

Eligibility criteria and corpus delimitation

Records were included if they matched the search strategy and were indexed as articles, reviews, or conference papers. These document types were retained because they represent the most established and analysable forms of scholarly output in bibliometric studies. Records outside the topical scope of the study, as well as document types beyond the retained categories, were excluded. After screening and final cleaning, the dataset comprised 1,211 documents published across 518 sources and authored by 4,222 authors. The corpus included 839 articles, 293 conference papers, and 79 reviews.

Data cleaning and preprocessing

The retrieved records were screened and cleaned prior to analysis to improve consistency and analytical reliability. This process involved removing document types outside the retained categories and checking bibliographic fields for formatting inconsistencies that could affect descriptive summaries and network construction. Keyword expressions were also reviewed to reduce fragmentation caused by spelling, hyphenation, and closely related variants. For conceptual interpretation, Author's Keywords were prioritized over broader indexing terms when thematic clarity was required.

Bibliometric analysis

The cleaned dataset was analysed using Bibliometrix/Biblioshiny for descriptive bibliometric outputs and VOSviewer for science mapping and network visualization. Descriptive analysis was used to summarize the overall profile of the field, including publication growth, source productivity, author productivity, citation characteristics, document composition, and collaboration indicators. To examine the structure of the field, several bibliometric techniques were employed. (1) Co-authorship analysis was used to identify collaboration patterns among authors; (2) Co-occurrence analysis was conducted to map the conceptual structure of the field based on recurring keyword relationships; (3) Bibliographic coupling analysis at the source level was used to identify links among publication outlets based on shared references, thereby revealing contemporary thematic proximities; (4) Co-citation analysis was used to identify the intellectual structure of the field by examining which cited items were frequently referenced together; In addition (5) country collaboration mapping was used to visualize international research linkages; while (6) trend topic analysis was used to examine the temporal prominence of recurring themes.

 © 2026 ARD Asociación Española

Network thresholds and visualization parameters

Thresholds were selected to balance inclusiveness with interpretive clarity. Rather than maximizing the number of displayed items, the study retained thresholds that yielded cleaner and more analytically meaningful network structures. The final thresholds were set at a minimum of three (3) documents for co-authorship analysis, ten (10) occurrences for keyword co-occurrence analysis, five (5) documents for bibliographic coupling at the source level, and twenty (20) citations for co-citation analysis. In the network maps, nodes represented authors, keywords, sources, or cited items depending on the analysis performed, while links represented the strength of association between nodes. Node size reflected relative prominence, and colours indicated clusters of closely related items.

Framework development

Following the bibliometric analyses, a responsible and integrative framework was developed through interpretive synthesis of the study findings. The framework was informed by the keyword co-occurrence, trend-topic, bibliographic coupling, and co-citation analyses, which collectively showed how sports analytics is organized around athlete monitoring, computational modelling, decision support, applied performance action, and governance concerns. Rather than serving as a separate statistical output, the framework represents a theory-oriented synthesis of the mapped field, positioning sports analytics as an interconnected system of data capture, analytical processing, human interpretation, practical translation, and ethical governance.

Ethical considerations

This study has been exempted for ethical review by the Bulacan State University-Ethics Research Committee (BulSU-ERC) with Protocol No. BulSUERC-2026-0160-EX.

RESULTS

Descriptive profile and publication growth

The final bibliometric dataset comprised 1,211 documents published between 2015 and 2025, distributed across 518 sources and authored by 4,222 scholars. The corpus was composed primarily of articles (*n* = 839), followed by conference papers (*n* = 293) and reviews (*n* = 79). Overall, the dataset showed an annual growth rate of 24.02%, a document average age of 4.06 years, and an average of 14.80 citations per document. Across all retrieved records, a total of 39,979 references were recorded. In terms of collaboration, the field demonstrated a relatively strong multi-authored pattern, with 4.56 co-authors per document, 66 single-authored documents, and 27.09% international co-authorship. These indicators suggest that research on sports analytics in applied sport science has developed into a rapidly expanding, collaborative, and increasingly visible area of scholarship. The annual scientific production further showed that the field experienced substantial growth across the study period (see Figure 1). During the earlier years of the corpus, publication output remained modest, but the number of documents increased progressively over time and accelerated markedly in the later years, particularly from the early 2020s onward. The sharp upward trend in recent years indicates that sports analytics has moved beyond a niche area of inquiry and has become a more established research domain within applied sport science. This growth likely reflects the increasing integration of data-driven approaches in athlete monitoring, performance optimization, workload assessment, and decision-making processes in sport settings.

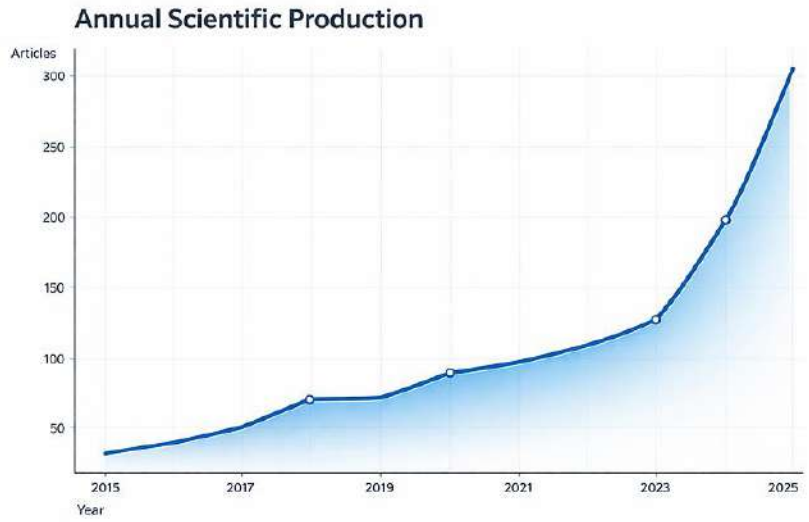


Figure 1. Annual scientific production in applied sport science research on sports analytics (2015–2025).

Leading sources, authors, affiliations, and influential documents

As can be seen in Table 2, the source distribution indicates that research on sports analytics in applied sport science is concentrated in journals with strong orientations toward performance, athlete monitoring, coaching, and applied physiology. The *Journal of Strength and Conditioning Research* was the most productive source with 79 documents, followed by the *International Journal of Sports Science and Coaching* with 69 documents and the *International Journal of Sports Physiology and Performance* with 49 documents. Other notable sources included *Sports* (31 documents), the *Journal of Sports Sciences* (24 documents), *Frontiers in Sports and Active Living* (22 documents), and *Sensors* (22 documents). This pattern suggests that the field is largely anchored in performance-focused and practice-oriented publication outlets, reflecting the applied nature of sports analytics within sport science.

Table 2. Most relevant sources (2015–2025).

Sources / Journal	Number of articles
Journal of Strength and Conditioning Research	79
International Journal of Sports Science and Coaching	69
International Journal of Sports Physiology and Performance	49
Sports	31
Journal of Sports Sciences	24
Frontiers in Sports and Active Living	22
Sensors	22
Journal of Functional Morphology and Kinesiology	15
Applied Sciences (Switzerland)	14
European Journal of Sport Science	14

In terms of author productivity, a relatively small group of scholars contributed prominently to the growth of the field, as shown in Table 3. Stone, M.H. emerged as the most productive author with 27 publications, followed by Coutts, A.J. (15) and Robertson, S. (13). Other leading contributors included Bunn, J.A. (11), as well as Cabarkapa, D., Esco, M.R., and Fry, A.C., each with 10 publications. These patterns suggest that the field is characterized by a core group of highly productive authors, indicating a degree of intellectual concentration and sustained research engagement in performance science, athlete monitoring, and analytics-related work.

 © 2026 ARD Asociación Española

Table 3. Most relevant authors (2015–2025).

Author	Number of articles
Stone, M.H.	27
Coutts, A.J.	15
Robertson, S.	13
Bunn, J.A.	11
Cabarkapa, D.	10
Esco, M.R.	10
Fry, A.C.	10
Ishida, A.	9
Jagim, A.R.	9
Jones, M.T.	9

At the institutional level, the most productive affiliations further reinforce the applied and performance-centred profile of the literature, as presented in Table 4. East Tennessee State University emerged as the leading affiliation with 38 documents, followed by Deakin University (25) and The Ohio State University (24). More broadly, the distribution of the top affiliations indicates that Australia and the United States serve as the principal institutional hubs of research activity in this field. Of the ten most productive affiliations, six were based in Australia and three were based in the United States, highlighting the concentration of institutional scholarship within these countries. This suggests that the field is being shaped primarily by universities with strong orientations toward athlete monitoring, high-performance sport, strength and conditioning, and sport technology.

Table 4. Most relevant affiliations (2015–2025).

Affiliation	Number of articles
East Tennessee State University, USA	38
Deakin University, Australia	25
The Ohio State University, USA	24
Edith Cowan University, Australia	22
Victoria University, Australia	22
Australian Catholic University, Australia	17
University of Technology Sydney, Australia	17
George Mason University, USA	16
La Trobe University, Australia	16
Leeds Beckett University, UK	16

The citation profile within the analysed corpus, based on local citations, revealed several documents with strong internal influence on the development of the field, as summarized in Table 5. Saw et al. (2016) emerged as the most cited document in the corpus with 61 citations, followed by R. Gathercole, Sporer, et al. (2015) with 28 citations and Thorpe et al. (2017) with 26 citations. Additional documents with notable corpus-level influence included studies by Rein and Memmert (2016), R. J. Gathercole et al. (2015), Sarlis and Tjortjis (2020), Robertson et al. (2017), R. J. Gathercole, Stellingwerff, et al. (2015), Heishman et al. (2020), and Schneider et al. (2018). Collectively, these documents indicate that the internal citation structure of the field is anchored in research on athlete monitoring, workload management, performance evaluation, and the application of analytical approaches to sport decision-making.

Taken together, the patterns observed across sources, authors, affiliations, and corpus-level citation influence suggest that research on sports analytics in applied sport science has developed within a relatively concentrated yet expanding scholarly community. The prominence of performance-oriented journals, recurring author contributors, productive institutional hubs, and internally influential documents indicates that

the field is being shaped by a shared applied focus on athlete monitoring, workload assessment, performance evaluation, and data-informed decision-making. Building on this productivity and influence profile, the next section examines how these scholarly actors are connected through collaborative relationships at both the author and country levels.

Table 5. Most cited documents in the corpus (2015–2025).

Source	Total citations	Global citations
Saw, A. E., Main, L. C., & Gastin, P. B. (2016). Monitoring the athlete training response: Subjective self-reported measures trump commonly used objective measures: a systematic review. British Journal of Sports Medicine, 50(5), 281–291. https://doi.org/10.1136/bjsports-2015-094758	61	719
Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015). Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue. International Journal of Sports Physiology and Performance, 10(1), 84–92. https://doi.org/10.1123/ijspp.2013-0413	28	339
Thorpe, R. T., Atkinson, G., Drust, B., & Gregson, W. (2017). Monitoring Fatigue Status in Elite Team-Sport Athletes: Implications for Practice. International Journal of Sports Physiology and Performance, 12(s2), S2-27-S2-34. https://doi.org/10.1123/ijspp.2016-0434	26	255
Rein, R., & Memmert, D. (2016). Big data and tactical analysis in elite soccer: Future challenges and opportunities for sports science. SpringerPlus, 5(1), 1410. https://doi.org/10.1186/s40064-016-3108-2	18	437
Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. G. (2015). Comparison of the Capacity of Different Jump and Sprint Field Tests to Detect Neuromuscular Fatigue. Journal of Strength and Conditioning Research, 29(9), 2522–2531. https://doi.org/10.1519/JSC.0000000000000912	17	199
Sarlis, V., & Tjortjis, C. (2020). Sports analytics—Evaluation of basketball players and team performance. Information Systems, 93, 101562. https://doi.org/10.1016/j.is.2020.101562	16	152
Robertson, S., Bartlett, J. D., & Gastin, P. B. (2017). Red, Amber, or Green? Athlete Monitoring in Team Sport: The Need for Decision-Support Systems. International Journal of Sports Physiology and Performance, 12(s2), S2-73-S2-79. https://doi.org/10.1123/ijspp.2016-0541	16	99
Gathercole, R. J., Stellingwerff, T., & Sporer, B. C. (2015). Effect of Acute Fatigue and Training Adaptation on Countermovement Jump Performance in Elite Snowboard Cross Athletes. Journal of Strength and Conditioning Research, 29(1), 37–46. https://doi.org/10.1519/JSC.0000000000000622	15	116
Heishman, A. D., Daub, B. D., Miller, R. M., Freitas, E. D. S., Frantz, B. A., & Bemben, M. G. (2020). Countermovement Jump Reliability Performed With and Without an Arm Swing in NCAA Division 1 Intercollegiate Basketball Players. Journal of Strength and Conditioning Research, 34(2), 546–558. https://doi.org/10.1519/JSC.0000000000002812	14	165
Schneider, C., Hanakam, F., Wiewelhove, T., Döweling, A., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2018). Heart Rate Monitoring in Team Sports—A Conceptual Framework for Contextualizing Heart Rate Measures for Training and Recovery Prescription. Frontiers in Physiology, 9, 639. https://doi.org/10.3389/fphys.2018.00639	13	165

Collaborative structure of the field

The collaborative structure of research on sports analytics in applied sport science reflects a field that is both actively networked and selectively clustered (see Figure 2). As shown earlier, the dataset had an average of 4.56 co-authors per document and 27.09% international co-authorship, indicating that collaboration is a defining feature of publication in this area. To examine this pattern more closely, a co-authorship analysis

 © 2026 ARD Asociación Española

was conducted using a minimum threshold of 3 documents per author. Although 231 authors met this threshold, only 52 authors formed connected items in the final network, suggesting that the field is characterized by a combination of established collaborative groups and a larger number of authors who remain outside the main connected structure. The map further shows that Stone, M.H. occupied the most visually prominent node, suggesting a highly visible collaborative presence within the author network.

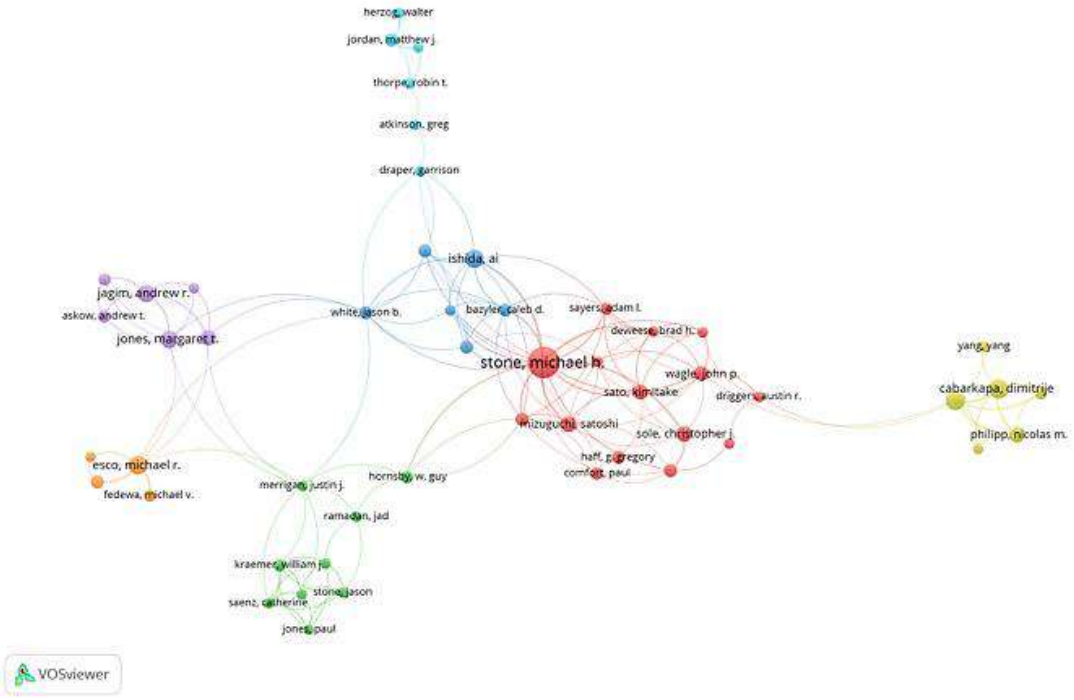


Figure 2. Co-authorship network of authors in applied sport science research on sports analytics (2015–2025).

The co-authorship map revealed several distinct collaboration clusters rather than a single fully integrated authorship network. This indicates that research in sports analytics is being advanced through multiple author groups working around related but not necessarily identical lines of inquiry, such as athlete monitoring, workload management, performance testing, and applied sport science support. The presence of cluster-based collaboration suggests that the field is developing through semi-concentrated scholarly communities, where repeated co-publication among familiar research teams appears to play an important role in knowledge production. At the same time, the limited number of connected authors relative to those meeting the publication threshold points to a degree of fragmentation, implying that the field has not yet fully matured into a broadly unified collaboration structure.

The country collaboration data further indicate that the field has developed through a clearly international research network, with particularly visible ties among countries in North America, Europe, Oceania, and Asia (see Figure 3). The strongest recorded collaboration link was between Australia and the United Kingdom (*f* = 27), followed by the USA and Australia (24), the USA and the United Kingdom (20), and the USA and Canada (16). Other notable cross-national collaborations included Australia and Canada (11), Spain and Italy (11), Australia and New Zealand (10), USA and India (10), and both United Kingdom-Canada and United Kingdom-Ireland collaborations (9 each). Additional visible ties such as Australia-Spain (9), USA-Brazil (8), and United Kingdom-Germany, United Kingdom-Italy, United Kingdom-Netherlands, and USA–Spain (7

each) further suggest that knowledge production in this field is being shaped by recurring transnational partnerships rather than isolated national research efforts.

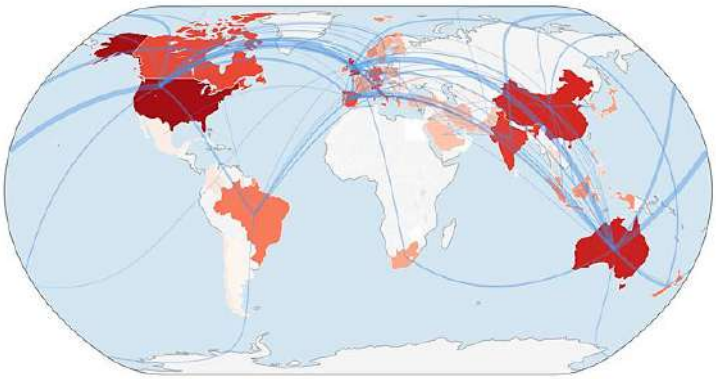


Figure 3. Country collaboration map in applied sport science research on sports analytics (2015–2025).

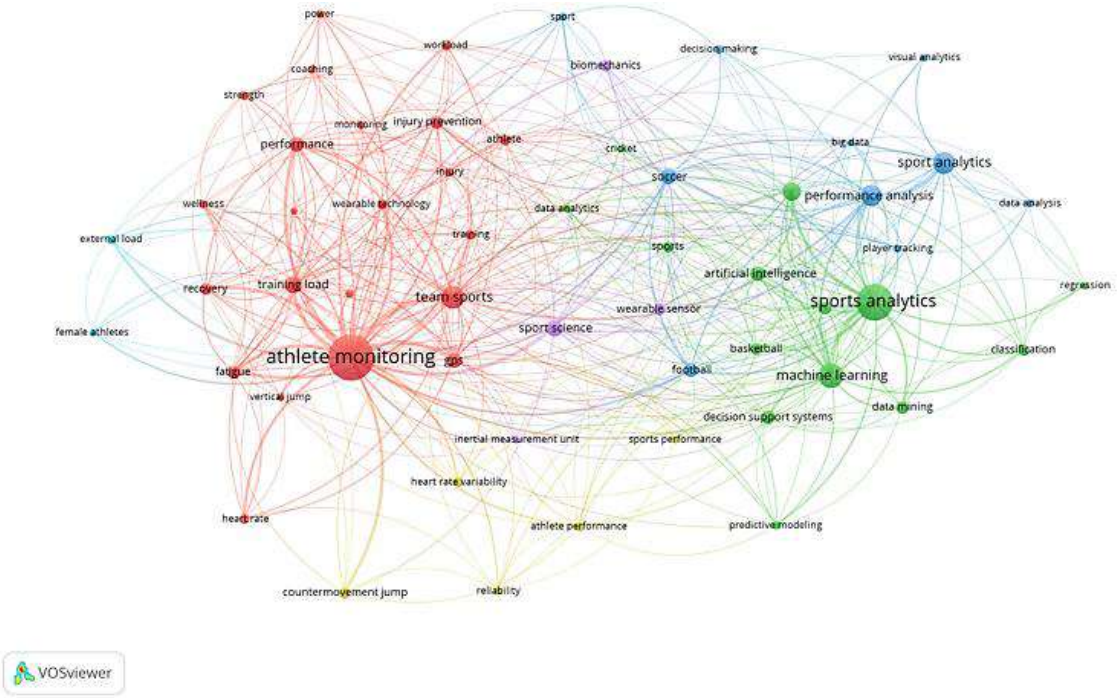


Figure 4. Keyword co-occurrence network in applied sport science research on sports analytics (2015–2025).

Conceptual structure of the field

The conceptual structure of research on sports analytics in applied sport science was examined through keyword co-occurrence analysis using a minimum threshold of 10 occurrences (see Figure 4). The network revealed several closely related thematic groupings, suggesting that the field is not organized around a single keyword domain but around overlapping concerns involving athlete monitoring, performance analysis, computational modelling, and decision support. The prominence of "*athlete monitoring*" and "*sports analytics*," alongside frequently connected terms such as "*performance analysis*," "*athletic performance*," "*machine learning*," "*sport analytics*," and "*decision support systems*," indicates that the field is developing at

 © 2026 ARD Asociación Española

the intersection of applied athlete-support practices and data-driven analytical methods. The network further shows that athlete monitoring is closely linked with terms such as "*workload*," "*team sports*," "*head impact*," and "*performance assessment*," while the sports analytics cluster connects with "*machine learning*," "*classification*," "*data mining*," "*prediction modelling*," and "*decision support*." A related performance-analysis grouping includes "*data analysis*" and "*video analysis*," highlighting the continuing importance of observational and technical evaluation in sport performance. These patterns suggest that the field's conceptual structure is anchored in a practical tension between traditional sport science concerns and newer computational approaches, with sports analytics increasingly functioning as the link between monitoring, modelling, and applied decision-making.

Table 6 further highlights the conceptual profile of the field by identifying the most frequent Author's Keywords in sports analytics research. Machine learning emerged as the most frequent keyword and also recorded the highest total link strength, indicating its strong conceptual prominence in the literature. This was followed by sport analytics, performance analysis, and deep learning, suggesting that the field is increasingly shaped by the integration of computational methods with performance-focused inquiry. At the same time, keywords such as training load, sports science, GPS, and fatigue show that the literature remains closely tied to applied concerns related to workload monitoring, athlete assessment, and performance management.

Table 6. Most frequent Author's Keywords in applied sport science research on sports analytics (2015–2025).

Rank	Author's Keyword	Occurrences	Total link strength
1	Machine learning	93	141
2	Sport analytics	75	81
3	Performance analysis	67	106
4	Deep learning	51	74
5	Training load	44	78
6	Sports science	41	82
7	Soccer	40	68
8	Performance	36	82
9	GPS	36	79
10	Fatigue	26	59

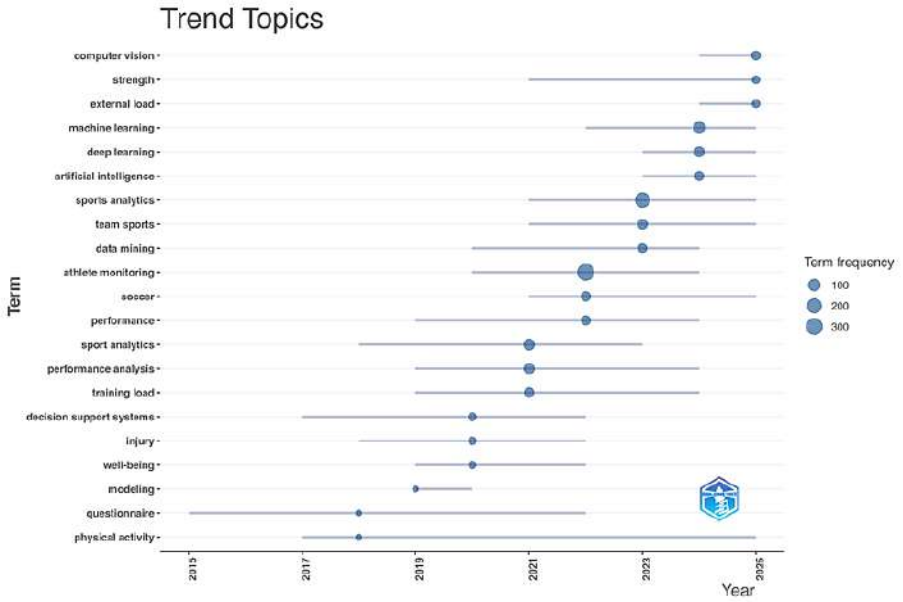


Figure 5. Trend topics on applied sport science research on sports analytics (2015–2025).

The trend-topic analysis indicates that sports analytics in applied sport science has moved toward more specialized and computationally oriented themes over time (see Figure 5). Recent terms such as "*computer vision*," "*machine learning*," "*deep learning*," "*artificial intelligence*," "*sports analytics*," and "*external load*" point to a growing emphasis on automated, predictive, and technology-assisted approaches to performance assessment. However, the continued presence of "*athlete monitoring*," "*performance analysis*," "*training load*," "*team sports*," and "*decision support systems*" shows that the field remains grounded in practical sport science concerns. This temporal pattern suggests that sports analytics is not replacing traditional monitoring and performance evaluation but increasingly extending them through computational and predictive methods.

Intellectual structure of the field

The intellectual structure of research on sports analytics in applied sport science was examined through bibliographic coupling and co-citation analyses. Bibliographic coupling was conducted at the source level using a minimum threshold of five documents to identify publication outlets connected by shared reference patterns. The analysis produced six clusters, although only the four major clusters were retained for substantive interpretation because the remaining two were represented by peripheral single-source groupings (see Figure 6). This structure suggests that the contemporary literature is not concentrated within one publication space but distributed across related source communities connected to applied sport science, athlete monitoring, coaching, physiology, rehabilitation, and interdisciplinary sport health research. Thus, the field appears intellectually broad but thematically coherent, with different publication outlets contributing to a shared concern with data-informed performance support.

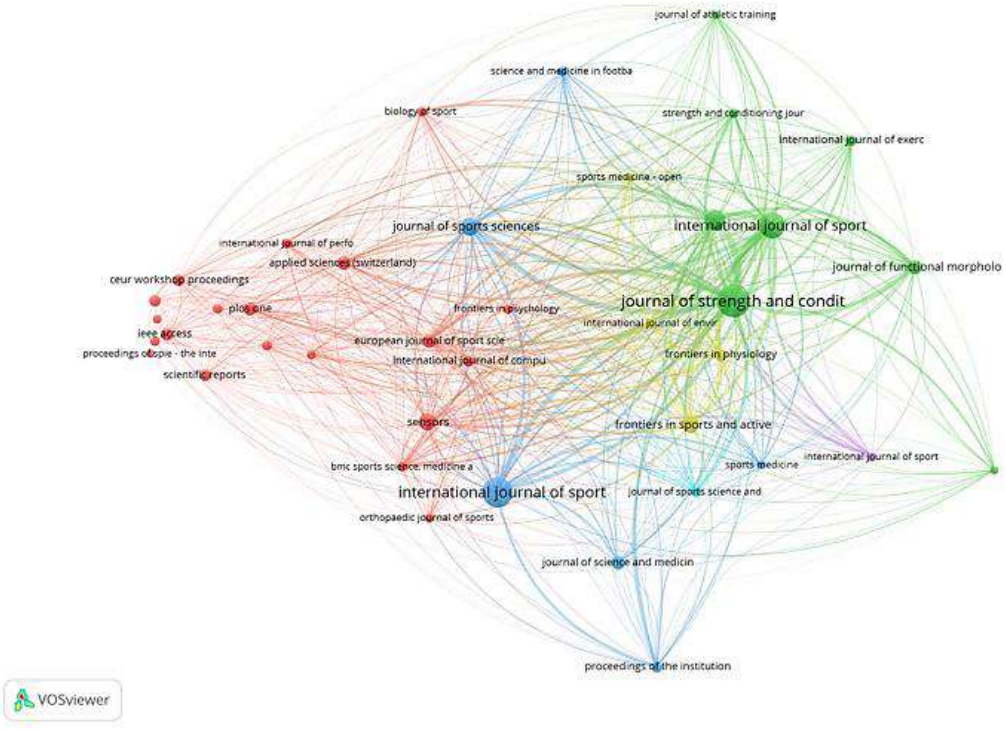


Figure 6. Bibliographic coupling network of sources in applied sport science research on sports analytics (2015–2025).

Table 7 summarizes the major bibliographic coupling clusters of sources in sports analytics research and highlights the thematic orientations of the field's contemporary publication structure. The largest cluster,

 © 2026 ARD Asociación Española

comprising twenty (20) sources, was labelled "*applied sport science, rehabilitation, and performance support*." Representative outlets in this group included Applied Sciences (Switzerland), Biology of Sport, and BMC Sports Science, Medicine and Rehabilitation. This cluster suggests a strong contemporary emphasis on applied sport science research that connects performance support with broader rehabilitation and practitioner-oriented concerns.

The second cluster, consisting of eight (8) sources, was labelled "*exercise physiology, athlete monitoring, and athletic training*," represented by sources such as International Journal of Exercise Science, International Journal of Sport Physiology and Performance, and Journal of Athletic Training. This grouping reflects a more focused intellectual space centred on physiological monitoring, training responses, and athlete care.

The third cluster, with six (6) sources, was labelled "*coaching, sport performance, and applied sport science practice*" and included International Journal of Sports Science and Coaching, Journal of Science and Medicine in Sport, and Journal of Sports Sciences. This cluster points to a practice-facing body of literature concerned with coaching, performance enhancement, and field-based sport science applications.

The fourth major cluster, consisting of four (4) sources, was labelled "*physiology, active living, and interdisciplinary sport health research*," represented by Frontiers in Physiology, Frontiers in Sports and Active Living, and International Journal of Environmental Research and Public Health. This cluster suggests that part of the field is also connected to wider interdisciplinary work involving physiology, public health, and active-living perspectives.

Table 7. Bibliographic coupling clusters of sources in applied sport science research on sports analytics (2015–2025).

Cluster	Theme	Sources (n)	Representative sources
1	Applied sport science, rehabilitation, and performance support	20	Applied Sciences (Switzerland); Biology of Sport; BMC Sports Science, Medicine and Rehabilitation
2	Exercise physiology, athlete monitoring, and athletic training	8	International Journal of Exercise Science; International Journal of Sport Physiology and Performance; Journal of Athletic Training
3	Coaching, sport performance, and applied sport science practice	6	International Journal of Sports Science and Coaching; Journal of Science and Medicine in Sport; Journal of Sports Sciences
4	Physiology, active living, and interdisciplinary sport health research	4	Frontiers in Physiology; Frontiers in Sports and Active Living; International Journal of Environmental Research and Public Health

The co-citation analysis, using a minimum threshold of twenty citations, complemented the bibliographic coupling results by identifying the shared knowledge base of the field. While bibliographic coupling captured contemporary source-level affinities (Takahashi et al., 2023), co-citation analysis revealed the references that are repeatedly cited together and therefore function as the field's intellectual foundations (Small, 1973). The resulting structure shows that sports analytics in applied sport science remains grounded in work on athlete monitoring, workload assessment, fatigue profiling, performance evaluation, and data-informed training support (see Figure 7). This indicates that even as the field becomes more computationally sophisticated, its foundational literature continues to be anchored in practical sport science concerns related to managing athlete status, interpreting performance demands, and supporting applied decision-making.

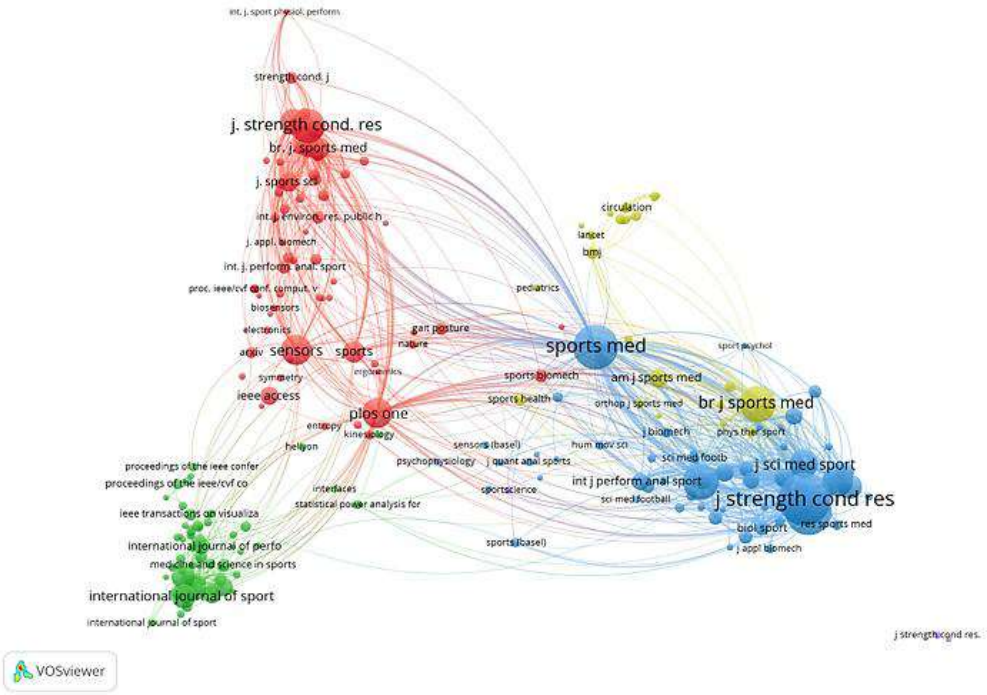


Figure 7. Co-citation network of cited references in applied sport science research on sports analytics (2015–2025).

DISCUSSION

Sports analytics as a shift from measurement to decision architecture

The present study suggests that sports analytics in applied sport science should be understood less as a simple expansion of measurement and more as a shift toward decision architecture. The field is not merely producing more athlete data through wearable devices, GPS systems, workload indicators, or monitoring platforms; it is reorganizing how sport scientists, coaches, and performance staff interpret athlete states and act on them. This shift matters because internal and external load indicators are only useful when they are connected to decisions about training adjustment, fatigue management, recovery, injury prevention, and performance planning (Impellizzeri et al., 2019; Thornton et al., 2019). Recent work similarly shows that athlete monitoring is valued primarily because it helps practitioners make informed and timely decisions, not because data collection is valuable in itself (Timmerman et al., 2024). Thus, sports analytics marks a movement from measurement as documentation to measurement as decision support. Its theoretical importance lies in how it positions applied sport science as a field increasingly concerned with translating complex athlete information into context-sensitive professional judgment (Houtmeyers et al., 2021; Ward et al., 2019).

The predictive turn in applied sport science

Another implication is that applied sport science is entering a predictive turn. Sports analytics is no longer limited to describing what happened after training or competition; it increasingly seeks to anticipate what may happen next through machine learning, AI, deep learning, computer vision, and probabilistic modelling. This represents a methodological shift from retrospective performance analysis toward prediction, classification, automated detection, and decision forecasting (Baumer et al., 2023; Davis et al., 2024). This development is valuable because predictive models may help identify injury risk, performance tendencies, movement

 © 2026 ARD Asociación Española

patterns, training responses, and tactical possibilities before they become visible through conventional observation (Claudino et al., 2019; Cust et al., 2019; Leckey et al., 2025). However, prediction should not be treated as automatic truth. Predictive authority becomes fragile when models are trained on narrow datasets, poorly validated, difficult to interpret, or detached from the realities of sport practice. Therefore, the field's next challenge is not only to build more advanced models, but to ensure that prediction remains transparent, context-sensitive, and practically meaningful (Reis et al., 2024; Zhou et al., 2025).

The human–technology tension in analytics-informed practice

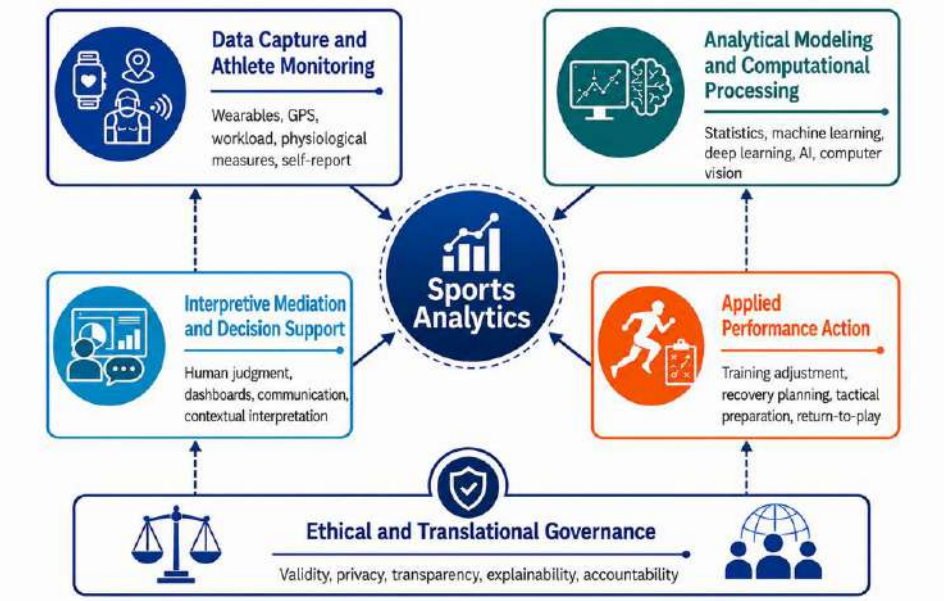
The rise of sports analytics also reveals a persistent human–technology tension in applied sport science. Although the field increasingly depends on automated systems, dashboards, wearable technologies, and decision-support platforms, the interpretation of these outputs remains deeply human. Sport is not a closed technical environment where data can simply produce action. Coaches, athletes, sport scientists, and medical staff make decisions under uncertainty, time pressure, emotional demands, and organizational constraints. This means that analytical systems should be treated as interpretive aids rather than substitutes for professional judgment (Wilson et al., 2025). Human-centred AI scholarship reinforces this point by arguing that trustworthy technologies must preserve human agency, accountability, and meaningful control (Shneiderman, 2020). In sport settings, this is particularly important because even highly sophisticated tracking systems may vary in quality, validity, reliability, and practical usability (Robertson, Duthie, et al., 2023; Robertson, Zendler, et al., 2023). Thus, sports analytics is most valuable when it strengthens practitioner reasoning, supports collaborative sense-making, and helps professionals ask better questions. It becomes problematic only when dashboards or algorithms begin to replace contextual judgment rather than refine it (Hecksteden et al., 2023; Naughton et al., 2024).

The risk of reducing athletes into data profiles

The final critical issue concerns the risk that increasingly powerful analytics may reduce athletes into data profiles. This risk does not diminish the value of sports analytics, but it reminds the field that athlete data are partial representations rather than complete accounts of human performance. A readiness score, GPS output, fatigue index, workload value, injury-risk category, or algorithmic classification may reveal important patterns, but it does not fully capture the athlete as an embodied, psychological, relational, and situational person. This concern becomes more important as AI and machine-learning systems gain influence in performance evaluation, injury prediction, and athlete monitoring. Ethical discussions in sport already highlight issues of privacy, bias, transparency, accountability, and responsible data use (Kim et al., 2025). Broader work on explainable and interpretable AI likewise warns that black-box systems are problematic when their outputs influence high-stakes human decisions (Barredo Arrieta et al., 2020; Rudin, 2019). For sports analytics to mature responsibly, it must remain athlete-centred and interpretively humble. In this regard, its future contribution should not be defined only by predictive accuracy, but by its ability to support better decisions without allowing the athlete to disappear behind the metric.

Toward a responsible and integrative framework for sports analytics

This study proposes a responsible and integrative framework for sports analytics in applied sport science. The proposed framework positions sports analytics not as a single method, technology, or computational technique, but as an interconnected system through which athlete data are captured, processed, interpreted, translated into action, and governed ethically. Its central contribution is the integration of five dimensions: (a) data capture and athlete monitoring, (b) analytical modelling and computational processing, (c) interpretive mediation and decision support, (d) applied performance action, and (e) ethical and translational governance. These dimensions clarify how sports analytics can advance applied sport science while avoiding a narrow technological view of athlete performance.



Note: The framework positions sports analytics as the central hub through which athlete monitoring, analytical modelling, interpretive decision support, and applied performance action are integrated in applied sport science. The solid arrows indicate the contribution of these four operational components to sports analytics, while the dashed connectors show ethical and translational governance as a foundational layer that guides the responsible use of data, models, interpretation, and practice. The model emphasizes that sports analytics becomes meaningful only when data are validly collected, responsibly processed, humanly interpreted, practically translated, and ethically governed.

Figure 8. Responsible and integrative framework for sports analytics in applied sport science.

Data capture and athlete monitoring

This forms the evidentiary base of sports analytics. In applied sport science, this involves the systematic collection of athlete-related information through monitoring systems, wearable devices, GPS units, physiological measures, workload indicators, self-report tools, and performance-tracking technologies. Theoretically, this reflects the field's movement toward more continuous and multidimensional evidence generation. Practically, however, monitoring should not be reduced to collecting as many indicators as possible. The value of athlete data depends on whether the selected measures are aligned with the performance question, the sport context, the athlete's training phase, and the practitioner's decision needs. Internal and external load remain useful distinctions because they help clarify both what athletes do and how they respond to imposed demands (Impellizzeri et al., 2019). Yet monitoring becomes meaningful only when data are organized, visualized, and communicated in ways that support practical interpretation rather than overwhelm decision-makers (Thornton et al., 2019; Timmerman et al., 2024).

Analytical modelling and computational processing

This convert athlete data into structured outputs that can support interpretation, prediction, and decision-making. This includes statistical modelling, machine learning, deep learning, computer vision, AI, and other computational approaches used to identify patterns, classify movements, estimate risk, or forecast performance outcomes. Theoretically, this component explains why sports analytics is becoming more than descriptive performance analysis; it introduces predictive and pattern-recognition capacities that extend what can be observed through conventional sport science methods. Practically, computational processing can support injury-risk modelling, tactical analysis, movement recognition, training-response estimation, and workload interpretation (Claudino et al., 2019; Cust et al., 2019). However, its value depends on

 © 2026 ARD Asociación Española

methodological discipline. A model may appear technically advanced but remain weak if it is trained on narrow datasets, poorly validated, difficult to interpret, or detached from the applied context in which it will be used. For this reason, analytical outputs should be evaluated not only for accuracy, but also for transparency, transferability, contextual relevance, and usefulness in real sport settings (Davis et al., 2024; Reis et al., 2024; Zhou et al., 2025).

Interpretive mediation and decision support

This emphasize that analytics does not move automatically from data to action. Between computational output and practical decision-making lies the interpretive work of coaches, sport scientists, athletic trainers, medical staff, and athletes themselves. This is where analytics becomes humanly meaningful. A fatigue score, load warning, readiness profile, or injury-risk estimate may guide attention, but it still needs to be interpreted in relation to athlete history, competition schedule, psychological state, tactical role, recovery capacity, and coaching priorities. Theoretically, this component places human judgment at the centre of sports analytics and resists the assumption that algorithmic outputs are self-explanatory. Practically, it frames dashboards and decision-support systems as tools for sharpening practitioner reasoning rather than replacing it. Recent work on AI implementation in sport science and sport medicine highlights the importance of workflow integration, communication, trust, and user readiness in translating analytical outputs into practice (Naughton et al., 2024). Human-centred AI also reinforces the need to preserve meaningful human control and accountability when technologies influence high-stakes decisions (Shneiderman, 2020).

Applied performance action

This refers to the translation of analytics into practical intervention. This includes modifying training loads, adjusting recovery strategies, informing return-to-play decisions, designing individualized conditioning programs, preparing tactical plans, identifying performance trends, and communicating athlete needs across multidisciplinary teams. Theoretically, this component shows that sports analytics becomes fully meaningful only when it enters the applied cycle of action, evaluation, and refinement. Practically, it prevents analytics from becoming a detached reporting exercise. Data dashboards, predictive models, and monitoring reports should lead to clearer questions, better discussions, and more defensible decisions. This aligns with the movement from descriptive to prescriptive analytics in elite sport, where data are expected to guide training management rather than merely summarize prior performance (Houtmeyers et al., 2021). It also reflects the growing role of sport scientists in translating evidence into organizational decision support (Ward et al., 2019). However, applied action should remain cautious and iterative. Analytics should support professional experimentation, reflection, and adjustment rather than create rigid prescriptions that ignore athlete variability and context.

Ethical and translational governance

Ethical and translational governance cuts across the entire framework because sports analytics involves human data, institutional decisions, and practical consequences. Athlete data are not neutral objects. They are collected from bodies, interpreted within performance systems, and used to make decisions that may affect workload, health, privacy, selection, opportunity, and career development. Theoretically, this component situates sports analytics within broader concerns about responsibility, fairness, transparency, and athlete-centred practice. Practically, it requires clear standards for data quality, consent, privacy protection, bias reduction, explainability, data security, and accountability. These concerns become especially important as AI and machine-learning systems become more influential in sport settings, where opaque outputs may shape high-stakes decisions without being fully understood by users (Barredo Arrieta et al., 2020; Rudin, 2019). Ethical analyses of AI in sport similarly emphasize privacy, fairness, transparency, and responsible implementation as central issues for the field (Kim et al., 2025). In this proposed framework, governance

ensures that sports analytics remains practically transferable, ethically defensible, and athlete-centred rather than merely technologically impressive.

CONCLUSION

This study shows that sports analytics in applied sport science has developed from a dispersed technical area into a more visible and conceptually organized field shaped by athlete monitoring, performance analysis, machine learning, AI, decision support, and workload management. Beyond documenting growth, the study contributes a responsible and integrative framework that positions sports analytics as a connected system of data capture, computational processing, human interpretation, applied performance action, and ethical governance. The central implication is that sports analytics becomes meaningful not through data volume or technological sophistication alone, but through its capacity to support valid, interpretable, context-sensitive, and athlete-centred decisions in real sport settings.

Implications for research, practice, and technology development

The study carries implications for researchers, practitioners, and technology developers working within applied sport science. For researchers, the findings suggest that sports analytics should be examined not only as a set of computational tools, but as an emerging analytical framework that is reshaping how evidence, prediction, and decision-making are conceptualized in sport. Therefore, future scholarly work should give greater attention to model validation, interpretability, methodological transparency, data quality, and the contextual limits of predictive claims. For practitioners, the study emphasizes that analytics should support professional judgment rather than replace it. Athlete monitoring systems, dashboards, workload indicators, and predictive models are most useful when they help coaches, sport scientists, athletic trainers, and performance staff make better-informed decisions about training, recovery, readiness, injury risk, and performance planning. For technology developers, the proposed framework highlights the need to design systems that are not only technically powerful, but also usable, explainable, ethically responsible, and aligned with the realities of sport practice. The practical value of sports analytics depends on whether its outputs can be interpreted, communicated, and translated into action without reducing athletes to data profiles or allowing algorithmic recommendations to override contextual expertise.

Limitations

This study should be interpreted within several methodological boundaries. The analysis was limited to Scopus-indexed English-language publications, which provided a structured and high-quality bibliographic dataset but may have excluded relevant studies indexed in other databases, non-English publications, books, technical reports, policy documents, and industry-based analytics work. This limitation is important because sports analytics is a rapidly developing field where some innovations may emerge first in professional sport organizations, technology companies, conference proceedings, or practitioner-oriented outlets before appearing in indexed journal literature. As with other bibliometric studies, the findings were also shaped by database coverage, search-string design, author keyword practices, citation age, source-title variation, and metadata quality, despite screening and data-cleaning procedures. Citation indicators may favour older documents, while newer work on AI, computer vision, athlete data governance, and explainable analytics may not yet have accumulated strong citation influence. Finally, bibliometric mapping can identify publication trends, collaboration patterns, conceptual structures, and intellectual foundations, but it cannot directly assess the methodological rigor, practical effectiveness, ethical quality, or real-world implementation success of individual analytics systems.

 © 2026 ARD Asociación Española

Future research directions

Future research should move beyond mapping the expansion of sports analytics and examine how analytical systems actually shape decision-making in applied sport environments. Additional focused reviews are needed on specific subdomains such as athlete monitoring, AI, computer vision, training-load analytics, decision-support systems, injury-risk prediction, and return-to-play analytics. Comparative bibliometric studies using multiple databases may also clarify whether the intellectual structure identified in this study remains stable across different indexing systems and publication cultures. Empirical research should examine how coaches, sport scientists, athletes, medical staff, and performance leaders interpret analytics outputs in real settings, particularly when data conflict with professional judgment or athlete-reported experience. Greater attention is also needed to ethical and translational questions, including privacy, consent, bias, explainability, data ownership, athlete surveillance, and accountability in algorithm-supported decisions. Future studies may also test, refine, or extend the responsible and integrative framework proposed in this study across different sport levels, including elite sport, university sport, youth sport, para-sport, women's sport, and resource-limited sport systems. This would help determine whether sports analytics can mature not only as a technically advanced field, but also as a responsible, interpretable, and athlete-centred mode of applied sport science.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, generative artificial intelligence tools (ChatGPT 5.3, OpenAI) were used to assist in language refinement, structural organization, and editing of the manuscript. All intellectual content, analysis, interpretation of results, and final decisions remain the sole responsibility of the author.

REFERENCES

Barredo Arrieta, A., Díaz-Rodríguez, N., Del Ser, J., Bennetot, A., Tabik, S., Barbado, A., Garcia, S., Gil-Lopez, S., Molina, D., Benjamins, R., Chatila, R., & Herrera, F. (2020). Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. Information Fusion, 58, 82-115. https://doi.org/10.1016/j.inffus.2019.12.012

Baumer, B. S., Matthews, G. J., & Nguyen, Q. (2023). Big ideas in sports analytics and statistical tools for their investigation. WIREs Computational Statistics, 15(6), e1612. https://doi.org/10.1002/wics.1612

Buchheit, M., & Simpson, B. M. (2017). Player-Tracking Technology: Half-Full or Half-Empty Glass? International Journal of Sports Physiology and Performance, 12(s2), S2-35-S2-41. https://doi.org/10.1123/ijspp.2016-0499

Burger, J., Henze, A.-S., Voit, T., Latzel, R., & Moser, O. (2024). Athlete Monitoring Systems in Elite Men's Basketball: Challenges, Recommendations, and Future Perspectives. Translational Sports Medicine, 2024(1), 6326566. https://doi.org/10.1155/2024/6326566

Claudino, J. G., Capanema, D. D. O., De Souza, T. V., Serrão, J. C., Machado Pereira, A. C., & Nassis, G. P. (2019). Current Approaches to the Use of Artificial Intelligence for Injury Risk Assessment and Performance Prediction in Team Sports: A Systematic Review. Sports Medicine - Open, 5(1), 28. https://doi.org/10.1186/s40798-019-0202-3

Cust, E. E., Sweeting, A. J., Ball, K., & Robertson, S. (2019). Machine and deep learning for sport-specific movement recognition: A systematic review of model development and performance. Journal of Sports Sciences, 37(5), 568-600. https://doi.org/10.1080/02640414.2018.1521769

Davis, J., Bransen, L., Devos, L., Jaspers, A., Meert, W., Robberechts, P., Van Haaren, J., & Van Roy, M. (2024). Methodology and evaluation in sports analytics: Challenges, approaches, and lessons learned. Machine Learning, 113(9), 6977-7010. https://doi.org/10.1007/s10994-024-06585-0

Dello Iacono, A., Datson, N., Clubb, J., Lacome, M., Sullivan, A., & Shushan, T. (2026). Data analytics practices and reporting strategies in senior football: Insights into athlete health and performance from over 200 practitioners worldwide. Science and Medicine in Football, 10(1), 80-95. https://doi.org/10.1080/24733938.2025.2476478

Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. G. (2015). Comparison of the Capacity of Different Jump and Sprint Field Tests to Detect Neuromuscular Fatigue. Journal of Strength and Conditioning Research, 29(9), 2522-2531. https://doi.org/10.1519/JSC.0000000000000912

Gathercole, R. J., Stellingwerff, T., & Sporer, B. C. (2015). Effect of Acute Fatigue and Training Adaptation on Countermovement Jump Performance in Elite Snowboard Cross Athletes. Journal of Strength and Conditioning Research, 29(1), 37-46. https://doi.org/10.1519/JSC.0000000000000622

Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015). Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue. International Journal of Sports Physiology and Performance, 10(1), 84-92. https://doi.org/10.1123/ijspp.2013-0413

Hasan, M. F., Apriantono, T., Winata, B., Septina, T. A., Latief, G. R. G., & Pambudi, Y. T. (2024). Developments in research on monitoring training loads in athletes: Bibliometric analysis. Retos, 60, 937-946. https://doi.org/10.47197/retos.v60.108223

Hecksteden, A., Keller, N., Zhang, G., Meyer, T., & Hauser, T. (2023). Why Humble Farmers May in Fact Grow Bigger Potatoes: A Call for Street-Smart Decision-Making in Sport. Sports Medicine - Open, 9(1), 94. https://doi.org/10.1186/s40798-023-00641-0

Heishman, A. D., Daub, B. D., Miller, R. M., Freitas, E. D. S., Frantz, B. A., & Bemben, M. G. (2020). Countermovement Jump Reliability Performed With and Without an Arm Swing in NCAA Division 1 Intercollegiate Basketball Players. Journal of Strength and Conditioning Research, 34(2), 546-558. https://doi.org/10.1519/JSC.0000000000002812

Hoang, A.-D. (2025). Evaluating Bibliometrics Reviews: A Practical Guide for Peer Review and Critical Reading. Evaluation Review, 49(6), 1074-1102. https://doi.org/10.1177/0193841X251336839

Houtmeyers, K. C., Jaspers, A., & Figueiredo, P. (2021). Managing the Training Process in Elite Sports: From Descriptive to Prescriptive Data Analytics. International Journal of Sports Physiology and Performance, 16(11), 1719-1723. https://doi.org/10.1123/ijspp.2020-0958

Hughes, M. D., & Bartlett, R. M. (2002). The use of performance indicators in performance analysis. Journal of Sports Sciences, 20(10), 739-754. https://doi.org/10.1080/026404102320675602

Impellizzeri, F. M., Marcora, S. M., & Coutts, A. J. (2019). Internal and External Training Load: 15 Years On. International Journal of Sports Physiology and Performance, 14(2), 270-273. https://doi.org/10.1123/ijspp.2018-0935

 © 2026 ARD Asociación Española

Jia, Y., Anida Abdullah, N., Eliza, H., Lu, Q., Si, D., Guo, H., & Wang, W. (2025). A narrative review of deep learning applications in sports performance analysis: Current practices, challenges, and future directions. BMC Sports Science, Medicine and Rehabilitation, 17(1), 249. https://doi.org/10.1186/s13102-025-01294-0

Jiang, L., Li, J., Wider, W., Tanucan, J. C. M., Lobo, J., Fauzi, M. A., Hidayat, H., & Zou, R. (2025). A bibliometric insight into immersive technologies for cultural heritage preservation. Npj Heritage Science, 13(1), 126. https://doi.org/10.1038/s40494-025-01704-z

Kang, M., & Lee, S. (2025). Is Sport Analytics a Saving Boat for Traditional Measurement and Evaluation in Kinesiology? Measurement in Physical Education and Exercise Science, 1-12. https://doi.org/10.1080/1091367X.2025.2600451

Kim, J.-H., Kim, J., Kang, H., & Youn, B.-Y. (2025). Ethical implications of artificial intelligence in sport: A systematic scoping review. Journal of Sport and Health Science, 14, 101047. https://doi.org/10.1016/j.jshs.2025.101047

Leckey, C., Van Dyk, N., Doherty, C., Lawlor, A., & Delahunt, E. (2025). Machine learning approaches to injury risk prediction in sport: A scoping review with evidence synthesis. British Journal of Sports Medicine, 59(7), 491-500. https://doi.org/10.1136/bjsports-2024-108576

Naughton, M., Salmon, P. M., Compton, H. R., & McLean, S. (2024). Challenges and opportunities of artificial intelligence implementation within sports science and sports medicine teams. Frontiers in Sports and Active Living, 6, 1332427. https://doi.org/10.3389/fspor.2024.1332427

Öztürk, O., Kocaman, R., & Kanbach, D. K. (2024). How to design bibliometric research: An overview and a framework proposal. Review of Managerial Science, 18(11), 3333-3361. https://doi.org/10.1007/s11846-024-00738-0

Passfield, L., & Hopker, J. G. (2017). A Mine of Information: Can Sports Analytics Provide Wisdom From Your Data? International Journal of Sports Physiology and Performance, 12(7), 851-855. https://doi.org/10.1123/ijspp.2016-0644

Rein, R., & Memmert, D. (2016). Big data and tactical analysis in elite soccer: Future challenges and opportunities for sports science. SpringerPlus, 5(1), 1410. https://doi.org/10.1186/s40064-016-3108-2

Reis, F. J. J., Alaiti, R. K., Vallio, C. S., & Hespanhol, L. (2024). Artificial intelligence and Machine Learning approaches in sports: Concepts, applications, challenges, and future perspectives. Brazilian Journal of Physical Therapy, 28(3), 101083. https://doi.org/10.1016/j.bjpt.2024.101083

Robertson, S., Bartlett, J. D., & Gastin, P. B. (2017). Red, Amber, or Green? Athlete Monitoring in Team Sport: The Need for Decision-Support Systems. International Journal of Sports Physiology and Performance, 12(s2), S2-73-S2-79. https://doi.org/10.1123/ijspp.2016-0541

Robertson, S., Duthie, G. M., Ball, K., Spencer, B., Serpiello, F. R., Haycraft, J., Evans, N., Billingham, J., & Aughey, R. J. (2023). Challenges and considerations in determining the quality of electronic performance & tracking systems for team sports. Frontiers in Sports and Active Living, 5, 1266522. https://doi.org/10.3389/fspor.2023.1266522

Robertson, S., Zendler, J., De Mey, K., Haycraft, J., Ash, G. I., Brockett, C., Seshadri, D., Woods, C., Kober, L., Aughey, R., & Rogowski, J. (2023). Development of a sports technology quality framework. Journal of Sports Sciences, 41(22), 1983-1993. https://doi.org/10.1080/02640414.2024.2308435

Rudin, C. (2019). Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead. Nature Machine Intelligence, 1(5), 206-215. https://doi.org/10.1038/s42256-019-0048-x

Sampaio, T., Oliveira, J. P., Marinho, D. A., Neiva, H. P., & Morais, J. E. (2024). Transforming tennis with artificial intelligence: A bibliometric review. Frontiers in Sports and Active Living, 6, 1456998. https://doi.org/10.3389/fspor.2024.1456998

Sarlis, V., & Tjortjis, C. (2020). Sports analytics-Evaluation of basketball players and team performance. Information Systems, 93, 101562. https://doi.org/10.1016/j.is.2020.101562

Saw, A. E., Main, L. C., & Gastin, P. B. (2015). Monitoring athletes through self-report: Factors influencing implementation. Journal of Sports Science & Medicine, 14(1), 137-146.

Saw, A. E., Main, L. C., & Gastin, P. B. (2016). Monitoring the athlete training response: Subjective self-reported measures trump commonly used objective measures: a systematic review. British Journal of Sports Medicine, 50(5), 281-291. https://doi.org/10.1136/bjsports-2015-094758

Schneider, C., Hanakam, F., Wiewelhove, T., Döweling, A., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2018). Heart Rate Monitoring in Team Sports-A Conceptual Framework for Contextualizing Heart Rate Measures for Training and Recovery Prescription. Frontiers in Physiology, 9, 639. https://doi.org/10.3389/fphys.2018.00639

Shneiderman, B. (2020). Human-Centered Artificial Intelligence: Reliable, Safe & Trustworthy. International Journal of Human-Computer Interaction, 36(6), 495-504. https://doi.org/10.1080/10447318.2020.1741118

Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. Journal of the American Society for Information Science, 24(4), 265-269. https://doi.org/10.1002/asi.4630240406

Takahashi, R., Kaibe, K., Suzuki, K., Takahashi, S., Takeda, K., Hansen, M., & Yumoto, M. (2023). New concept of the affinity between research fields using academic journal data in Scopus. Scientometrics, 128(6), 3507-3534. https://doi.org/10.1007/s11192-023-04711-8

Thornton, H. R., Delaney, J. A., Duthie, G. M., & Dascombe, B. J. (2019). Developing Athlete Monitoring Systems in Team Sports: Data Analysis and Visualization. International Journal of Sports Physiology and Performance, 14(6), 698-705. https://doi.org/10.1123/ijspp.2018-0169

Thorpe, R. T., Atkinson, G., Drust, B., & Gregson, W. (2017). Monitoring Fatigue Status in Elite Team-Sport Athletes: Implications for Practice. International Journal of Sports Physiology and Performance, 12(s2), S2-27-S2-34. https://doi.org/10.1123/ijspp.2016-0434

Timmerman, W. P., Abbiss, C. R., Lawler, N. G., Stanley, M., & Raynor, A. J. (2024). Athlete monitoring perspectives of sports coaches and support staff: A scoping review. International Journal of Sports Science & Coaching, 19(4), 1813-1832. https://doi.org/10.1177/17479541241247131

Ward, P., Windt, J., & Kempton, T. (2019). Business Intelligence: How Sport Scientists Can Support Organization Decision Making in Professional Sport. International Journal of Sports Physiology and Performance, 14(4), 544-546. https://doi.org/10.1123/ijspp.2018-0903

Wilson, P. J., & Kiely, J. (2023). Developing Decision-Making Expertise in Professional Sports Staff: What We Can Learn from the Good Judgement Project. Sports Medicine - Open, 9(1), 100. https://doi.org/10.1186/s40798-023-00629-w

Wilson, P. J., Roe, G., & Kiely, J. (2025). Decisions, decisions, decisions. A qualitative exploration of decision-making in performance support leaders. Frontiers in Sports and Active Living, 7, 1664191. https://doi.org/10.3389/fspor.2025.1664191

Zhou, D., Keogh, J. W. L., Ma, Y., Tong, R. K. Y., Khan, A. R., & Jennings, N. R. (2025). Artificial intelligence in sport: A narrative review of applications, challenges and future trends. Journal of Sports Sciences, 1-16. https://doi.org/10.1080/02640414.2025.2518694

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

REVIEW ARTICLE

Sex differences in growth, skeletal maturation, and training load in youth sports: Implications for long-term athletic development

Arman Sargsyan . *Independent Soccer Coach. PFSA-Certified Scout. Glendale Community College. US Soccer Federation. United States of America.*

ABSTRACT

Competitive youth sport participation has been shown to benefit physical, psychological, and social development in children and adolescents. However, recent trends involving increased training volume, early sport specialization, and performance-based youth sport systems have elicited questions around youth biological maturation and skeletal development. These concerns include increased susceptibility to injury and overall athlete well-being later in life. This narrative review aimed to discuss sex-specific differences in growth and skeletal maturation as they relate to training load considerations in youth athletes. PubMed, Google Scholar, SPORTDiscus, and Scopus were used to search for peer-reviewed literature related to youth biological maturation, peak height velocity, skeletal development, training loads, risk of overuse injury, and sport participation. Results were synthesized according to themes including biological development and growth, injury susceptibility, training load considerations, and psychosocial implications of youth sport participation. Female athletes were found to mature earlier on average than their male counterparts, experiencing pubertal onset, peak height velocity, and subsequent skeletal maturation around 8–13 years of age. Compared to females, males experience this process later but over an extended period that can continue into late adolescence. Physiological changes during periods of rapid growth can temporarily alter coordination, movement efficiency, and injury susceptibility, especially under conditions of high training load and inadequate recovery. Failure to account for individual differences in training load relative to biological development may increase risk for overuse injury, growth plate injury, and psychological burnout. Researchers and coaches should be aware that training programs based on chronological age may not account for individual variability. Load management, movement competency, recovery, and long-term athlete development should be considered when developing training programs to reduce injury risk and promote healthy athletic development.

Keywords: Youth sports, Growth, Maturation, Sex differences, Skeletal development, Training load, Adolescent athletes, Growth plates.

Cite this article as:
Sargsyan, A. (2026). Sex differences in growth, skeletal maturation, and training load in youth sports: Implications for long-term athletic development. *Journal of Human Sport and Exercise, 21*(4), 1283-1300. https://doi.org/10.55860/kyv10r23

Corresponding author. *Independent Soccer Coach. United States of America.*
E-mail: armsarca@gmail.com
Submitted for publication April 23, 2026.
Accepted for publication June 01, 2026.
Published July 10, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/kyv10r23

INTRODUCTION

Childhood and adolescence represent important time periods during which individuals learn to engage in physical activity, develop fundamental movement skills, and establish social relationships within sport. Participating in sport during youth may have many immediate and long-term health benefits. Outside of promoting physical activity and health, involvement in organized sport may have immediate benefits to confidence and psychosocial well-being, teamwork, and emotional health during childhood and adolescence. Recent trends within youth sport have been characterized by early emphasis on performance outcomes, increased year-round training volumes, and sport specialization at younger ages.

Although early sport specialization and training can be beneficial for some athletes, developing fundamental movement skills at younger ages, there is concern that high training volumes in a single sport during periods of intense growth may increase risk of injury and illness and promote early sport dropout. Though variability in growth, maturation, and development are common among children and adolescents, training doses are often not adjusted to account for individual differences in maturity.

Considerable variability exists in the age at which children reach peak height velocity (PHV), defined as the point at which individuals reach their maximum height growth in a given year. Athletes who mature early or later than their peers can experience relative discrepancies in training load as well as physiological and psychological stress from training and competition. Early maturing athletes may face higher training loads relative to their late maturing peers due to increased size, strength, and skill. Late maturing adolescents may be overlooked by coaches and adults because of their smaller physique and lack of strength despite having the potential to reach similar or higher levels of maturity than early matures.

In addition to absolute differences in maturation between children of the same age, males and females exhibit differences in maturation and growth. On average, girls experience pubertal hormonal changes earlier than males and ultimately reach PHV earlier than their male counterparts. Whereas female growth in height plateaus after PHV, males continue to grow at a slower rate into their late teens and even into early adulthood. These differences in growth and maturation may have implications for injury risk, movement coordination, athletic performance, and training responses in male and female adolescent athletes.

Growth velocity plateaus, particularly rapid skeletal growth, have been of particular interest when considering training load in youth athletes. Growth plates and developing musculoskeletal structures may be more vulnerable to damage from repetitive micro-trauma during periods of rapid growth. Therefore, excessive training volumes, repetitive sport-specific skill development, and high training loads with inadequate recovery periods have previously been associated with increased injury risk in youth athletes. Additionally, temporary changes in coordination have been observed during PHV that may influence movement quality and injury risk.

Increased awareness regarding growth and maturation among youth athletes has led to discussion on modifying athletic training during sensitive periods of development. Although a reduction in training load and sport participation has been suggested during rapid growth phases, research does not currently justify restricting youth athletes from sport during periods of rapid growth.

Thus, this narrative review had three primary objectives: (1) discuss sex-related differences in growth, development, and maturation in youth athletes, (2) discuss training load considerations and injury risk during periods of rapid adolescent growth and maturation, and (3) highlight considerations for evidence-based training and long-term athletic development in youth sport.

 © 2026 ARD Asociación Española

METHODOLOGY

The methodology followed a conceptual analysis design, from which an extensive review of current scientific literature across human movement sciences, developmental biology, sport medicine literature and youth training theory was synthesized.

A conceptual analysis was suitable as the topic explored requires consideration of developmental factors that cannot be feasibly or ethically experimented within youth populations.

This topic review took on a narrative conceptual review design. Multiple databases including PubMed, Google Scholar, SPORTDiscus and Scopus were searched in order to review current literature regarding biological maturation, skeletal development, sex differences, training load, and long-term athlete development with youth sport populations.

Search terms included ("*youth athlete maturation*" OR "*peak height velocity*" OR "*skeletal development*" OR "*sex differences in growth*" OR "*training load*" OR "*growth plate injuries*" OR "*overuse injuries*") AND ("*late physical development*" OR "*physical development*" OR "*long term athlete development*"). Articles were primarily limited by date (published between 2000-2025) and peer-reviewed status.

Articles were included if they reviewed youth athletes and covered one or more of the topics of biological maturation, adolescent growth and development, injury risk, training load, or psychosocial implications of sport. Consensus statements, longitudinal studies, cross-sectional studies, as well as paediatric sport science literature were included. Articles were excluded if they focused only on adult samples or did not focus on the clinical topic of interest. Literature was then compiled into themes focused on the following:

1. Biological growth and maturation.
2. Skeletal development and injury risk.
3. Training load.
4. Psychological and developmental implications.

A narrative review was used due to the inability to experimentally isolate coaching, biological, physiological, and psychological factors in youth sport.

Growth patterns and pubertal timing

Puberty typically starts between the ages of 8-11 for girls and 10-13 for boys. Girls go through puberty much earlier than boys which means they experience their linear growth, increases in body mass, and skeletal maturity earlier.

PHV (Peak Height Velocity) is when the athlete experiences their greatest gain in height over a one-year period. Girls reach PHV around 11-13 while boys hit PHV closer to 13-15. This is also when girls will experience rapid increases in leg length, bone mineral accrual, and body proportions.

Since girls hit this peak earlier, they also recover from this point sooner than boys. Most girls will stop growing around 14-16 years old. When it comes to boys, they continue to grow later into their teenage years and even into their early 20's.

These developmental differences have important implications for youth sport participation and training design. During early adolescence, females may temporarily demonstrate advantages in coordination, stature,

and physical maturity due to earlier pubertal onset. In contrast, males often experience delayed but prolonged growth and maturation extending into late adolescence. These differences should be considered when evaluating athletic performance, prescribing training loads, and interpreting physical capabilities during developmental years.

Skeletal development and growth plates

Another thing to take note of with biological sex differences is growth plates (Caine et al.,2006). Growth plates, also known as phases, are areas of cartilage that connect the end of long bones to the epiphysis. They are the last portion of the bone to mature, thus they are responsible for longitudinal bone growth.

Growth plates typically close sooner for girls due to their earlier onset of puberty and oestrogens ability to speed up skeletal maturity. Growth plates for girls usually close between 14-16 years of age. For boys, growth plates take longer to close resulting in a longer timeframe for injury. Growth plates for boys can close anywhere between 16-18 years of age and some boys can even continue growing until they're 20 years old.

Due to prolonged periods of skeletal growth in males, growth plates remain susceptible to repetitive mechanical stress for longer durations during adolescence. Although physical activity itself does not negatively alter bone growth under normal conditions, growth plates are structurally weaker than mature bone and surrounding soft tissue structures during rapid developmental periods. Consequently, repeated exposure to high-intensity sprinting, jumping, cutting, and contact-based activities may increase susceptibility to overuse injuries and physical stress during sensitive growth stages.

This is why sports like football and basketball have high instances of growth plate injuries. These sports require athletes to perform lots of high-intensity movements while also growing at a rapid rate.

Hormonal influences on growth and performance

Oestrogen and testosterone also play a huge role when programming training for boys and girls (Hewett et al.,2006). As previously mentioned, oestrogen causes girls to reach PHV earlier and also quickens the closure of growth plates. During puberty, oestrogen increases a girls bone mineral density.

Testosterone has different effects on boys. Testosterone increases lean body mass, strength, and power. Testosterone also increases bone mineral density and how bone is structured.

Times of accelerated growth, where muscle strength and limb length are increasing at a faster rate than neurological and movement adaptations can occur, the athlete may experience periods of decreased balance, coordination, movement efficiency and motor control. These deficits occur during growth spurts and are normal and expected, so practitioners should not use these fluctuations when determining potential or progression.

In a perfect world, boys would get stronger and faster while maintaining proper coordination and skill. However, this is not always the case during rapid growth. Coaches should focus less on training max output and more on movement quality and coordination during this time.

Sex differences in physical maturity and sport selection

Sex is another factor that can affect sport selection. Many times younger athletes are selected based on their physical ability and not their skill. Since most girls reach puberty earlier than boys, they are often bigger, faster, and stronger than boys of the same age.

 © 2026 ARD Asociación Española

This creates a problem for boys who are late bloomers. These late-maturing boys are often overlooked during sport selection despite having the potential to be just as good as the athletes selected.

Many people do not know this, but most elite level athletes were not the best athletes in their youth. They just matured at a later time allowing them to overtake other athletes once they caught up.

Implications for youth sports training

Boys and girls grow and mature at different rates, and awareness of these distinctions in maturation timing allows practitioners to develop safe training systems that maximize biological differences. Programs that do not consider maturation often place both sexes at risk of experiencing inappropriate training loads relative to their individual biological capability, which can contribute to higher injury, burnout and dropout rates. Developmentally-driven training that is relative to athlete biology through manipulations of intensity, training volume, and systemic expectations can help athletes become better skill learners, decrease injury risk, and create safer training environments for long-term athletic development.

Ultimately, growth and maturation should not be seen as barriers to performance but as opportunities to improve movement technique, coordination, and movement skill competency.

RESULTS

Adolescence is a period of increased risk for injury in youth sport because of the mismatch between rapid biological growth and development on one hand, and maturation-independent training loads on the other hand. Organized sport participation can be beneficial from a physical and psychosocial standpoint, however excessive or inappropriate loads during sensitive periods of rapid growth may lead to increased injury risk, maladaptation, or pathologies that extend into adulthood. Adolescent athletes, specifically males between 13–15 years old, often experience rapid linear growth during their peak height velocity that their bones experience years before the required muscular and neuromuscular strength to control and adapt to their new body dimensions catches up.

During periods of peak height velocity, bones will grow at a much quicker rate than muscles, tendons, and neuromuscular control can adapt. This results in a temporary shift in movement mechanics, joint loads, and shock absorption capacity. This may lead to athletes displaying poorer coordination and a loss of flexibility while undergoing higher degrees of mechanical stress.

High-load repeated sprinting, jumping, cutting, and contact movements may place high amounts of stress through growth plates, apophyses, and tendon attachments. Apophysitis conditions such as Osgood–Schlatter disease and Sever's disease are common training-related injuries during periods of accelerated growth. These conditions are not caused by a disease but rather represent an overflow of the training stimulus on the ability of the athlete to biologically handle that load at that given time.

Overuse injuries in young athletes

Upwards of 30–50% of musculoskeletal injuries in active youth are overuse injuries. Unlike acute traumatic injuries that occur suddenly when a force surpasses tissue tolerance, overuse injuries are the result of repeated sub-maximal micro-trauma that cumulatively exceeds the tissue's ability to adapt and recover from the imposed load. Risk factors for overuse injuries include high training volumes, low recovery periods, early sport specialization, and playing for multiple teams simultaneously.

Football and basketball are year-round sports for many athletes. This training model often lacks planned rest periods which can lead to overuse or chronic adaptations of bone and soft tissue injuries, particularly when linear growth is at its peak. Due to open growth plates and incomplete physical maturation, adolescent boys between the ages of 13–15 are susceptible to stress reactions from insufficient load management.

Does heavy training during adolescence stunt growth?

One popular belief from parents and the general population is that playing sports and engaging in heavy training will stunt an athlete's growth. Research does not support the claim that growth will be stunted from properly implemented training during adolescence.

Longitudinal research monitoring athletes' height during their active years of sport have shown that athletes retain their genetically predetermined height potential even while being active in sport. With that being said, when yearly training loads are excessive compared with the ability for the body to recover from that load, injuries can happen. These chronic stress injuries to growth plates can alter the growth of that local area of the bone if left unidentified or not properly managed. Energy availability can also play a factor with growth and training. If athletes are not consuming enough calories to support their training volumes, hormone disturbances can occur which can affect growth and bone mineralization.

Should I take my adolescent athlete out of sport?

There is insufficient evidence that athletes should completely stop participating in sport throughout their years of accelerated growth and development. While training should still occur, participants in structured training programs during adolescence can gain important physiological, psychological and social benefits. Modifications in overall training load, competition schedules, and repetitive high intensity movements may benefit the adolescent athlete during their PHV to decrease unnecessary stress to growing musculoskeletal tissues.

Minimizing high intensity training and exposure to competitions may be beneficial during these adolescent years. Modifications can include decreasing number of competitions, limit repetitive maximal sprinting and jump bouts, and including low-impact cross-training activities to help decrease injury risk. Emphasis should be placed on movement quality, coordination, flexibility, skill development, and recovery during these times of sensitive growth.

How does overtraining affect adolescent mental health?

Heavy training loads may not only affect physiological outcomes, but psychological health as well. Chronic fatigue, underperformance, poor sleep, and repeat injuries have been linked to psychological distress, burnout and demotivation in youth athletes. Additionally, adolescence is a time where there is heightened brain development and psychological changes, so adolescents may be especially susceptible to outside pressure to perform and be competitive.

Motivational climates that focus heavily on outcomes can lead to burnout, anxiety and dropout from sport. Creating a more supportive environment for the athlete that focuses on long-term development and skills, autonomy, fun and freedom from fear of failure may promote positive health and sport longevity.

Modifying training loads during adolescence

So you know training shouldn't be stopped during adolescent growth, but how do you actually modify training? Like previously stated, training should be individualized based on the athlete's stage of development.

 © 2026 ARD Asociación Española

Although this takes research, time, and knowledge, there are simple ways to modify an athlete's training that does not need to be completed by coaches alone.

Some simple methods to modify training loads during adolescence:

- Track height over years to determine when PHV occurs.
- During PHV, reduce training volume and intensity.
- Emphasize technique, coordination, flexibility.
- Allow for enough recovery time and sleep.
- Monitor dietary habits to ensure energy demands are being met.
- Educate coaches and parents on Adolescent Growth and Development.

Coaching considerations

Coaches can also unknowingly impact how their athletes adapt to their training based on their knowledge of growth and development. Many coaches see results quickly when they start coaching. They expect the same when they start coaching young athletes. These coaches don't understand that paediatric athletes are growing and maturing at different rates.

If coaches are not educated on how growth and maturation can affect athletes, they may become frustrated with athletes that are not progressing like their peers or "*look*" older or younger than the rest of the team. These coaches will often misjudge athletes that are late bloomers and forget about these athletes when long-term athlete development comes into play.

Remember there is always a reason why athletes perform the way they do. Just because they may be underperforming during their growth spurt, doesn't mean they don't have the potential to be a gifted athlete in the long term.

Practical training implications for football(soccer) and basketball during growth and maturation

Understanding of growth and maturation is useless if it does not drive action and decision-making by coaches. Often environments for youth football and basketball place too much emphasis on early success, game playing volume, and physical domination without consideration for variations in maturity status between boys and girls. This article provides translation of growth and maturation science into practice by providing training principles based on evidence that allow for long-term athletic development and a reduced risk of injury and dropout.

Chronological age vs biological age in training design

The biggest issue in youth sport is that maturity is not accounted for when programming training loads, placing kids into competition groups, and selecting who makes the team. Chronological age does not matter when you consider inter-individual differences at any given age can be up to 2 years of biological maturation.

Strength and speed differences in football and basketball are usually more pronounced during early maturation. Consequently, early-maturing athletes may be seen as better coaches and placed under higher loads and expectations. On the other hand, late-maturing athletes may appear less talented due to their lack of size and strength, even though they have the technical or tactical qualities necessary to be successful.

If we consider these aspects of maturation in our training programs we can:

- Create homogenous groups based on maturation for certain training activities.

- Increase or decrease training load in response to growth spurt.
- Benchmark performance against players biological age not final score.

Training considerations for female athletes aged 8–13

Puberty begins earlier for most female athletes. Some may even begin puberty by age 8. Due to rapid increases in muscle and fat gain, torso length, and limb growth, girls may temporarily suffer decreases in coordination and movement efficiency. As coaches, we cannot allow early physical development to cloud our judgement of these players (Côté et al.,2007).

During this stage of development, coaches should focus on:

- General movement skills.
- Basic posture and balance.
- Coordination.
- Building technical skills.
- Fostering confidence and independence.

Strength training is perfectly safe and beneficial for girls who are taught proper exercise technique and provided proper supervision. While too much volume, intensity, or early specialization can lead to injuries and burnout.

Additionally, some girls may feel more pressure from coaches and parents during early maturation. These athletes need to feel supported by their coaches and safe to express themselves.

Training considerations for male athletes aged 13–15

Most male athletes will experience their peak height velocity between ages 13 and 15. Because the skeleton often grows faster than nerves can adapt to new limb lengths, coordinative abilities and skill expression may temporarily regress or fluctuate. Some athletes may even show decreases in performance during this time. Let athletes know that this is normal and does not mean they are regressing or aren't trying (Lloyd & Oliver,2012).

Between the ages of 13-15, coaches should focus on:

- Movement Quality
- Posture and Balance
- Flexibility
- Restoring load after growth spurt

Male athletes should take caution with their training volume during this time. Too much sprinting, maximal strength, or year-round competition can lead to injuries or mental burnout.

Instead of taking time off, reduce load and allow the body time to adapt.

Early specialization vs diversified athletic development

Allowing athletes to sample different sports is something that has been discussed at length. However, early sport specialization is still common among football and basketball coaches. While research is limited, early specialization has been linked with overuse injuries, burnout, and dropout from sport.

 © 2026 ARD Asociación Española

Sampling allows athletes to learn new movement skills and enhance their abilities in multiple movement patterns. Motor learning is improved when children are exposed to different sports. In turn, they can become better athletes and less prone to injury. While early sport specialization does not guarantee poor performance in the future, encouraging athletes to participate in multiple sports during childhood and early adolescence can only benefit them (Ford et al., 2011).

Coaches and sport organizations can discourage early specialization by:

- Allowing athletes to participate in multiple sports during their early stages.
- Periodizing their off season and season training to focus on different sports.
- Help athletes develop skills that transfer across sports.
- Avoid year round competition.

This is especially important during peak growth periods because sports that require a high amount of repetition may overload tissues.

Monitoring training loads & recovery

Monitoring training loads during periods of growth is difficult because there is no cookie cutter program that works for every athlete (Frisch, 1994). Athletes are experiencing multiple changes that can influence their training capacity. Some signs of taking on too much load are:

- Fatigue.
- Inconsistent performance.
- Irritability.
- Recurrent or increased pain.
- Loss of motivation.

Coupled with a training diary, coaches can use simple tools like questionnaires, rating of perceived exertion, and even measuring their athletes growth to try to identify athletes who are at risk. Although sometimes the best tool is just asking your athletes how they feel.

Regardless of how you monitor your athletes, here are some recovery strategies to implement during periods of high growth:

- Sleep.
- Use reload weeks.
- Nutrition.
- Foster psychological recovery by giving athlete's freedom and fun.

The coach's responsibility

Coaches have the ability to influence youth athletes' experiences and impact athletic performance as well as physical and psychosocial health. Educating coaches about the relationship between biological age, training load, and fluctuations in development may help to facilitate training environments and skill development that focus on the athlete's long-term development rather than on short-term performance goals. Understanding that children's and adolescents' development does not occur on a fixed schedule can help coaches realize that fluctuations in coordination, movement quality, and sports performance are normal and may not be reflective of athletes with low sporting potential or lack of motivation. Coaching practices grounded in motor development and human growth principles should value technique, movement skill, injury prevention, psychological well-being, and progression based on biological age. If coaches understand how factors related

to growth and maturation can influence sports performance, they may be better prepared to aid athletes through these sensitive periods and minimize unnecessary stress.

Ethical responsibility in youth sport training

When you decide to coach or train children you are taking on the responsibility of that athlete's development. Some coaches will make decisions that they think are in the best interest of the athlete and program. But we have to ask ourselves, is it really in the best interest of that child?

As coaches, parents, or administrators, we can change the way we think about training children. The decisions you make can alter someone's health for the rest of their life, but it can also change who they believe they are (Malina et al., 2004).

If we take these stages of growth and development into consideration, we can start building better athletes that will stay healthy and happy playing the sport they love.

DISCUSSION

Integrating growth, maturation, and training load in youth sport development

Results/Concepts presented above have demonstrated the importance of viewing training in youth sport with a development and maturation approach. Sports such as football and basketball are high intensity intermittent sports that require the body to perform mechanically demanding tasks while also coordinating complex movement patterns. As a result, if we ask these athletes to participate in football and basketball without taking into account their biological age, maturation rate, and sex-related growth characteristics there can be a high potential for maladaptation (Rowland, 2005).

Growth-related variability as a central developmental factor

Probably the biggest theme to come from the previous sections is that growth and maturation is not linear. Children and adolescents do not grow consistently or predictably in their physical capabilities. Instead, their performances ebb and flow based on a wide variety of growth related factors. Too often these fluctuations are attributed to a lack of effort, poor discipline, or lack of talent (Malina et al., 2015).

For boys especially, the months before and after their peak height velocity is reached can be very frustrating. Simply put, their limbs are getting longer quicker than their bodies can adapt to. This creates temporary weaknesses in leverage, joint loading, and muscle coordination. In girls, early matures can appear to be further ahead than they actually are. This sometimes leads to training and competition volumes that are too high too early.

Understanding that growth related variability is normal is an important step in avoiding premature athlete classification and minimizing unnecessary dropout.

Talent identification and selection should be questioned

Many talent identification programs in football and basketball reward the most physically dominant athletes at a young age. This has created a system that favours athletes who mature early and punishes athletes who mature later. Research has shown again and again that early physical dominance does not translate into late adolescence and that technical, perceptual, and cognitive qualities separate elite athletes from their competition (Vaeyans et al., 2008).

 © 2026 ARD Asociación Española

But early selection does more than miss out on late bloomers. It also places a larger training load on young athletes during periods where they are more susceptible to injury and burnout. Late blooming boys and early blooming girls are put under greater physical and mental stress during these sensitive growth periods.

A better framework for selection would focus less on current physical prowess and more on an athlete's capacity to learn and develop. Factors like adaptability and decision-making ability should be valued over purely physical traits.

Load accumulates rapidly and injury risk is high

Training load increases have been shown to increase injury risk dramatically during adolescence. Growth changes adolescents undergo cause fluctuations in bone density, muscle-tendon stiffness, and neuromuscular coordination which decrease the tolerance to repetitive stress. When volume, intensity, and frequency of training are all increased at once like they often are in competition settings, accumulated load can reach dangerous levels.

Another thing to note about injuries during periods of growth is that they can have long-term consequences. Adolescents who experience injuries that affect their movement patterns can suffer from chronic pain, fear of movement, and lack of confidence years down the road. These types of injuries don't just affect their athletic performance, but their overall activity levels throughout their life (DiFiori et al., 2014).

This evidence lends support to a model of load regulation that bases training load off of growth rather than arbitrary age categories.

Psychological implications of growth-sensitive training

Physical development is inherently linked to psychological development. Periods of significant growth can make athletes feel more self-conscious and aware of their peers. Adolescents who may not be performing up to their physical peak during these growth periods can be subjected to frustration, loss of confidence, and fear of failure.

Training programs that normalize growth variability and emphasize effort, learning, and autonomy help to reduce some of these negative psychological responses (Meyers et al., 2017). But training environments that make athletes feel as though their worth is solely based on their performance can cause some serious issues. These issues range from temporary stress to burnout and dropout.

Is temporary reduction or modification of training necessary?

Alteration to training load may be warranted during periods of accelerated growth and maturation. Emerging research indicates that high training volumes, repetitive loading, and inadequate recovery during periods of peak height velocity may contribute to an increased risk of overuse injuries and movement impairment in youth athletes. Withdrawal from sport does not have to be the method used to alter training load.

Participation in training that is technically and developmentally sound may have benefits for skill development and psychological growth during adolescence. Movement quality, coordination, technical skills, flexibility, and recovery should be emphasized during these critical periods of development while competitive stress and high-volume training may be reduced.

Implications for coaches & sport organizations

Ideally new information like this would cause coaches to throw out all of their training programs and start over. But realistically coaches, sport organizations, and parents are stuck in a system that reinforces poor

training practices. Programs don't change because they've been around for a long time, institutions don't change because "*that's how they've always done it*," and coaches don't change because win-loss records do (Cumming et al., 2017).

As long as these things continue to be the case, there will be coaches trying their best to provide athletes with developmentally appropriate training but feeling defeated by outside sources.

Early specialization can be thought of as a high training volume in one sport prior to pubertal maturation , typically exclusive of other forms of physical activity. Although early specialization may give children who specialize an advantage early on in their athletic careers (primarily those who mature early), longitudinal studies have found that early sport specialists are more likely to suffer from injury, burnout, psychological stress and dropout from sport.

From a biological perspective,, early specialization loads skeletal and neuromuscular structures during windows of increased biological growth. Sport-specific stresses, such as directional changes, jumping, sprints, and movements on one leg place large amounts of force on immature structures such as growth plates and connective tissue. If continued without proper rest these high amounts of stress can alter normal bone modelling, which coupled with improper technique can lead to ongoing musculoskeletal issues later in development. This problem is prevalent in boys between the ages of 13–15 due to their increased training load from playing sports at this age coupled with their peak height velocity. Conversely, research has shown that exposure to a variety of sports during childhood and early adolescence has been shown to promote better coordination into later adolescence and early adulthood. Playing multiple sports promotes consistent loading of the musculoskeletal system, allows for better perceptual motor development and challenges athletes to problem solve in multiple movement scenarios. There is no benefit to early specialization if the goal is to be successful in that sport. Many experts have found that elite athletes actually specialize later than non-elite athletes. For this reason long-term athletic development models recommend waiting on specializing until late adolescence.

Implications for policy, coach education, and athlete retention

Competitive sport programs that group children based on their date of birth alone need to be reformed. Grouping by chronological age does not account for the different rates at which children develop, leaving late matures at a distinct disadvantage. This is especially true in early to mid- adolescence where the late maturing boy is often mistaken for being uncoordinated or not trying hard enough. Education of coaches is one of the easiest ways to try and inform athletes during these sensitive times of growth. Many coaches are not aware of the effects of growth and maturation on athletic performance. If coaches knew how to better identify signs of growth, they could use that information to their advantage when dealing with athletes. Implementing education that focuses on biological age vs. chronological age, monitoring of growth, and training techniques that alter training load based on the athletes' stage of maturation can help to better equip coaches to make informed decisions.

Coaches who understand that many athletes will display poorer coordination or fluctuations in performance are growth are more likely to work with the athlete through these difficult stages (Myer et al., 2015). Ensuring that athletes feel safe and comfortable is one of the best ways to keep them participating in sport. Adolescents who feel as if they are constantly being evaluated on their athletic abilities during these tough stages of growth are more likely to drop out of sport. Sport programs should strive to keep kids active by rewarding them for things other than their athletic ability. If kids are praised during their participation for factors such as learning, improving or even their effort, less kids will quit sports.

 © 2026 ARD Asociación Española

Is it okay to get young athletes injured if they want to become professional?

Ideally, training programs take injury prevention into account and consider periodizing for training load as well as considering general long-term athlete development (LTAD) guidelines. Unfortunately, some youth sport settings have unhealthy values that applaud early specialization and high workload despite the years of research demonstrating that high loads during sensitive periods can contribute to injury risk, burnout, and dropout. Furthermore, early relative age effects in sport can lead to young athletes playing sports who are less mature being at risk for poor psychosocial experiences from negative sporting environments. For example, late-developing athletes may lack confidence from fewer playing opportunities or poor taste coaching with early developers being taken advantage of their physique and not learning proper technique.

Future directions for research and applied practice

There is potential for future work to assess biological age concurrently with biological, psychological and performance variables longitudinally to investigate interactions between maturation and training exposure over time. Future studies may consider following cohorts over time to determine how altering training loads during youth impacts adult performance outcomes, injury rates, and sport attrition rates. Qualitative data from athletes can also be used to contextualize the experiences that athletes face throughout development.

Additionally, future applied work may consider implementing bio-banding, alternative competition structures, and individualized training into youth sport programs as the foundation rather than as an alternative option. If youth sport scientists, coaches, paediatric sport medicine doctors and policymakers work together to bridge the gap between research and practice, we can design better future studies and start moving toward a youth sport system that is based on evidence.

Remember kids grow, plan their training accordingly. Although female athletes may mature earlier than males, they both grow and should be trained differently than elite adult athletes.

As coaches, parents, and mentors we can control the training that we are giving our athletes. If we continue to train young athletes like elite adult athletes we are putting them at risk for injury and early dropout. By programming appropriately for their age we can help ensure that athletes can have long and healthy careers in the sports they love.

Growth, training loads, and injury potential

This article highlighted that growth isn't the injury cause, but when growth is paired with excessive or inappropriate training loads can increase injury risk. During growth spurts athletes can get much taller overnight and their limbs can lengthen rapidly. This drastically changes an athlete's biomechanics, coordination, and how their body handles load through muscles, bones, and tendons.

If an athlete's training load (intensity, volume, and competition load) does not decrease during these time periods while they are growing, they become susceptible to overuse injuries, growth plate injuries, and increased neuromuscular risk.

Maturation is characterized by different patterns in boys and girls. Girls mature faster than boys. Girls start puberty earlier and finish puberty earlier as well. In girls there is a rapid development of height, weight, and skeletal age between ages 8 and 13 years old. Girls have a performance advantage over their younger counterparts and opposite sex early on due to advanced coordination and size. Girls also experience higher risks of ligament injury due to increased laxity during this time of accelerated growth. Hormonal changes also impact training load tolerance and recovery. Boys experience this rapid development later than girls which

can shift the age of these pros and cons. Increased muscle mass and strength continues into young adulthood for males. Training could be adjusted based on sex to avoid unfair workload expectations. If biological sex is considered a moderator for maturation there can be more individualized training and development can occur while reducing the risk of overloading young athletes.

The article is not implying that youth athletes should take time off from their sport to allow themselves to grow, especially boys who are between the ages of 13-15. What we can do is alter how we train these athletes by appropriately manipulating training load, exercise selection, and competition volume to accommodate their growth (Philippaerts et al., 2006).

Implications for coaching practice

If you coach youth athletes, it is your responsibility to train them in a way that will help them grow as athletes while not risking their health or development. These athletes, just like any other athlete you have coached, want to get better at their sport.

However, just because two athletes are the same age does not mean they are the same maturity level. Two athletes can be the same chronological age but one may still be growing while the other has stopped growing. As a coach, you should:

- Keep track of your athletes growth and maturation.
- Take unnecessary training load out of their workouts when they are growing.
- Use growth as an opportunity to really focus on athletes technique and decision making.
- Help your athletes move better.
- Ensure your athletes are in a positive environment that values their mental health.

Not only can this decrease injury and dropout but also can allow athletes to continue to play the sport they love for longer.

Directions for future research include conducting prospective longitudinal studies that combine data on biological growth and maturation, biological assessments, psychological measures, and athletic performance outcomes. This will allow researchers to better examine the relationship between maturation and training over time. Longitudinal studies can also provide insight into how different training interventions during adolescence may impact performance outcomes, injury rates, and sport participation later in life. Researchers should also consider using a mixed-methods approach that incorporates qualitative interviews with athletes to better understand their experiences. From a practical standpoint, sport organizations can consider adopting bio-banding, tournament play, and individualized training as the normative approach instead of utilizing them as an alternative method. Sport scientists, coaches, paediatricians, and sport governing bodies should work together to implement findings into practice.

Implications for parents and sport organizations

Parents can help by helping set reasonable expectations for their children. The growth phases that we talked about can cause athletes to have good days and bad days. This unknown fluctuation in performance can be frustrating to both the athlete and parents. As parents we want our kids to be the best they can be, but setting unrealistic expectations can cause stress to the athlete and lead to burnout.

Sport federations and academies should take a look at their current early age sport specializations and high competition volumes. In many sports, athletes are selected very early on and rewarded for being talented when they are young. Naturally, this tends to select for athletes who mature early and not necessarily who

 © 2026 ARD Asociación Española

will be the best athlete. Until sport federations and academies change their athlete groupings to be based on maturity and limit the amount of competition that youth athletes are facing during growth sensitive times, they are failing their athletes.

Ethical responsibility in youth sport training and selection

This article took a lot of different articles and combined their information to get a better understanding of how growth affects training. However, there is always more research that can be done on a topic. Some suggestions for future research would be:

- Track athletes training load while measuring their growth.
- Look at injuries in male vs female athletes during growth stages.
- Study the effects of training based on athletes maturity level.
- Look at the psychological effects that these growth phases have on athletes.

The current training practices used in youth sport systems place undue emphasis on early performance outcomes at the expense of health and relative age equity. There is an ethical obligation to protect the health and well-being of youth athletes and allow for their long-term development. Selecting against late bloomers and training athletes through growth stages without considering individual rates of maturation has ethical implications of justice, fairness, and autonomy. Youth athletes are unable to fully grasp what high training loads will mean for their development in the long-term and do not understand why they may not make a team or play as much during growth years. For this reason, there is an ethical responsibility of the adults in youth sport to make decisions in the athlete's best interest.

To practice ethically in youth sport there are many considerations. Parents and coaches should be transparent with their athletes about their decision-making. They should continue to monitor athletes' growth and overall well-being. Parents, coaches, and sport organizations should avoid putting pressure on young athletes to play through growth or tie their self-worth to sport performance. Athletes should not perceive taking time off during a growth spurt as being unfair to the team or a sign of weak work ethic. If we can alter coaching certification programs and the policies of youth sport to think more ethically, we can change the culture of youth sport to one that values human development.

CONCLUSION

The purpose of this article was to share important information about growth and development as it relates to safely and successfully participating in sports. The research discussed within this article reaffirms the notion that growth and development are imperative when understanding how to safely and successfully participate in sports at a young age. Growth and development vary between boys and girls, with girls experiencing their growth spurt and skeletal maturity at a younger age (around 8-13 years old) while boys continue to develop later into their teenage years and even into early adulthood. By not taking this into consideration, you open young athletes up to unfair training expectations and potential injuries that could have long-lasting effects.

While some may see this as an advantage to push young girls to perform at higher levels for longer amounts of time, there is a negative feedback loop that occurs when girls stop developing at a young age. What you may see as a performance plateau or physical disadvantage during adolescent years (especially in boys 13–15 years old) is not a reason to give up on the child. Instead, we know that too much stress from training loads, early specialization, and chronic overuse can lead to injury (fatigue to bone), affect final height, and alter musculoskeletal health. A better solution would be to scale the workload (developmentally appropriate training) versus quitting the sport.

As you can see, youth sport needs to move from a win-at-all-cost philosophy to a long-term development approach. Parents, coaches, and sport organizations should all take responsibility for providing proper training loads and recovery based on the athlete's level of development and not their age. If we can keep young athletes healthy and training smart we can continue to see them grow not only as athletes but also as lifelong enthusiasts of sport.

Summary of key findings

In conclusion, this article found that females mature faster than males between the ages of 8–13 years old. However, males experience more growth than females between the ages of 13-15 years old and continue to develop physically into their early twenties.

Since this information directly relates to training load management, injury susceptibility, athlete well-being, and long-term development, we can better cater our training practices to athletes based on this information. For example, many coaches misinterpret early success in female athletes and early maturing boys as signs of talent. On the contrary, many coaches may misinterpret the physical setbacks that some athletes experience during growth spurts as a lack of motivation or poor work ethic.

Adolescents experience significant changes in height, weight, and limb length that affect biomechanics and muscle activation patterns (Rogol et al., 2000). Adolescents also experience phases of rapid growth that can result in transient decreases in motor skills, joint stability, and movement efficiency. Applying high training loads during these times without proper accommodation can increase risk of overuse injury, movement breakdown, and fatigue. Additionally, athletes are more susceptible to these effects during periods of rapid growth so it is important to take consideration of biological age versus chronological age when developing training programs. While being easily injured during growth may seem like a weakness, it is part of the natural development process (Till et al., 2017). Coaches should not perceive an athlete hitting a growth spurt as weakness or lack of motivation. Adding more stress on the athlete while they are more prone to injury can lead to increased risk of both physical and mental injury. Load management, movement assessments, and tracking growth should all be implemented into training to help reduce unnecessary stress and risk of injury while allowing athletes to reach their full potential.

In conclusion, this article found that females mature faster than males between the ages of 8–13 years old. However, males experience more growth than females between the ages of 13-15 years old and continue to develop physically into their early twenties.

Since this information directly relates to training load management, injury susceptibility, athlete well-being, and long-term development, we can better cater our training practices to athletes based on this information. For example, many coaches misinterpret early success in female athletes and early maturing boys as signs of talent. On the contrary, many coaches may misinterpret the physical setbacks that some athletes experience during growth spurts as a lack of motivation or poor work ethic.

Adolescents experience significant changes in height, weight, and limb length that affect biomechanics and muscle activation patterns. Adolescents also experience phases of rapid growth that can result in transient decreases in motor skills, joint stability, and movement efficiency. Applying high training loads during these times without proper accommodation can increase risk of overuse injury, movement breakdown, and fatigue. Additionally, athletes are more susceptible to these effects during periods of rapid growth so it is important to take consideration of biological age versus chronological age when developing training programs. While being easily injured during growth may seem like a weakness, it is part of the natural development process.

 © 2026 ARD Asociación Española

Coaches should not perceive an athlete hitting a growth spurt as weakness or lack of motivation. Adding more stress on the athlete while they are more prone to injury can lead to increased risk of both physical and mental injury. Load management, movement assessments, and tracking growth should all be implemented into training to help reduce unnecessary stress and risk of injury while allowing athletes to reach their full potential.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The author retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Baxter-Jones, A. D. G., Eisenmann, J. C., & Sherar, L. B. (2005). Controlling for maturation in pediatric exercise science. Pediatric Exercise Science, 17(1), 18-30. https://doi.org/10.1123/pes.17.1.18

Beunen, G. P., & Malina, R. M. (2008). Growth and biological maturation: Relevance to athletic performance. In The Young Athlete (Vol. 3, pp. 3-17). https://doi.org/10.1002/9780470696255.ch1

Brenner, J. S. (2016). Sports specialization and intensive training in young athletes. Pediatrics, 138(3), e20162148. https://doi.org/10.1542/peds.2016-2148

Caine, D., DiFiori, J., & Maffulli, N. (2006). Physeal injuries in children's and youth sports: Reasons for concern? British Journal of Sports Medicine, 40(9), 749-760. https://doi.org/10.1136/bjsm.2005.017822

Côté, J., Baker, J., & Abernethy, B. (2007). Practice and play in the development of sport expertise. In G. Tenenbaum & R. C. Eklund (Eds.), Handbook of sport psychology (pp. 184-202). Wiley. https://doi.org/10.1002/9781118270011.ch8

Cumming, S. P., Lloyd, R. S., Oliver, J. L., Eisenmann, J. C., & Malina, R. M. (2017). Bio-banding in sport: Applications to competition, talent identification, and strength and conditioning of youth athletes. Strength and Conditioning Journal, 39(2), 34-47. https://doi.org/10.1519/SSC.0000000000000281

DiFiori, J. P., Benjamin, H. J., Brenner, J., Gregory, A., Jayanthi, N., Landry, G. L., & Luke, A. (2014). Overuse injuries and burnout in youth sports. British Journal of Sports Medicine, 48(4), 287-288. https://doi.org/10.1136/bjsports-2013-093299

Ford, P. R., De Ste Croix, M., Lloyd, R. S., Meyers, R., Moosavi, M., Oliver, J., Till, K., & Williams, C. A. (2011). The long-term athlete development model: Physiological evidence and application. Journal of Sports Sciences, 29(4), 389-402. https://doi.org/10.1080/02640414.2010.536849

Frisch, R. E. (1994). Body fat, menarche, fitness and fertility. Human Reproduction, 9(12), 2272-2278. https://doi.org/10.1093/oxfordjournals.humrep.a138427

Hewett, T. E., Myer, G. D., & Ford, K. R. (2006). Anterior cruciate ligament injuries in female athletes. The American Journal of Sports Medicine, 34(2), 299-311. https://doi.org/10.1177/0363546505282619

Lloyd, R. S., & Oliver, J. L. (2012). The youth physical development model. Strength and Conditioning Journal, 34(3), 61-72. https://doi.org/10.1519/SSC.0b013e31825760ea

Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). Growth, maturation, and physical activity (2nd ed.). Human Kinetics. https://doi.org/10.5040/9781492596837

Malina, R. M., Rogol, A. D., Cumming, S. P., Coelho e Silva, M. J., & Figueiredo, A. J. (2015). Biological maturation of youth athletes. British Journal of Sports Medicine, 49(13), 852-859. https://doi.org/10.1136/bjsports-2015-094623

Meyers, R. W., Oliver, J. L., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2017). The influence of maturity status on sprint speed and power in youth soccer players. Journal of Strength and Conditioning Research, 31(2), 439-445. https://doi.org/10.1519/JSC.0000000000001507

Myer, G. D., Jayanthi, N., DiFiori, J. P., Faigenbaum, A. D., Kiefer, A. W., Logerstedt, D., & Micheli, L. J. (2015). Sports specialization, part I: Does early sports specialization increase negative outcomes and reduce the opportunity for success in young athletes? Sports Health, 7(5), 437-442. https://doi.org/10.1177/1941738115598747

Philippaerts, R. M., Vaeyens, R., Janssens, M., Van Renterghem, B., Matthys, D., Craen, R., Bourgois, J., Vrijens, J., Beunen, G., & Malina, R. M. (2006). The relationship between peak height velocity and physical performance in youth soccer players. Journal of Sports Sciences, 24(3), 221-230. https://doi.org/10.1080/02640410500189371

Rogol, A. D., Clark, P. A., & Roemmich, J. N. (2000). Growth and pubertal development in children and adolescents. Journal of Adolescent Health, 26(2), 75-89.

Rowland, T. W. (2005). Children's exercise physiology (2nd ed.). Human Kinetics.

Till, K., Jones, B., Geeson-Brown, T., & Highton, J. (2017). Maturity-associated variation in training load in youth athletes. European Journal of Sport Science, 17(5), 626-635.

Vaeyens, R., Lenoir, M., Williams, A. M., & Philippaerts, R. M. (2008). Talent identification and development in sport. Sports Medicine, 38(9), 703-714. https://doi.org/10.2165/00007256-200838090-00001

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

REVIEW ARTICLE

Punching performance, physiological responses and lower-limb neuromuscular characteristics in boxing: A systematic review

Giuseppe Penna . *Faculty of Kinesiology. University of Split. Split, Croatia.*
Igor Jelaska. *Faculty of Kinesiology. University of Split. Split, Croatia.*
Gaetano Altavilla. *Department of Education Sciences and Sport. Pegaso Online University. Naples, Italy.*

ABSTRACT

Introduction: Boxing is a high-intensity intermittent sport in which performance depends on the ability to produce effective punches and sustain their intensity during repeated efforts. Punching performance, physiological responses, and lower-limb neuromuscular characteristics are key factors in understanding boxing-specific performance; however, current evidence remains fragmented. Objective: To systematically analyse the literature on punching performance, physiological responses, and lower-limb neuromuscular characteristics in boxing, and to examine the relationships between these variables. Methods: The review followed PRISMA 2020 guidelines and was structured according to the PICOS model. Literature searches were conducted in PubMed and Google Scholar for studies published between January 2010 and January 2026. After screening titles, abstracts, and full texts, 46 studies were included in the qualitative synthesis. Results: A high methodological heterogeneity was observed across study designs, samples, protocols, measurement tools, and outcomes. Punching performance was the most investigated domain, while physiological responses mainly included heart rate, oxygen uptake, blood lactate, and perceived exertion. Lower-limb neuromuscular characteristics were less explored, and no study directly assessed muscle–tendon stiffness. Conclusions: Current evidence remains fragmented and future studies should adopt integrated approaches to improve performance assessment and training prescription in boxing.

Keywords: sports performance; punch impact; heart rate; oxygen uptake; muscle–tendon stiffness; explosive strength.

Cite this article as:
Penna, G., Jelaska, I., & Altavilla, G. (2026). Punching performance, physiological responses and lower-limb neuromuscular characteristics in boxing: A systematic review. *Journal of Human Sport and Exercise, 21*(4), 1301-1320. https://doi.org/10.55860/9304ke09

Corresponding author. *Faculty of Kinesiology. University of Split. Teslina 6. 21 000 Split, Croatia.*
E-mail: giuseppe.penna85@gmail.com
Submitted for publication May 07, 2026.
Accepted for publication June 22, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/9304ke09

INTRODUCTION

Boxing is a combat sport in which performance depends on the interaction of technical, tactical, and physical components (Ceruso et al., 2019), as well as on the ability to execute effective offensive and defensive actions during a bout (Chaabène et al., 2015; Slimani et al., 2017). In this context, competitive success is closely associated with the ability to sustain high match intensity, as in many other sports (Di Lascio et al., 2026; D'Isanto et al., 2022), and to repeatedly produce fast and powerful punches throughout the entire duration of the contest (Chaabène et al., 2015; Finlay et al., 2023; Wilson et al., 2020). The literature also describes boxing as a high-intensity intermittent sport characterised by alternating explosive actions and short, often incomplete, recovery periods (Franchini, 2020; Slimani et al., 2017; Thomson & Lamb, 2017b). Studies conducted during boxing-specific protocols have highlighted high physical and technical demands, with repeated high-intensity offensive and defensive actions across all rounds of competition (Finlay et al., 2018; Thomson & Lamb, 2017a, 2017b; Xu et al., 2025).

Within this performance model, increasing attention has been directed towards the assessment of indicators of punching performance (Lenetsky et al., 2013; Loturco et al., 2016). Variables such as punch impact force, punch velocity, and punch power, as well as additional parameters derived from measurement devices, have been used to objectively describe the athlete's ability to produce potentially more effective strikes in performance terms (Dunn et al., 2022; Lenetsky et al., 2013; Pinto et al., 2025). Several studies suggest that higher-level boxers tend to produce greater mechanical output during punching, confirming the relevance of indicators of punching performance in the evaluation of boxing performance (Loturco et al., 2016; Pinto et al., 2025). However, the available literature shows marked methodological heterogeneity, as indicators of punching performance has been assessed through maximal single-punch tests, repeated or continuous boxing-specific punching protocols—including simulated bouts, sparring, pad work, and heavy-bag training—as well as protocols structured in rounds or with an intermittent work organisation, and boxing-specific incremental tests, using different tools such as force platforms, instrumented targets, dummies, sensor-equipped punching bags, or systems based on accelerometers and inertial sensors (Finlay et al., 2018; Liu et al., 2022; Venckunas et al., 2022; Xu et al., 2025). This variability limits direct comparability between studies and makes a unified synthesis of the available evidence difficult.

In parallel, boxing imposes a high physiological load (Franchini, 2020; Slimani et al., 2017). Numerous studies have reported elevated values of heart rate, oxygen uptake, and blood lactate concentration during simulated bouts and sport-specific training, highlighting substantial physiological demands sustained over time (Arseneau et al., 2011; de Lira et al., 2013; El-Ashker et al., 2018; Ghosh, 2010; Venckunas et al., 2022). It has also been observed that the magnitude of physiological responses varies according to exercise intensity, suggesting a relationship between physiological load and sport-specific performance in boxing (Finlay et al., 2018; Thomson and Lamb, 2017b; Usher and Babraj, 2024). Nevertheless, studies that jointly examine indicators of punching performance and physiological responses during boxing-specific protocols remain limited, resulting in only partial understanding of the interactions between internal load and performance output.

A further area of interest concerns lower-limb neuromuscular characteristics. Although boxing is frequently associated with the upper limbs, available evidence indicates that punching effectiveness depends on the coordinated involvement of the whole body and on the ability to generate force from the ground up (Lenetsky et al., 2015; Stanley et al., 2018). In particular, lower-limb explosive strength parameters such as jump height, force, power, rate of force development (RFD), and ground reaction force (GRF) have been associated in some studies with indicators of punching performance (Chottidao et al., 2022; Dunn et al., 2022; Loturco et

 © 2026 ARD Asociación Española

al., 2016; Loturco et al., 2021). In parallel, growing attention has been directed towards lower-limb muscle-tendon stiffness, a property of the muscle-tendon unit associated with the ability to optimise force production during dynamic and explosive actions (Brazier et al., 2019; Wdowski et al., 2023). However, in boxing the available evidence remains limited, and no studies have directly examined lower-limb muscle-tendon stiffness in relation to punching performance (Chottidao et al., 2022).

Overall, the literature appears fragmented: indicators of punching performance represent the most extensively investigated domain, whereas physiological responses and lower-limb neuromuscular characteristics have often been studied separately, with limited integration with indicators of punching performance. This limits a comprehensive understanding of the main components of boxing performance and their possible interactions.

From a broader theoretical perspective, boxing performance may be interpreted as the result of the dynamic interaction between mechanical output during punching, physiological load, and lower-limb neuromuscular characteristics. This perspective suggests that the ability to produce high levels of punching performance does not depend exclusively on the technical characteristics of the movement, but also on the integration between physiological responses and lower-limb neuromuscular characteristics involved in the production and maintenance of performance. In this context, a multidimensional interpretation of boxing performance could contribute to a deeper understanding of the relationships between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics involved in the production and maintenance of performance during intermittent high-intensity efforts (Franchini, 2020; Loturco et al., 2016; Venckunas et al., 2022).

In light of these considerations, the present systematic review aims to analyse the available evidence regarding indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics in boxing, as well as to examine the potential relationships between these domains. The aim is to identify methodological convergences, major knowledge gaps, and future research perspectives. Furthermore, the integration of these domains could support the development of more comprehensive methodological models for the analysis of boxing performance, contributing to the definition of a more comprehensive theoretical framework applicable to future research, with potential applications in athlete assessment, monitoring, and training prescription.

MATERIAL AND METHODS

Study design and reporting guidelines

The present review was conducted as a systematic review with qualitative synthesis, in accordance with the PRISMA 2020 guidelines (Page et al., 2021), and the research question was structured according to the PICOS model (Population, Intervention/Exposure, Comparator, Outcomes, and Study design). Considering the heterogeneity of study designs, experimental protocols, and variables reported in the included studies, no meta-analysis was performed.

Information sources and search strategy

The literature search was conducted using the PubMed and Google Scholar databases, limiting the time frame to publications between January 2010 and January 2026. For PubMed, the search was performed using combinations of keywords relevant to the aims of the review, combined through Boolean operators (AND, OR) and the resulting records were exported. For Google Scholar, the search was conducted using

keyword combinations consistent with the same aims; for each combination, the first 100 results were screened, and records considered relevant were exported. Overall, 327 records were identified.

Research question and PICOS model

The research question was defined a priori according to the PICOS model.

Population

Boxers, with no restrictions regarding sex, competitive level, or age, provided they were active participants in training or competitive settings.

Intervention/Exposure

Exposure to different types of punching protocols, classified as: (i) maximal single-punch tests; (ii) repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, heavy-bag training, as well as protocols structured in rounds or with an intermittent exercise format; (iii) boxing-specific incremental tests.

Comparator

Between-group comparisons and/or within-subject comparisons across experimental conditions.

Outcomes

(i) indicators of punching performance; (ii) physiological responses; (iii) lower-limb neuromuscular characteristics.

Study design

Observational and experimental studies reporting original data, including cross-sectional, pre–post, repeated-measures, and case-study designs.

Eligibility criteria

Studies were considered eligible if they met the following criteria:

(i) *Population*: Boxers, with no restrictions regarding sex, competitive level, or age, provided they were active participants in training or competitive settings.
(ii) *Study design*: Observational and experimental studies reporting original data, including cross-sectional, pre–post, repeated-measures, and case-study designs.
(iii) *Outcomes*: Indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics.
(iv) *Protocols*: Use of valid protocols classified as: maximal single-punch tests; repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, heavy-bag training, as well as protocols structured in rounds or with an intermittent exercise format; and boxing-specific incremental tests.

Studies were excluded if the full-text was unavailable, if they reported non-boxing-specific outcomes, if outcomes were not relevant to the aims of the review, or if they did not provide original data (e.g., reviews, editorials, or conference abstracts).

Study selection

All identified records were imported into reference management software (Zotero, Corporation for Digital Scholarship, Vienna, VA, USA), within which duplicates were identified and removed prior to the screening phase.

 © 2026 ARD Asociación Española

A total of 327 records were initially identified. After duplicate removal (n = 174), 153 records underwent title and abstract screening. At this stage, 78 articles were excluded.

Subsequently, 75 articles were assessed in full-text to determine eligibility. Of these, 46 studies were included in the final qualitative synthesis, whereas 29 were excluded for the following reasons: full-text unavailable (n = 15), non-boxing-specific outcomes (n = 10), and outcomes not relevant to the aims of the review (n = 4).

The study selection process is summarised in the PRISMA 2020 flow diagram (Figure 1).

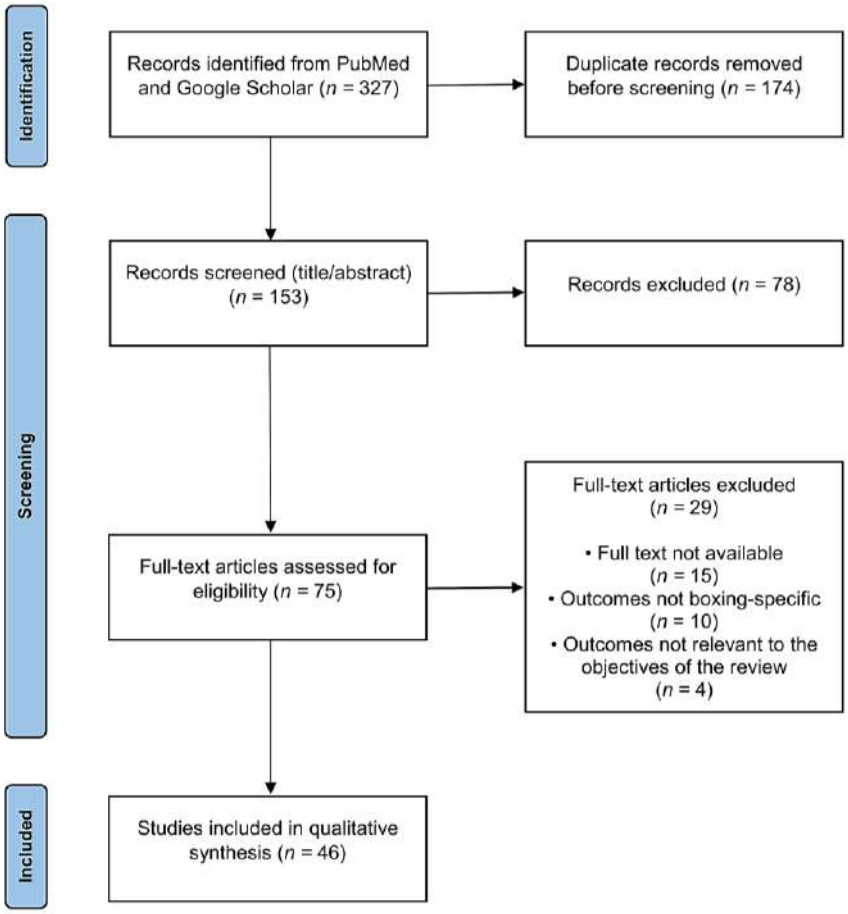


Figure 1. PRISMA 2020 flow diagram of the study selection process.

Data extraction

Data extraction was conducted systematically for all included studies. For each article, the following information was collected:

(i) General study characteristics (authors, year of publication, study design, and setting);
(ii) Sample characteristics (sample size, sex, competitive level, age, and sporting experience, where reported);
(iii) Description of the protocols used (type, structure, and applied context);
(iv) Indicators of punching performance;
(v) Physiological responses;
(vi) Lower-limb neuromuscular characteristics.

Qualitative synthesis

Given the methodological heterogeneity of the included studies, the synthesis of results was conducted using a structured qualitative approach.

Studies were analysed descriptively, with particular attention to sample characteristics, protocols adopted, indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics.

The synthesis was organised according to a systematic framework aimed at identifying convergences, divergences, and gaps within the literature, while ensuring internal consistency and traceability of the evidence supporting the identification of research gaps.

RESULTS

Study selection process

The study selection process is illustrated in Figure 1. Overall, 327 records were identified through searches of the PubMed and Google Scholar databases. After duplicate removal (n = 174), 153 records underwent title and abstract screening, resulting in the exclusion of 78 non-relevant studies.

Subsequently, 75 articles were assessed in full-text to determine eligibility. Of these, 29 studies were excluded for the following reasons: full-text unavailable (n = 15), non-boxing-specific outcomes (n = 10), and outcomes not relevant to the aims of the review (n = 4).

At the end of the selection process, a total of 46 studies were included in the qualitative synthesis of the present systematic review.

Study characteristics

The main characteristics of the included studies (n = 46) are summarised in Table 1. Overall, the included studies were published between 2010 and 2025 and involved boxers of different sex, competitive level, and age categories, with a predominance of male amateur and elite samples.

The most frequently represented study designs were observational, predominantly cross-sectional, and experimental, including pre–post and repeated-measures designs. The protocols employed mainly comprised maximal single-punch tests, repeated or continuous boxing-specific punching protocols, and boxing-specific incremental tests. In some studies, these protocols were incorporated into training interventions or experimental conditions aimed at evaluating acute or chronic adaptations in boxing-specific performance.

The outcomes analysed primarily concerned indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics.

DISCUSSION

Descriptive synthesis

Overall, the findings highlight marked heterogeneity among the included studies in terms of study designs, sample characteristics, experimental protocols, measurement tools, and outcomes analysed. This variability reflects a methodological landscape that remains fragmented and limits direct comparison of the available findings.

 © 2026 ARD Asociación Española

Table 1. Characteristics of the included studies (n = 46).

Study (First author, year)	Study design	Sample (n)	Sex	Competitive level
Ghosh, 2010	Repeated-measures	6	Male	Elite
Arseneau et al., 2011	Cross-sectional	9	Male	Amateur
de Lira et al., 2013	Cross-sectional	10	Male – Female	Highly trained
Loturco et al., 2016	Cross-sectional	15	Male – Female	Elite
Cunniffe et al., 2017	Repeated-measures	6	Male	Elite
Hukkanen and Häkkinen, 2017	Repeated-measures	7	Male	National
Thomson and Lamb, 2017a	Experimental	28	Male	Amateur
Thomson and Lamb, 2017b	Experimental	28	Male	Amateur
El-Ashker et al., 2018	Repeated-measures	11	Male	Elite
Finlay et al., 2018	Experimental	9	Male	Elite
Kamandulis et al., 2018	Experimental	18	Male	Experienced amateur
Kim et al., 2018	Experimental	15	Male	Elite
Lenetsky et al., 2018	Cross-sectional	20	Male	Trained vs untrained
Finlay et al., 2020	Experimental	14	Male	Elite
Herrera-Valenzuela et al., 2021	Experimental	16	Male	National
Loturco et al., 2021	Experimental	8	Male	Elite
Brown et al., 2022	Cross-sectional	22	Male	Amateur
Bu, 2022	Experimental	20	Female	Elite
Chottidao et al., 2022	Experimental	24	Male	Junior amateur
Dunn et al., 2022	Cross-sectional	28	Male	Highly trained
Finlay et al., 2022	Experimental	10	Male	Elite
Liu et al., 2022	Cross-sectional	16	Male	Elite and junior
Venckunas et al., 2022	Cross-sectional	11	Male	High-level amateur
Chwała et al., 2023	Cross-sectional	18	Male	Competitive
Maciel et al., 2023	Cross-sectional	12	Male – Female	Amateur
Merlo et al., 2023	Cross-sectional	227	Male – Female	Amateur
Cui et al., 2024a	Experimental	24	Female	Elite
Cui et al., 2024b	Experimental	24	Male	Elite
de Oliveira et al., 2024	Cross-sectional	10	Male	Competitive
Finlay et al., 2024	Experimental	10	Male	Elite
Liu et al., 2024	Experimental	24	Female	Elite
Mosler et al., 2024a	Cross-sectional	13	Male	Advanced
Mosler et al., 2024b	Cross-sectional	13	Male	Advanced
Niu et al., 2024	Experimental	37	Female	Elite
Usher and Babraj, 2024	Cross-sectional	10	Male	Professional
Venckunas et al., 2024	Cross-sectional	12	Male	Elite
Wu et al., 2024	Cross-sectional	174	Male	Elite
Finlay, 2025	Case study	3	Male	Elite
Jin et al., 2025	Experimental	18	Male	Amateur
Kacprzak et al., 2025	Cross-sectional	30	Male	Trained
Liu et al., 2025	Experimental	29	Male	Elite
Pinto et al., 2025	Cross-sectional	69	Male	Practitioners
Sánchez-Ramírez et al., 2025	Experimental	29	Male	Amateur
Singh et al., 2025	Experimental	30	Male	Adolescents
Söyler et al., 2025	Experimental	20	Male	National
Xu et al., 2025	Experimental	36	Male	Amateur

The literature is characterised by the coexistence of observational studies, predominantly cross-sectional in design (Arseneau et al., 2011; Dunn et al., 2022; Lenetsky et al., 2018), experimental studies (Finlay et al., 2020; Liu et al., 2024; Thomson and Lamb, 2017a, 2017b), and a limited number of case studies (Finlay, 2025).

Samples were heterogeneous with regard to sex, competitive level, and age, with a clear predominance of male amateur and elite boxers and more limited representation of female athletes or mixed samples (Bu,

2022; Cui et al., 2024a, 2024b; Maciel et al., 2023; Merlo et al., 2023). This distribution reduces the generalisability of the available evidence to the wider boxing population.

Substantial differences were also observed in the protocols adopted, including maximal single-punch tests, boxing-specific protocols, and boxing-specific incremental tests, which varied in type, structure, and applied context (de Oliveira et al., 2024; Herrera-Valenzuela et al., 2021; Jin et al., 2025).

Additional limitations emerged regarding the measurement tools used, including force platforms, instrumented targets, inertial sensors, accelerometers, heart rate monitors, metabolic analysers, and portable lactate analysers (Brown et al., 2022; Finlay et al., 2022; Liu et al., 2022; Venckunas et al., 2024). Although these tools have expanded the possibilities for performance monitoring, their methodological heterogeneity restricts direct comparison across studies.

The outcomes analysed mainly included indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics (Brown et al., 2022; Finlay et al., 2024; Wu et al., 2024). However, most studies focused on indicators of punching performance and physiological responses, whereas fewer investigations examined lower-limb neuromuscular characteristics. In particular, no study reported direct measurements of lower-limb muscle-tendon stiffness.

Overall, these findings suggest the need for methodologically integrated approaches capable of jointly analysing the principal components of boxing performance.

Qualitative synthesis

Punching performance

The included literature assigned a central role to indicators of punching performance, which were considered the principal reference for the evaluation of sport-specific performance in boxing. From a qualitative perspective, punching performance was examined through a heterogeneous set of indicators, mainly including punch impact force, punch velocity, and punch power (Cui et al., 2024a, 2024b; Jin et al., 2025; Liu et al., 2024).

Studies assessed punching performance in different experimental contexts. A substantial proportion of the literature employed maximal single-punch tests, generally performed using force platforms, instrumented targets, dummies, sensor-equipped punching bags, or systems based on accelerometers and inertial sensors (Kamandulis et al., 2018; Kim et al., 2018; Liu et al., 2022; Sánchez-Ramírez et al., 2025; Söyler et al., 2025). In other studies, attention shifted towards repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, and heavy-bag training, as well as protocols structured in rounds or with an intermittent work organisation, within which punching performance was also examined in relation to its changes over time (El-Ashker et al., 2018; Usher & Babraj, 2024; Xu et al., 2025). A further line of evidence concerned boxing-specific incremental tests, in which punching performance was analysed under progressively increasing intensity until exhaustion (de Oliveira et al., 2024; Venckunas et al., 2022).

Overall, the qualitative synthesis suggests that indicators of punching performance has been investigated both as a maximal expression, particularly in maximal single-punch tests, and as an expression of mechanical output during repeated or prolonged punching efforts typical of boxing-specific protocols. However, marked heterogeneity emerges in the variables considered, protocols adopted, and measurement systems used, which limits direct comparability between studies. Although a general consensus appears regarding the

 © 2026 ARD Asociación Española

importance of indicators of punching performance as a central reference for sport-specific boxing performance, the methodological framework remains fragmented.

Indicators of punching performance therefore represent the most frequently analysed outcomes in the included literature, providing a robust characterisation of punching performance. However, these indicators have mainly been studied as independent variables, with limited integration with other components of performance. In particular, no systematic approaches have emerged that jointly examine indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics, highlighting the need for integrated models capable of providing a more comprehensive description of sport-specific performance in boxing.

Physiological responses

The physiological responses reported in the included literature mainly concerned heart rate, oxygen uptake, blood lactate concentration, and rating of perceived exertion (Chwała et al., 2023; de Lira et al., 2013; Finlay et al., 2018, 2024). These variables were investigated primarily during repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, and heavy-bag training, as well as protocols structured in rounds or with an intermittent work organisation (de Lira et al., 2013; El-Ashker et al., 2018; Ghosh, 2010), and during boxing-specific incremental tests (de Oliveira et al., 2024; Venckunas et al., 2022), aimed at quantifying physiological load during repeated efforts over time.

Regarding the instrumentation used, most studies employed heart-rate monitors for heart-rate assessment, portable or laboratory metabolic analysers for oxygen uptake measurement, and portable analysers for blood lactate determination (Brown et al., 2022; Hukkanen and Häkkinen, 2017; Venckunas et al., 2024). Additional measures were obtained through scales assessing perceived exertion (Thomson and Lamb, 2017a, 2017b; Xu et al., 2025).

Overall, the qualitative synthesis suggests that physiological responses have mainly been investigated as indicators of internal load associated with boxing-specific protocols. However, comparability between studies is limited by the marked heterogeneity of the variables considered, protocols adopted, and instruments employed, resulting in a methodologically fragmented framework.

Furthermore, although the available evidence describes the physiological responses associated with different boxing-specific protocols, these variables have predominantly been analysed independently rather than in direct relation to indicators of punching performance. In this context, no systematic and integrated analyses of the relationships between physiological responses and indicators of punching performance have emerged, highlighting the need for studies capable of simultaneously examining internal load and punching performance during boxing-specific protocols.

Lower-limb neuromuscular characteristics

Lower-limb neuromuscular characteristics were investigated in a still limited number of studies included in the present review, predominantly through explosive strength parameters derived from jump tests, such as the countermovement jump (CMJ) (Cui et al., 2024a; Finlay et al., 2024; Singh et al., 2025), or through maximal strength tests in the squat (1RM) (Kim et al., 2018; Niu et al., 2024; Wu et al., 2024). Among the principal parameters reported were jump height and, in some cases, variables such as force, power, rate of force development (RFD), and ground reaction force (GRF) (Brown et al., 2022; Chottidao et al., 2022; Dunn et al., 2022; Loturco et al., 2016). These parameters were generally considered expressions of lower-limb

explosive capability and, in some studies, were analysed in relation to indicators of punching performance (Dunn et al., 2022; Loturco et al., 2021; Pinto et al., 2025).

With regard to instrumentation, most studies employed force platforms, contact mats, and optoelectronic systems (e.g. Optojump), mainly aimed at assessing lower-limb explosive strength parameters during jump testing (Finlay et al., 2024; Liu et al., 2024; Sánchez-Ramírez et al., 2025).

Table 2. Summary of findings and main limitations of the included studies.

Domain	Variables/ Outcomes	Methods/ Assessment	Main findings	Main limitations
Punching performance	Punch impact force; punch velocity; punch power; impulse; RFD; acceleration; effective mass; number/frequency of punches; cumulative output	Force platforms; instrumented targets; dummies; sensor-equipped punching bags; accelerometers; inertial sensors; video analysis systems; maximal single-punch tests; boxing-specific protocols; incremental tests	Punching performance represents the most extensively investigated domain and has been analysed both as a maximal expression of a single punch and as mechanical output during repeated or continuous punching efforts. This dual perspective allows the description of both maximal capability and performance over time.	The marked heterogeneity in variables considered, protocols adopted, and measurement systems used limits comparability between studies. Outcomes have mainly been analysed as independent variables rather than within integrated models, with limited integration with physiological responses and lower-limb neuromuscular characteristics.
Physiological responses	Heart rate; VO_2; blood lactate; rating of perceived exertion; pulmonary ventilation; respiratory rate; respiratory exchange ratio; muscle oxygenation; skin temperature	Heart-rate monitors; portable or laboratory metabolic analysers; portable lactate analysers; perceived exertion scales; boxing-specific protocols; incremental tests; training interventions	Physiological responses have primarily been investigated as indicators of internal load associated with boxing-specific protocols. Heart rate, VO_2, and blood lactate represent the most frequently investigated variables.	The marked heterogeneity in variables considered, protocols adopted, and instruments used limits comparability between studies. Physiological variables have mainly been analysed independently rather than in direct relation to punching performance, limiting understanding of the interactions between physiological load and sport-specific performance in boxing.
Lower-limb neuromuscular characteristics	Jump height; force; power; RFD; GRF; maximal squat strength	Force platforms; contact mats; optoelectronic systems (e.g. Optojump); CMJ; maximal squat strength tests (1RM)	Lower-limb neuromuscular characteristics have been less frequently investigated and have mainly been assessed through explosive strength parameters derived from jump tests. Some evidence indicates potential associations between selected variables (e.g. jump height, force, power) and indicators of punching performance.	The limited number of studies, the marked heterogeneity of tests used, and the frequent absence of integrated statistical analyses reduce the robustness of conclusions. Integrated analyses between explosive strength parameters and indicators of punching performance remain limited. Furthermore, no direct measurements of lower-limb muscle-tendon stiffness have been reported, nor have integrated approaches jointly examined its relationships with explosive strength and indicators of punching performance.

Note. CMJ = Countermovement Jump; GRF = Ground Reaction Force; 1RM = One-Repetition Maximum; RFD = Rate Of Force Development; VO_2 = Oxygen Uptake.

 © 2026 ARD Asociación Española

Overall, the qualitative synthesis suggests that some lower-limb neuromuscular characteristics, particularly specific explosive strength parameters, may be associated with indicators of punching performance. However, the limited number of studies, the marked heterogeneity of the tests employed, and the frequent absence of integrated statistical analyses reduce the robustness of current conclusions. In most of the included studies, lower-limb neuromuscular characteristics and indicators of punching performance were analysed independently or compared across experimental conditions, without direct assessment of their relationships. Moreover, the current literature does not report studies that have directly examined lower-limb muscle-tendon stiffness in boxing. This absence highlights an important knowledge gap and supports the need for integrated approaches that jointly examine muscle-tendon stiffness, lower-limb explosive strength, and indicators of punching performance. An additional limitation of the present review is the absence of a formal assessment of the methodological quality and risk of bias of the included studies. Therefore, the synthesized evidence should be interpreted while considering the potential methodological variability across studies and the differing robustness of the reported findings. Future systematic reviews should incorporate specific methodological quality assessment tools in order to provide a more accurate estimation of the strength of the available evidence.

To summarise the principal domains of analysis, variables considered, methodological approaches adopted, and main limitations emerging from the present qualitative synthesis, Table 2 is provided.

Towards an integrated model of boxing performance

The evidence emerging from the present review suggests that boxing performance should not be interpreted through the isolated analysis of single variables but rather considered as the result of the interaction between mechanical, physiological, and neuromuscular components. Although indicators of punching performance represents the most extensively investigated domain, the available literature shows limited integration between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics, resulting in a methodological and interpretative framework that remains fragmented.

In boxing, the ability to produce and maintain high levels of punching performance during intermittent high-intensity efforts represents one of the key aspects of sport-specific performance (Finlay et al., 2018; Loturco et al., 2016; Thomson & Lamb, 2017a, 2017b). In this context, physiological responses may be interpreted as expressions of the internal load imposed by the activity and of the athlete's capacity to sustain high-intensity actions over time (Franchini, 2020; Ruddock et al., 2021; Venckunas et al., 2022). Similarly, lower-limb neuromuscular characteristics, particularly explosive strength, may contribute to the production and maintenance of punching performance by influencing the athlete's ability to generate high levels of mechanical output during punching (Dunn et al., 2022; Loturco et al., 2016; Pinto et al., 2025). This interpretation is consistent with contemporary athlete monitoring models, according to which performance emerges from the interaction between external load, internal load, and the athlete's functional capacities. From this perspective, indicators of punching performance may be considered an expression of both external load and sport-specific performance output, whereas physiological responses represent the internal load imposed by the activity.

In parallel, lower-limb neuromuscular characteristics constitute a functional component capable of influencing both the production and maintenance of performance during intermittent high-intensity efforts. Although the available evidence does not allow definitive causal relationships to be established, the findings included in the present review suggest a potential interpretative model. In particular, the increase in physiological load associated with intermittent high-intensity efforts may contribute to the onset of fatigue-related phenomena capable of reducing the expression of lower-limb explosive strength. Such a reduction may compromise the

effective transfer of forces along the kinetic chain and lead to a decrease in punching performance, particularly during the final stages of prolonged protocols or the concluding rounds of a bout. Conversely, superior lower-limb neuromuscular characteristics may contribute to maintaining mechanical output during punching despite the increase in physiological load, thereby supporting performance sustainability over time.

Despite these findings, the included studies have predominantly investigated these domains independently, limiting the understanding of the potential interactions between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics. In particular, the current literature does not yet clarify to what extent physiological responses and lower-limb neuromuscular characteristics may contribute to sport-specific performance in boxing.

An additional relevant aspect concerns lower-limb muscle-tendon stiffness. Although this property has been associated, in other sporting contexts, with the ability to optimize force production during dynamic and explosive actions (Brazier et al., 2019; Wdowski et al., 2023), none of the included studies directly investigated lower-limb muscle-tendon stiffness in boxing. This absence represents a relevant knowledge gap and highlights the need for future studies capable of integrating the analysis of muscle-tendon stiffness with the main lower-limb explosive strength parameters and with indicators of punching performance.

From this perspective, the adoption of multidimensional approaches could contribute to the development of more comprehensive methodological models for the analysis of boxing performance, promoting a deeper understanding of the interactions between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics. An integrated approach could also support the development of assessment, monitoring, and training prescription strategies more specifically oriented toward the demands of boxing performance.

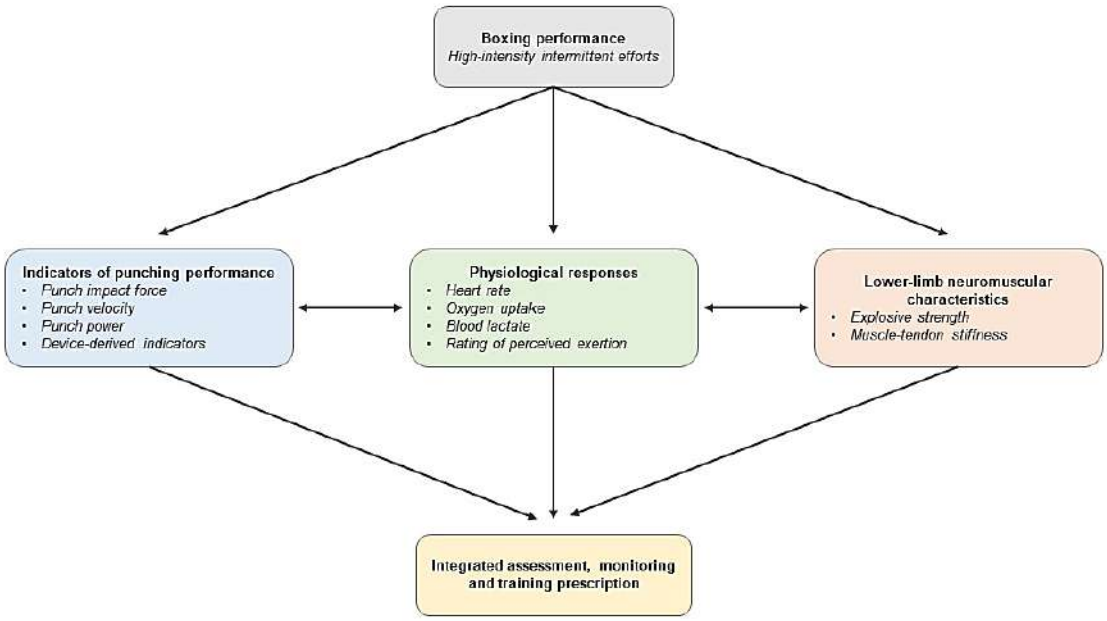


Figure 2. Integrated model of boxing performance.

The proposed integrated perspective is also consistent with recent developments in applied biomechanics, motor control, and performance analytics, disciplines that interpret sport performance as a complex system

 © 2026 ARD Asociación Española

emerging from the interaction between multiple functional components (Raiola et al., 2025). In this context, the integration of mechanical, physiological, perceptual, and neuromuscular variables may support the development of predictive performance models and more comprehensive monitoring procedures, contributing to a multidisciplinary understanding of boxing performance.

The proposed integrated model of boxing performance is summarised in Figure 2.

Scientific and practical implications

The evidence emerging from the present review suggests the need to move beyond approaches based on the isolated analysis of single variables of boxing performance, promoting the development of integrated methodological models. In particular, the integration between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics could contribute to a more comprehensive understanding of the main components of boxing performance and their potential interactions. From this perspective, boxing performance could be interpreted as the result of the interaction between the ability to produce high levels of mechanical output during punching, the ability to sustain the physiological load imposed by the activity, and the lower-limb neuromuscular characteristics involved in the production and maintenance of sport-specific performance.

From a scientific perspective, the findings of the present review highlight the need to develop integrated research approaches capable of simultaneously analysing the mechanical, physiological, and neuromuscular components of boxing performance. Such an approach could contribute to improving the understanding of the mechanisms associated with the production and maintenance of performance, while promoting the development of more comprehensive and in-depth methodological models for performance analysis. Furthermore, the limited integration observed between the different domains suggests the need for greater standardization of experimental protocols, assessment procedures, and measurement tools in order to improve the comparability of the available evidence.

From a practical perspective, an integrated approach could provide useful insights for optimizing boxing-specific training. In particular, the combined analysis of indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics could allow a more comprehensive and in-depth evaluation of the specific demands of boxing performance and of the capacities involved in sustaining and modulating punch intensity during repeated efforts over time. In this context, the use of portable devices and wearable sensors could support the development of more accessible assessment and monitoring procedures, facilitating the transfer of scientific evidence into applied practice.

Finally, the inclusion of boxers with different competitive levels and sex emerges as a particularly important aspect from both scientific and practical perspectives, contributing to addressing a relevant gap in the existing literature, which is often limited to homogeneous samples. The possibility of identifying differences in the mechanical, physiological, and neuromuscular components of performance could contribute to the development of more individualized training and monitoring strategies, oriented toward the specific characteristics of the athlete and the demands of boxing performance.

Future research directions

The evidence emerging from the present review suggests the need to develop future research lines oriented toward integrated and methodologically standardized approaches for the analysis of boxing performance. In particular, it appears necessary to overcome the tendency to investigate indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics separately, promoting studies

capable of simultaneously analysing these domains within boxing-specific protocols. An integrated approach could contribute to a deeper understanding of the interactions between mechanical output during punching, physiological load, and lower-limb neuromuscular characteristics involved in the production and maintenance of performance during intermittent high-intensity efforts.

In particular, future research should develop integrated performance analysis models capable of simultaneously examining the contribution of mechanical, physiological, and neuromuscular variables through longitudinal and multidimensional approaches. Such models could contribute to a better understanding of the causal relationships between the different domains of performance and support the development of monitoring procedures more specifically oriented toward the demands of competitive boxing.

Another relevant aspect concerns the need for greater methodological standardization. The marked heterogeneity observed in experimental protocols, measurement tools, and analysed outcomes limits the comparability of the available evidence. Future research should therefore promote greater standardization of experimental protocols, measurement tools, and outcomes, in order to improve the comparability of evidence and support the development of integrated models for the assessment and monitoring of boxing performance. An important methodological consideration concerns the ecological validity of the protocols used in the available literature. Many studies have assessed different components of boxing performance through isolated tests or highly controlled conditions which, although ensuring high experimental precision, may not fully reflect the physiological, neuromuscular, and technical-tactical demands of actual boxing competition (D'Isanto et al., 2021; Giardullo et al., 2026; Ceruso et al., 2026). Future research should therefore promote the use of protocols that are more representative of competitive conditions, simultaneously integrating mechanical, physiological, and neuromuscular measures within applied and sport-specific contexts.

Particular attention should also be directed toward lower-limb muscle-tendon stiffness. Although evidence from other sporting contexts suggests a potential role of stiffness in force production during dynamic and explosive actions, none of the studies included in the present review reported direct measurements of lower-limb muscle-tendon stiffness in boxing. Future research should therefore further investigate the potential contribution of muscle-tendon stiffness to sport-specific performance in boxing and examine its relationships with the main lower-limb explosive strength parameters and with indicators of punching performance.

Future developments in research should also consider more systematically the differences associated with sex and competitive level. The available literature is still predominantly based on male samples, limiting the generalizability of the evidence. The inclusion of female boxers and mixed samples, as well as athletes from different competitive levels, could contribute to a more comprehensive understanding of the variables associated with boxing performance and their potential interactions.

Finally, future research could further explore the use of portable devices and wearable sensors for performance monitoring in more ecological and applied contexts. The integration of these technologies with multidimensional approaches could support the development of more accessible assessment and monitoring procedures directly transferable to sport practice, contributing to the advancement of scientific knowledge and practical applications in boxing and, potentially, in other combat sports.

CONCLUSIONS

The present systematic review highlighted that indicators of punching performance represent the most extensively investigated domain within the boxing literature, whereas physiological responses and lower-limb

 © 2026 ARD Asociación Española

neuromuscular characteristics are still analysed in a relatively limited and frequently independent manner. Overall, the available evidence shows marked methodological heterogeneity in experimental protocols, measurement tools, and analysed outcomes, limiting comparability across studies and the possibility of developing an integrated understanding of boxing performance.

Current evidence suggests that boxing performance should be interpreted as the result of the interaction between the ability to produce high levels of mechanical output during punching, the ability to sustain the physiological load imposed by the activity, and the lower-limb neuromuscular characteristics involved in the production and maintenance of performance during intermittent high-intensity efforts. However, the limited integration observed between these domains still represents a relevant gap within the scientific literature.

Particular attention emerges regarding lower-limb neuromuscular characteristics. Although explosive strength has been associated in some studies with indicators of punching performance, none of the included studies reported direct measurements of lower-limb muscle-tendon stiffness in boxing. This absence highlights a relevant and still underexplored area of research and suggests the need to further investigate the potential contribution of muscle-tendon stiffness to sport-specific performance in boxing.

In this perspective, integrated and multidimensional approaches capable of simultaneously analysing indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics appear necessary. Such approaches could contribute to a more comprehensive understanding of the main components of boxing performance, support the development of integrated methodological models for performance assessment and monitoring, and provide useful insights for optimizing boxing-specific training.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Giuseppe Penna. Methodology: Giuseppe Penna, Igor Jelaska. Formal analysis: Gaetano Altavilla. Investigation: Giuseppe Penna. Data curation: Giuseppe Penna, Igor Jelaska. Writing – original draft: Giuseppe Penna. Writing – review & editing: Igor Jelaska. Supervision: Gaetano Altavilla.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and

readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Arseneau, E., Mekary, S., & Léger, L. A. (2011). VO_2 requirements of boxing exercises. *Journal of Strength and Conditioning Research, 25*(2), 348–359. https://doi.org/10.1519/JSC.0b013e3181ef64cb

Brazier, J., Maloney, S., Bishop, C., Read, P. J., & Turner, A. N. (2019). Lower extremity stiffness: Considerations for testing, performance enhancement, and injury risk. *Journal of Strength and Conditioning Research, 33*(4), 1156–1166. https://doi.org/10.1519/JSC.0000000000002283

Brown, L., Doyle, G., Hastings, K., Thornton-White, C., & Galbraith, A. (2022). Profiling the physiological parameters of boxers in the parachute regiment. *International Journal of* Strength *and Conditioning, 2*(1). https://doi.org/10.47206/ijsc.v2i1.157

Bu, X. (2022). Experimental study on the effect of speed strength training on the special strikes of Chinese female boxers. *Journal of Environmental and* Public Health, 2022, 5912231. https://doi.org/10.1155/2022/5912231

Ceruso, R., Esposito, G., & D'Elia, F. (2019). Analysis and evaluation of the qualitative aspects of the young players. *Journal of Physical Education and Sport, 19*(5), 1814–1819.

Ceruso, R., Esposito, G., Aliberti, S., D'Isanto, T., & D'Elia, F. (2026). Training decision-making in youth football: A comparative study of traditional, ecological dynamics approach, and hybrid eSport-based protocol. *Applied Sciences, 16*(5), 2407. https://doi.org/10.3390/app16052407

Chaabène, H., Tabben, M., Mkaouer, B., Franchini, E., Negra, Y., Hammami, M., Amara, S., Chaabène, R. B., & Hachana, Y. (2015). Amateur boxing: Physical and physiological attributes. Sports *Medicine,* 45(3), 337–352. https://doi.org/10.1007/s40279-014-0274-7

Chottidao, M., Kuo, C. H., Tsai, S. C., Hwang, I. S., Lin, J. J., & Tsai, Y. S. (2022). A comparison of plyometric and jump rope training programs for improving punching performance in junior amateur boxers. *Frontiers in Bioengineering and Biotechnology, 10*, 878527. https://doi.org/10.3389/fbioe.2022.878527

Chwała, W., Wąsacz, W., Rydzik, Ł., Mirek, W., Snopkowski, P., Pałka, T., & Ambroży, T. (2023). Special boxing fitness test: Validation procedure. *Archives of* Budo *Science of* Martial Arts *and* Extreme Sports, 19, 41–50.

Cui, W., Chen, Y., & Wang, D. (2024a). The effect of optimal load training on punching ability in elite female boxers. *Frontiers in Physiology, 15*, 1455506. https://doi.org/10.3389/fphys.2024.1455506

Cui, W., Chen, Y., & Wang, D. (2024b). Research on the effect of post-activation potentiation under different velocity loss thresholds on boxers' punching ability. *Frontiers in Physiology, 15*, 1429550. https://doi.org/10.3389/fphys.2024.1429550

Cunniffe, B., Ellison, M., Loosemore, M., & Cardinale, M. (2017). Warm-up practices in elite boxing athletes: Impact on power output. *Journal of Strength and Conditioning Research, 31*(1), 95–105. https://doi.org/10.1519/JSC.0000000000001484

de Lira, C. A., Peixinho-Pena, L. F., Vancini, R. L., de Freitas Guina Fachina, R. J., de Almeida, A. A., Andrade, M. S., & da Silva, A. C. (2013). Heart rate response during a simulated Olympic boxing match is predominantly above ventilatory threshold 2: A cross-sectional study. Open Access *Journal of* Sports *Medicine,* 4, 175–182. https://doi.org/10.2147/OAJSM.S44807

de Oliveira, L. H., Sant'Ana, J., Freccia, G. W., Coswig, V. S., & Diefenthaeler, F. (2024). Validity of a mobile-based specific test to estimate metabolic thresholds in boxers. *Proceedings of the Institution of*

 © 2026 ARD Asociación Española

Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 238(1), 15–22. https://doi.org/10.1177/17543371221084563

Di Lascio, G., Giardullo, G., Mazza, F., Esposito, G., Manzi, V., & Raiola, G. (2026). Influence of ankle joint mobility on stretch-shortening cycle contribution in vertical jump performance. *Applied Sciences, 16*(8), 3668. https://doi.org/10.3390/app16083668

D'Isanto, T., Di Domenico, F., Sannicandro, I., & D'Elia, F. (2022). Improvement of qualitative and quantitative aspects of the sports performance of young players through high intensity interval training. *Physical Education Theory and Methodology, 22*(1), 70–76. https://doi.org/10.17309/tmfv.2022.1.10

D'Isanto, T., Di Domenico, F., D'Elia, F., Aliberti, S., & Esposito, G. (2021). The effectiveness of constraints-led training on skill development in football. International Journal of Human *Movement* and Sports Sciences, 9(6), 1344–1351. https://doi.org/10.13189/saj.2021.090630

Dunn, E. C., Humberstone, C. E., Franchini, E., Iredale, K. F., & Blazevich, A. J. (2022). Relationships between punch impact force and upper- and lower-body muscular strength and power in highly trained amateur boxers. *Journal of* Strength *and Conditioning Research,* 36(4), 1019–1025. https://doi.org/10.1519/JSC.0000000000003585

El-Ashker, S., Chaabène, H., Negra, Y., Prieske, O., & Granacher, U. (2018). Cardiorespiratory endurance responses following a simulated 3 × 3 minutes amateur boxing contest in elite level boxers. Sports, 6(4), 119. https://doi.org/10.3390/sports6040119

Finlay, M. (2025). A four-week contrast training programme enhances punch performance and physical qualities in senior elite amateur boxers: A physical preparation case study for an international tournament. *International Journal of* Strength *and Conditioning, 5*(1). https://doi.org/10.47206/ijsc.v5i1.426

Finlay, M. J., Bridge, C. A., Greig, M., & Page, R. M. (2022). Postactivation performance enhancement of amateur boxers' punch force and neuromuscular performance following 2 upper-body conditioning activities. *International Journal of* Sports *Physiology and Performance,* 17(11), 1621–1633. https://doi.org/10.1123/ijspp.2022-0159

Finlay, M. J., Greig, M., Bridge, C. A., & Page, R. M. (2024). Post-activation performance enhancement of punch force and neuromuscular performance in amateur boxing: Toward a more individualized and real-world approach. *Journal of* Strength *and Conditioning Research,* 38(6), 1063–1071. https://doi.org/10.1519/JSC.0000000000004740

Finlay, M. J., Greig, M., McCarthy, J., & Page, R. M. (2020). Physical response to pad- and bag-based boxing-specific training modalities. *Journal of* Strength *and Conditioning Research,* 34(4), 1052–1061. https://doi.org/10.1519/JSC.0000000000002928

Finlay, M. J., Greig, M., & Page, R. M. (2018). Quantifying the physical response to a contemporary amateur boxing simulation. *Journal of* Strength *and Conditioning Research,* 32(4), 1005–1012. https://doi.org/10.1519/JSC.0000000000001926

Finlay, M. J., Greig, M., Page, R. M., & Bridge, C. A. (2023). Acute physiological, endocrine, biochemical and performance responses associated with amateur boxing: A systematic review with meta-analysis. *European Journal of* Sport *Science,* 23(5), 774–788. https://doi.org/10.1080/17461391.2022.2063072

Franchini, E. (2020). High-intensity interval training prescription for combat-sport athletes. *International Journal of Sports Physiology and Performance, 15*(6), 767–776. https://doi.org/10.1123/ijspp.2020-0289

Giardullo, G., Ceruso, R., Di Lascio, G., Taleb, M., Esposito, G., & D'Elia, F. (2026). Comparison of traditional and ecological dynamical training approaches in Brazilian Jiu-Jitsu: effects on Force Development, reactivity, and distress perception. Frontiers in Psychology, 17, 1794709. https://doi.org/10.3389/fpsyg.2026.1794709

Ghosh, A. K. (2010). Heart rate, oxygen consumption and blood lactate responses during specific training in amateur boxing. *International Journal of Applied* Sports *Sciences,* 22(1), 1–12. https://doi.org/10.24985/ijass.2010.22.1.1

Herrera-Valenzuela, T., Carter, J., Leiva, E., Valdés-Badilla, P., Ojeda-Aravena, A., & Franchini, E. (2021). Effect of a short HIIT program with specific techniques on physical condition and activity during simulated combat in national-level boxers. Sustainability, 13(16), 8746. https://doi.org/10.3390/su13168746

Hukkanen, E., & Häkkinen, K. (2017). Effects of sparring load on reaction speed and punch force during the precompetition and competition periods in boxing. *Journal of* Strength *and Conditioning Research,* 31(6), 1563–1568. https://doi.org/10.1519/JSC.0000000000001885

Jin, R., Huang, M., Yi, W., Finlay, M. J., & Chen, C. (2025). The acute effects of boxing-specific dumbbell activity on punch performance in male amateur boxers. *Frontiers in Physiology, 16*, 1607933. https://doi.org/10.3389/fphys.2025.1607933

Kacprzak, J., Mosler, D., Tsos, A., & Wasik, J. (2025). Biomechanics of punching-The impact of effective mass and force transfer on strike performance. Appl. Sci., 15(7), 4008. https://doi.org/10.3390/app15074008

Kamandulis, S., Bruzas, V., Mockus, P., Stasiulis, A., Snieckus, A., & Venckunas, T. (2018). Sport-specific repeated sprint training improves punching ability and upper-body aerobic power in experienced amateur boxers. *Journal of* Strength *and Conditioning Research,* 32(5), 1214–1221. https://doi.org/10.1519/JSC.0000000000002056

Kim, K. J., Lee, S. B., & Park, S. (2018). Effects of boxing-specific training on physical fitness and punch power in Korean national boxers. Exerc. Sci., 27(4), 296-302. https://doi.org/10.15857/ksep.2018.27.4.296

Lenetsky, S., Brughelli, M., Nates, R. J., Cross, M. R., & Lormier, A. V. (2018). Variability and reliability of punching impact kinetics in untrained participants and experienced boxers. J. Strength Cond. Res., 32(7), 1838-1842. https://doi.org/10.1519/JSC.0000000000002352

Lenetsky, S., Harris, N. K., & Brughelli, M. (2013). Assessment and contributors of punching forces in combat sports athletes: Implications for strength and conditioning. Strength Cond. J., 35(2), 1-7. https://doi.org/10.1519/SSC.0b013e31828b6c12

Lenetsky, S., Nates, R. J., Brughelli, M., & Harris, N. K. (2015). Is effective mass in combat sports punching above its weight? Hum. Mov. Sci., 40, 89-97. https://doi.org/10.1016/j.humov.2014.11.016

Liu, Y., Huang, Z., Zhou, Z., Zhang, L., Guo, Y., & Chen, C. (2024). Effects of variable resistance training within complex training on strength and punch performance in elite amateur boxers. *Frontiers in Physiology, 15*, 1472258. https://doi.org/10.3389/fphys.2024.1472258

Liu, Y., Jin, R., & Chen, C. (2025). Post-activation potentiation's impact on specialized strike strength in elite male boxers: An acute study. Sensors, 25(20), 6356. https://doi.org/10.3390/s25206356

Liu, Y., Zhu, Z., Chen, X., Deng, C., Ma, X., & Zhao, B. (2022). Biomechanics of the lead straight punch of different level boxers. Front. Physiol., 13, 1015154. https://doi.org/10.3389/fphys.2022.1015154

Loturco, I., Nakamura, F. Y., Artioli, G. G., Kobal, R., Kitamura, K., Cal Abad, C. C., Cruz, I. F., Romano, F., Pereira, L. A., & Franchini, E. (2016). Strength and power qualities are highly associated with punching impact in elite amateur boxers. *Journal of Strength and Conditioning Research, 30*(1), 109–116. https://doi.org/10.1519/JSC.0000000000001075

Loturco, I., Pereira, L. A., Kobal, R., Fernandes, V., Reis, V. P., Romano, F., Alves, M., Freitas, T. T., & McGuigan, M. (2021). Transference effect of short-term optimum power load training on the punching impact of elite boxers. J. Strength Cond. Res., 35(9), 2373-2378. https://doi.org/10.1519/JSC.0000000000003165

 © 2026 ARD Asociación Española

Maciel, A. R., Lambertucci, R. H., Barbosa, F. M., & Guerra, R. L. F. (2023). Proposal and reproducibil-ity of a specific test for amateur boxing. J. Martial Arts Anthropol., 23(4), 8-15.

Merlo, R., Rodríguez-Chávez, Á., Gómez-Castañeda, P. E., Rojas-Jaramillo, A., Petro, J. L., Kreider, R. B., & Bonilla, D. A. (2023). Profiling the physical performance of young boxers with unsuper-vised machine learning: A cross-sectional study. Sports, 11(7), 131. https://doi.org/10.3390/sports11070131

Mosler, D., Kacprzak, J., & Wąsik, J. (2024a). Higher values of force and acceleration in rear cross than lead jab: Differences in technique execution by boxers. Appl. Sci., 14(7), 2830. https://doi.org/10.3390/app14072830

Mosler, D., Kacprzak, J., & Wąsik, J. (2024b). The influence of effective mass on the striking force of lead jab and rear cross punches of boxers. Appl. Sci., 14(17), 7785. https://doi.org/10.3390/app14177785

Niu, Z., Huang, Z., Zhao, G., & Chen, C. (2024). Impact of three weeks of integrative neuromuscular training on the athletic performance of elite female boxers. PeerJ, 12, e18311. https://doi.org/10.7717/peerj.18311

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71

Pinto, M., Crisóstomo, J., Kirk, C., Abián-Vicén, J., & Monteiro, L. (2025). Influence of anthropometric characteristics and muscle performance on punch impact. Sports, 13(8), 281. https://doi.org/10.3390/sports13080281

Raiola, G., Esposito, G., Aliberti, S., & D'Elia, F. (2025). Effects on performance, perception, and awareness of plyometric training in youth volleyball: a novel methodological approach to training. Applied Sciences, 15(3), 1581. https://doi.org/10.3390/app15031581

Sánchez-Ramírez, C., Cid-Calfucura, I., Hernández-Martínez, J., Cancino-López, J., Aedo-Muñoz, E., Valdés-Badilla, P., Franchini, E., García-García, J. M., Calvo-Rico, B., Abián-Vicén, J., & Herrera-Valenzuela, T. (2025). Submaximal accentuated eccentric jump training improves punching performance and countermovement jump force-time variables in amateur boxers. Appl. Sci., 15(14), 7873. https://doi.org/10.3390/app15147873

Singh, S., Deori, L. A., Chetry, P., Manamkandath, M. P., Astuti, Y., Saha, S., & Khati, A. (2025). The effectiveness of varying plyometric training intensities in improving punching force and muscular fitness in adolescent boxers. Phys. Educ. Theory Methodol., 25(5), 1193-1201. https://doi.org/10.17309/tmfv.2025.5.19

Slimani, M., Chaabène, H., Davis, P., Franchini, E., Cheour, F., & Chamari, K. (2017). Performance aspects and physiological responses in male amateur boxing competitions: A brief review. J. Strength Cond. Res., 31(4), 1132-1141. https://doi.org/10.1519/JSC.0000000000001643

Söyler, M., Gürkan, A. C., Kayantaş, İ., Aydın, S., Karataş, B., Eraslan, M., Şahin, M., Küçük, H., Badau, A., & Badau, D. (2025). Investigation of the effects of different plyometric training protocols on punching force and muscle performance in male boxers. Appl. Sci., 15(12), 6532. https://doi.org/10.3390/app15126532

Stanley, E., Thomson, E., Smith, G., & Lamb, K. L. (2018). An analysis of the three-dimensional kinetics and kinematics of maximal effort punches among amateur boxers. Int. J. Perform. Anal. Sport, 18(5), 835-854. https://doi.org/10.1080/24748668.2018.1525651

Thomson, E. D., & Lamb, K. L. (2017a). Reproducibility of the internal load and performance-based responses to simulated amateur boxing. J. Strength Cond. Res., 31(12), 3396-3402. https://doi.org/10.1519/JSC.0000000000001749

Thomson, E. D., & Lamb, K. L. (2017b). Quantification of the physical and physiological load of a boxing-specific simulation protocol. Int. J. Perform. Anal. Sport, 17(1-2), 136-148. https://doi.org/10.1080/24748668.2017.1304048

Usher, A., & Babraj, J. (2024). Use of NIRS to explore skeletal muscle oxygenation during different training sessions in professional boxing. Eur. J. Appl. Physiol., 124(2), 595-606. https://doi.org/10.1007/s00421-023-05305-1

Venckunas, T., Bruzas, V., Snieckus, A., Stasiule, L., Kniubaite, A., Mickevicius, M., Kamandulis, S., & Stasiulis, A. (2024). Anaerobic performance profiling in elite amateur boxers. Sports, 12(9), 231. https://doi.org/10.3390/sports12090231

Venckunas, T., Bruzas, V., Stasiulis, A., Snieckus, A., Mockus, P., & Kamandulis, S. (2022). Cardiorespiratory responses to specific and nonspecific exercise in high-profile amateur boxers. J. Strength Cond. Res., 36(3), 717-722. https://doi.org/10.1519/JSC.0000000000003496

Wdowski, M. M., Rosicka, K., & Hill, M. (2023). Influence of lower-limb muscular and tendon mechanical properties and strength on countermovement jump performance. J. Sports Med. Phys. Fitness, 63(1), 16-22. https://doi.org/10.23736/S0022-4707.22.13567-X

Wilson, D. C., Ruddock, A., Ranchordas, M. A., Thompson, S. W., & Rogerson, D. (2020). Physical profile of junior and senior amateur boxers. J. Phys. Educ. Sport, 20(6), 3452-3459.

Wu, G., Guo, Y., Zhang, L., & Chen, C. (2024). A physical fitness-evaluation system for outstanding Chinese male boxers. PeerJ, 12, e17271. https://doi.org/10.7717/peerj.17271

Xu, Q., Fei, J., Mao, R., Liu, L., & Fei, C. (2025). Effects of BFR-RST on upper limb performance in boxers: A study based on physiological indices, anthropometric measurement indices, anaerobic power, and punching performance. Front. Physiol., 16, 1453153. https://doi.org/10.3389/fphys.2025.1453153

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

REVIEW ARTICLE

From recreation to research: A bibliometric and conceptual mapping of pickleball science (2016–2026)

Dio Alif Airlangga Daulay. *State University of Surabaya. Surabaya, Indonesia.*
Abdul Rachman Syam Tuasikal. *State University of Surabaya. Surabaya, Indonesia.*
Agus Hariyanto. *State University of Surabaya. Surabaya, Indonesia.*
Basyaruddin Daulay. *State University of Medan. Medan, Indonesia.*
Muhammad Charis Fajar. *State University of Surabaya. Surabaya, Indonesia.*
Fifit Yeti Wulandari. *State University of Surabaya. Surabaya, Indonesia.*
Rene Mediana Babiera. *University of the Immaculate Conception. Davao, Philippines.*
Syed Kamaruzaman Syed Ali. *University of Malaya. Kuala Lumpur, Malaysia.*
Novadri Ayubi. *State University of Surabaya. Surabaya, Indonesia.*
Ainun Zulfikar Rizki . *State University of Surabaya. Surabaya, Indonesia.*

ABSTRACT

Pickleball has experienced explosive global growth, yet its scientific literature remains fragmented. This study presents the first comprehensive bibliometric analysis of pickleball research, aiming to map publication trends, collaboration networks, and thematic structures while proposing a conceptual framework for the field. Using PRISMA guidelines, we retrieved 285 documents from Scopus, PubMed, and ScienceDirect (2016–February 2026) and analysed them using Biblioshiny (R). Results reveal an exponential publication surge, particularly after 2024, with the United States dominating productivity (172 publications, 443 citations). Research bifurcates into a dual scientific paradigm: health promotion (psychosocial benefits, well-being, social capital) versus injury risk (fractures, sprains, falls in older adults). The conceptual framework we introduce integrates these axes across population demographics and research domains. Thematic analysis identifies serious leisure, ageing, and injury epidemiology as dominant clusters, yet methodological limitations—predominantly cross-sectional designs and lack of experimental studies persist. We propose a future research agenda emphasizing randomized controlled trials, biomechanical investigations, and international collaboration. This study provides a knowledge map for researchers, practitioners, and policymakers, positioning pickleball as a model for understanding how recreational activities transition into established research domains.

Keywords: bibliometrics; pickleball; sport science trends; ageing; injury epidemiology; serious leisure.

Cite this article as:
Daulay, D. A. A., Tuasikal, A. R. S., Hariyanto, A., Daulay, B., Fajar, M. C., Wulandari, F. Y., Ali, S. K. S., Ayubi, N., & Rizki, A. Z. (2026). From recreation to research: A bibliometric and conceptual mapping of pickleball science (2016–2026). *Journal of Human Sport and Exercise, 21*(4), 1321-1335. https://doi.org/10.55860/nckdht31

Corresponding author. *Universitas Negeri Surabaya, Surabaya, Indonesia.*
E-mail: ainunrizki@unesa.ac.id

Submitted for publication May 11, 2026.
Accepted for publication June 28, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/nckdht31

INTRODUCTION

Pickleball, a composite racquet sport integrating elements of table tennis, badminton, and tennis, has emerged as one of the fastest-growing physical activities globally. Played with a perforated plastic ball on a smaller court (13.41 × 6.1 m) compared to traditional tennis, the sport is characterized by slower ball speeds and simplified technical execution, making it accessible to individuals across diverse age groups and fitness levels (Lauxtermann & Stubbs, 2025). The Sport & Fitness Industry Association reported a 223.5% increase in U.S. pickleball participation from 2020 to 2023, with an estimated 36.5 million players nationally, while the two largest age brackets, those over 55 years and those aged 18–34 years, comprise 19.8% and 18.5% of participants, respectively (Lee et al., 2025). This remarkable growth trajectory has positioned pickleball not merely as a recreational phenomenon but as a significant subject of scientific inquiry within sports science, physical education, public health, and gerontology.

The inclusive nature of pickleball, requiring no fundamental adaptations for participation, has catalysed research interest across multiple disciplinary domains (Weiss et al., 2021). In educational contexts, the sport's moderate tempo and simple game design have been investigated as pedagogical tools for developing fundamental movement skills, coordination, and student engagement in physical education curricula (Sun & Chen, 2024). Concurrently, within performance sport training, structured interventions have demonstrated significant improvements in forehand, backhand, serve mechanics, and overall skill acquisition among adolescent athletes (Moreno-Torres et al., 2025), indicating a progressive shift from descriptive accounts of gameplay toward systematic learning and training model development.

Beyond pedagogical and technical dimensions, a substantial body of literature has examined the biopsychosocial benefits of pickleball participation, particularly among older adult populations. A systematic review by Lauxtermann and Stubbs (2025) found that pickleball enhances subjective well-being, life satisfaction ($p < .05$), happiness ($r = .263$, $p < .001$), and social integration while reducing depressive symptoms ($r = -.23$, $p < .01$), especially in older adults (Chidiebere Anugwolu, 2025; Stroesser et al., 2024). Groundbreaking work by Heo et al. (2018) established that serious leisure commitment to pickleball is inversely associated with depression, with higher commitment levels correlating with lower depression scores. Furthermore, Kim et al. (2021) demonstrated that pickleball participation positively predicts happiness, with social capital, encompassing feelings of trust, safety, and neighbourhood connections, mediating this relationship. Qualitative research has further elucidated that pickleball fosters psychological well-being through mechanisms of autonomy, purpose, and positive social connections, with intermediate and advanced players prioritizing community and belonging over competitive outcomes.

Notwithstanding the proliferating body of pickleball literature, the knowledge landscape remains fragmented and lacks systematic bibliometric mapping. While bibliometric analysis has been extensively employed in sport science to identify research hotspots, thematic trends, scientific collaborations, and influential publications, no comprehensive study has applied this methodology to synthesize pickleball research development. This gap precludes a macro-level understanding of dominant research directions, saturated versus underexplored domains, and emerging frontiers requiring further investigation. Specifically, the absence of bibliometric mapping obscures critical insights regarding the temporal evolution of publication output, the geographic and institutional distribution of research activity, collaboration networks among authors and countries, and the conceptual structure of the field as revealed through keyword co-occurrence analysis.

This study addresses broader questions critical to understanding emerging sports science: (1) How do emerging sports evolve scientifically from recreational phenomena to established research domains? (2) How

 © 2026 ARD Asociación Española

do health-promotion and injury-risk narratives coexist and compete within a new sport's literature? (3) What can pickleball's scientific trajectory teach us about the transition of recreational activities into formal research fields?

Therefore, this study aims to conduct a comprehensive bibliometric analysis of pickleball research indexed in leading scientific databases (Scopus, PubMed, and ScienceDirect) from inception through February 2026. Using the PRISMA framework for systematic literature selection and employing R Studio with Biblioshiny for quantitative analysis, this study will: (1) characterize annual publication and citation trends; (2) identify the most productive journals, affiliations, and countries; (3) map scientific collaboration networks; (4) analyse keyword co-occurrence to delineate major research themes; and (5) synthesize findings from the most highly cited articles. Theoretically, this study will contribute a systematic knowledge map of pickleball research, address a critical bibliometric gap and provide a conceptual framework for understanding emerging sport science evolution. Practically, the findings will inform future research agendas, guide evidence-based intervention development for injury prevention and health promotion, and support policymakers and practitioners in optimizing pickleball as an inclusive, health-enhancing physical activity.

METHODS

The study uses the bibliometric methodology of analysis in three phases: (1) data collection, (2) data analysis, and (3) synthesis and presentation of results. Specifically, the data collection phase is guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which involves literature identification, screening, eligibility assessment, and inclusion. Duplicates are deleted with Mendeley before the PRISMA pipeline starts. The cleaned dataset is then analysed in two stages. First, R studios for programming and then Biblioshiny are used to map the intellectual structure of the field. The combined outputs offer initial quantitative insights that guide subsequent detailed content analysis.

Data retrieval

Core Collection, which includes the Scopus, PubMed, and Science Direct databases from the beginning of publication to the present February 18, 2026. The database was chosen for its rigorous journal selection standards, comprehensive peer-review process, high data completeness, and clear citation linking, making it the platform of choice for bibliometric analysis and bibliographic knowledge graphs.

Table 1. The search strategy uses the comprehensive Boolean formula.

Database	Search strategy
Scopus	TITLE-ABS-KEY (pickleball)
Pubmed	("*pickleball*"[All Fields])
ScienceDirect	Title, abstract, or keywords: pickleball

Note. Search execution date: February 18, 2026 (all databases searched on the same day to ensure temporal consistency).

Study selection and screening process

The research selection was based on the following inclusion criteria: (1) original research articles, reviews, and notes focused on pickleball as the primary subject; (2) publication in English; and (3) availability of full bibliographic data (authors, affiliations, abstract, keywords, references). Studies are excluded if: (1) they are non-research publications (such as conference proceedings, book chapters, editorials, or reports) that lack original data; (2) they are duplicate publications; (3) they do not have complete bibliometric metadata; or (4) they are limited to abstracts only with no full-text access.

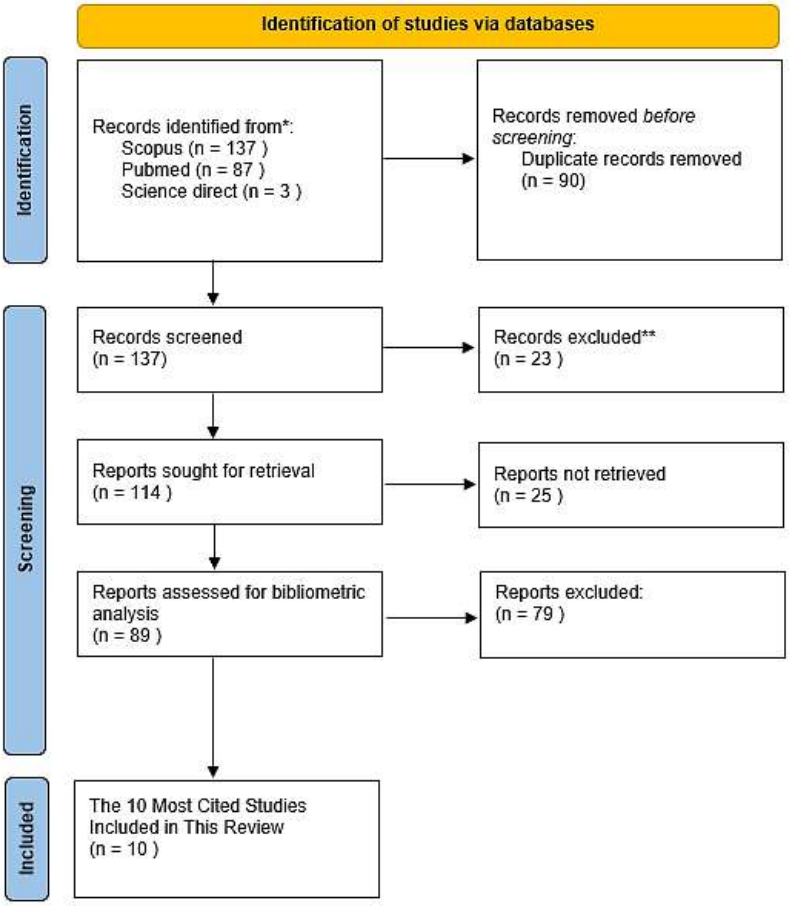


Figure 1. Prisma flow diagram.

Bibliometric analysis techniques

Bibliometric analysis was conducted using data from scientific publication sources to evaluate annual publication trends, average citation trends per year (MeanTCperYear) calculated as MeanTCperArt divided by CitableYears, as well as source impact metrics such as the H-index. The technique also includes mapping top affiliates, scientific production by country and time, as well as analysis of relevant keywords that stand out in a word cloud to illustrate the focus of the research.

RESULTS

Publication and citation trends

Data figure 2 or annual publication and citation trends reveal a dynamic growth trajectory in research output, starting modestly with just 1 article in 2016 and none in 2017, followed by a gradual increase to 2 articles in 2018 and 4 in 2019. Momentum built steadily through the early 2020s, with 6 articles in 2020, a slight dip to 4 in 2021, stabilization at 6 in 2022 and 4 in 2023, before surging dramatically to 14 articles in 2024 and an impressive peak of 45 in 2025. This pattern indicates accelerating scholarly interest, potentially driven by emerging research priorities in sports science or physical education, culminating in over a 45-fold increase from the initial year.

 © 2026 ARD Asociación Española

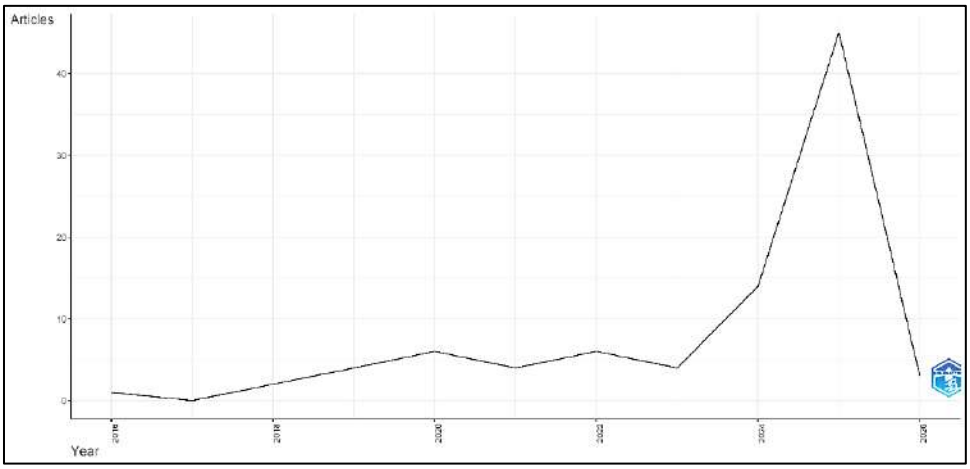


Figure 2. Annual publication and citation trends.

Citation impact

Figure 3 shows the trend of average citations per year (MeanTCperYear) for publications from different years. Citations per year reached the highest peak in the 2021 publication of 6.83 (from 41 total citations on 4 articles over 6 citable years), followed by 2020 (3.36) and 2018 (3.72). The trend declines generally after 2021, with recent years showing lower mean citation rates (2025: 0.44; 2026: 0.67). This pattern is expected given the shorter citation window for recent publications. Notably, early publications (e.g., 2016) had low citation accumulation (0.82), while the sharp increase in article numbers in 2024–2026 has not yet been matched by significant citation accumulation.

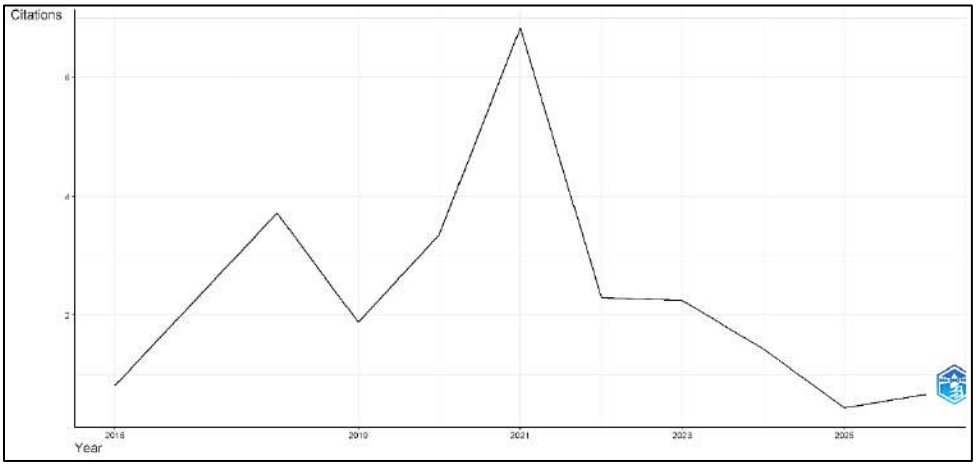


Figure 3. Average citations per year (MeanTCperYear).

Most relevant sources

Bibliometric analysis of publication sources shows that the Journal of Aging and Physical Activity dominates with the highest H-index of 4, supported by g-index 5, m-index 0.5, total citation (TC) 84 out of 5 publications since 2019, reflecting a strong local impact in the field of physical activity for the elderly. The Orthopaedic Journal of Sports Medicine follows with an H-index of 3, g-index 4, m-index 1, and TC 26 from 4 publications starting in 2024, signalling a significant influence in sports orthopaedics. Other journals such as the International Journal of Aging and Human Development and the Journal of Sports Sciences achieved an H-

index of 2 with low TC (8 and 7), respectively, while sources with an H-index of 1 such as the American Journal of Ophthalmology Case Reports and Arthroscopy, Sports Medicine, and Rehabilitation contributed a minimum TC (3-5) of recent publications (2024-2025), overall describing a portfolio of publications focused on sports medicine, Aging, and rehabilitation with a cumulative impact centred on Top journals.

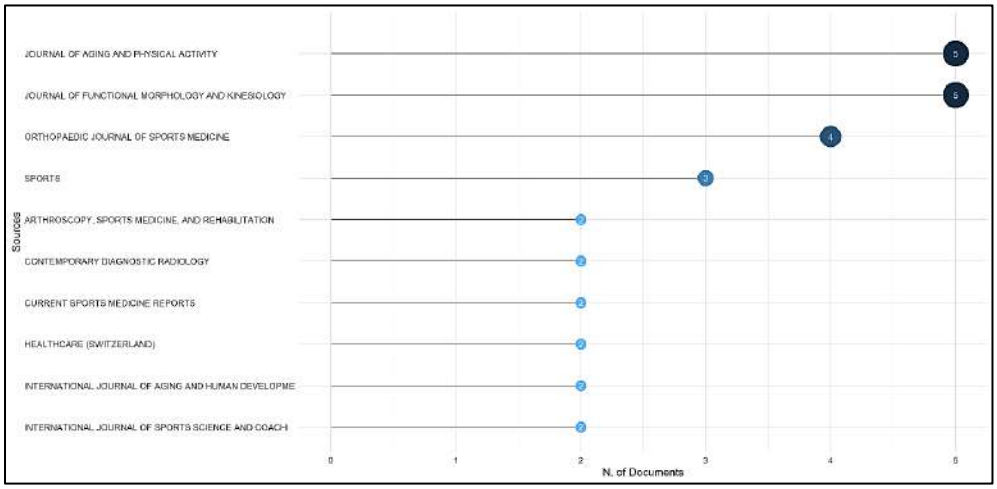


Figure 4. Most relevant sources.

Most relevant affiliations

The provided list highlights the most relevant affiliations based on their productivity in publishing articles, led by Yonsei University in South Korea with the highest output of 9 articles, followed closely by Marshall University in the United States with 6 articles. Several other prominent institutions tie or follow with notable contributions, including Florida State University, Moffitt Cancer Center, NC State University, and University of Nevada, each with 5 articles; while Asia University, University of Miami, University of Tennessee at Chattanooga, and Università degli Studi di Torino each produced 4 articles. This ranking underscores a strong representation from U.S.-based universities and research centres, alongside select international players like those from South Korea, Taiwan, and Italy, likely reflecting key contributors in fields such as sports science, physiology, or related research domains.

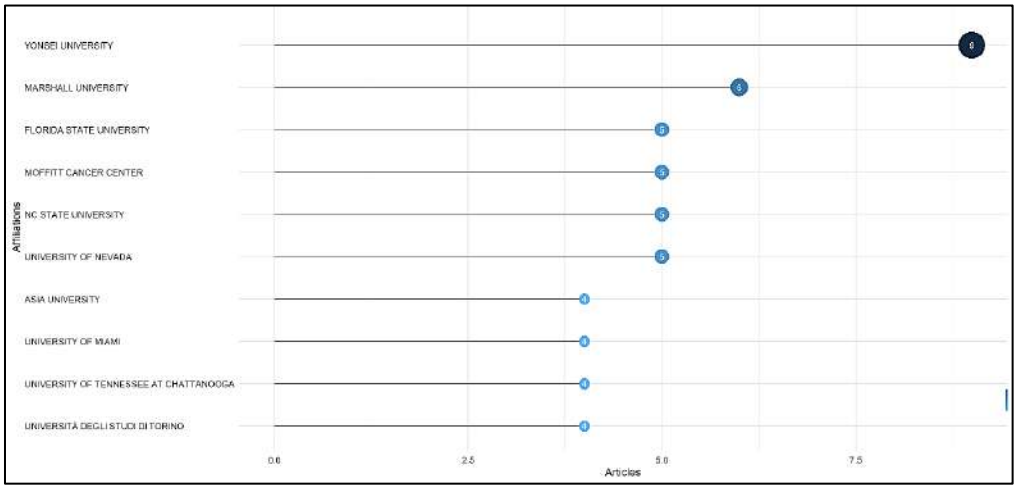


Figure 5. Most relevant affiliation.

 © 2026 ARD Asociación Española

Country scientific production

Data on country scientific production reveals a stark dominance by the United States, which leads with 172 publications, far surpassing all others and accounting for the vast majority of output. China and South Korea follow closely with 12 each, while Canada (9), Italy (8), and Spain (8) form a mid-tier group; the Philippines contributes 5, India and Japan 3 each, the Czech Republic 2, and Australia and France trail with just 1 apiece. This distribution underscores the USA's overwhelming influence in the field, likely driven by robust research funding and institutional capacity, contrasted by more modest contributions from emerging and European nations. Over time, the USA has dominated scientific article production in this dataset, starting with 2 articles in 2016 and surging dramatically to 172 by 2026, reflecting steady exponential growth that outpaces all others. South Korea follows with modest but consistent increases from 0 in 2016 to 12 in 2026, while Canada shows gradual rises from 0 to 9 articles over the same period. China emerges later, producing its first 4 articles in 2022 before reaching 12 by 2026, and both Italy and Spain enter the scene even later, with 0 articles until 2025 when each jumps to 8 by 2026. This trend highlights the USA's longstanding leadership, contrasted by emerging contributions from Asian and European countries in recent years.

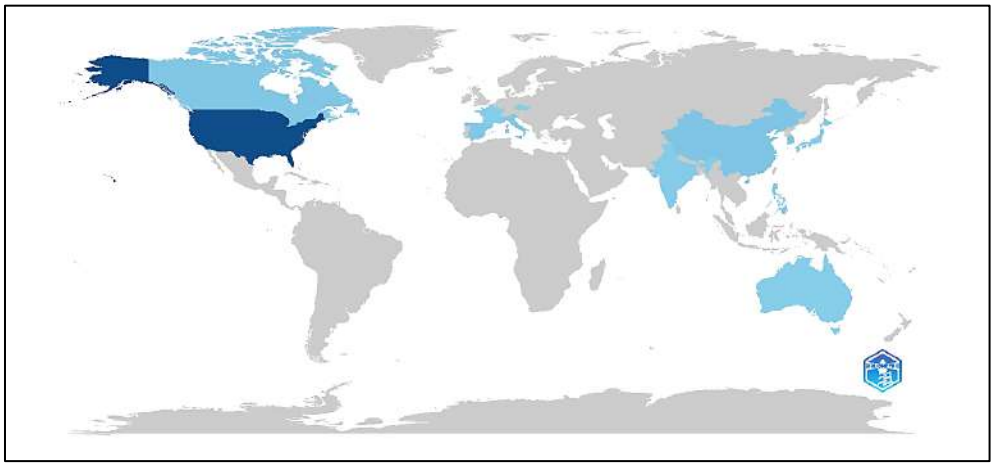


Figure 6. Country scientific production.

Most cited countries

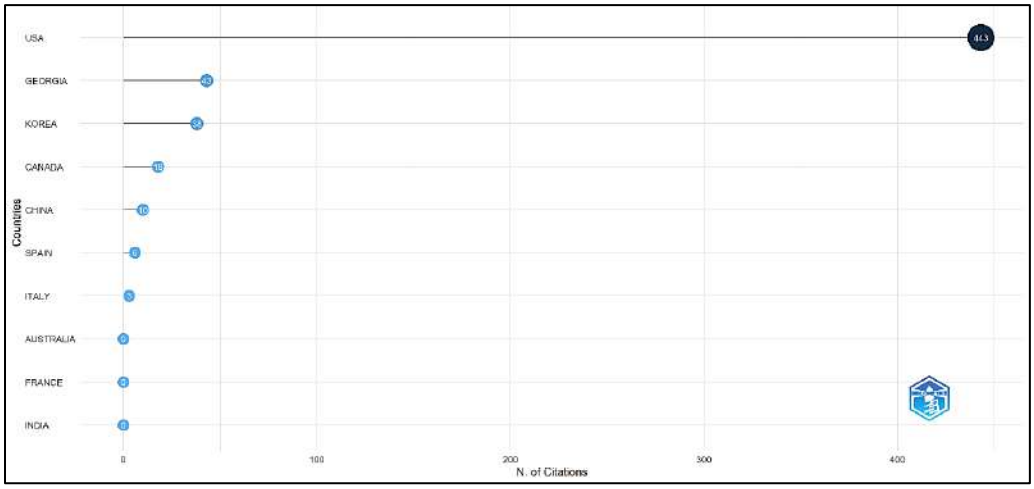


Figure 7. Most cited countries.

Figure 7 shows the dominance of the United States as the country with the highest total citations (TC) reaching 443, followed by an average citation per article of 8.10, reflecting the great influence of its research in related fields. Georgia stands out with a TC of 43 and an excellent citation average of 43.00 per article, signalling high quality despite low volume, while Korea (TC 38, average 6.30) and Canada (TC 18, average 6.00) also contribute significantly. China (TC 10, average 3.30), Spain (TC 6, average 2.00), and Italy (TC 3, average 1.50) showed moderate activity, while Australia, France, India, Japan, and the Philippines recorded zero citations, indicating minimal impact or publication from these countries in this dataset.

Keyword analysis and thematic clusters

The word cloud analysis reveals a strong emphasis on pickleball and human participants (each appearing 47 times), particularly male (36 occurrences) and female (33) adults (32) who are aged (32) or middle-aged (21), highlighting studies on demographics in this racket sport. References to sport injury (21 times) suggest a focus on injury risks or epidemiology, likely drawn from articles (35 mentions) reviewing humans (30) in pickleball contexts, painting a picture of research centred on adult players' health and safety across genders and age groups.

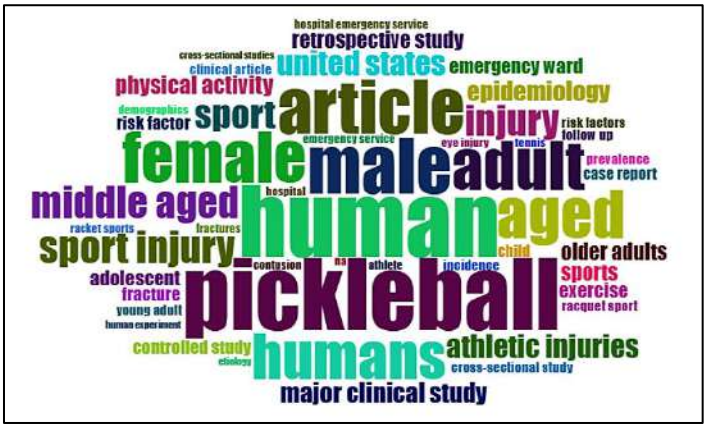


Figure 8. Word cloud in pickleball research.

Thematic cluster interpretation

1. Psychosocial well-being cluster: Serious leisure, happiness, life satisfaction, social capital, depression (centred on older adults).
2. Injury epidemiology cluster: Fractures, sprains, falls, emergency department, older adults, gender differences.
3. Participation and motivation cluster: Physical activity, motivation, skill mastery, competition, socialization.

This confirms the dual scientific paradigm identified in the narrative analysis.

Table 2 presents the 10 most frequently cited articles on the development of pickleball research, which mostly focused on the elderly population in the United States from 2017 to 2021, with lead authors such as Heo, Ryu, and colleagues dominating the top five. Initial research (2017–2018) explored the psychosocial benefits of pickleball for the elderly, showing that serious leisure significantly improved subjective well-being, life satisfaction, optimism, social integration, and reduced depression, while factors such as financial status or employment had less effect. Subsequent studies (2019–2021) revealed participation motives such as fitness, socialization, and mastery of techniques (more task-oriented than competitive), as well as the role of social

 © 2026 ARD Asociación Española

capital mediation in increasing happiness. However, the last four articles highlight the rapidly increasing risk of injury since 2013, especially in individuals aged 50 and older (90.9% of cases), with sprains/strains (28.7%), fractures (27.7%), and falls as the leading causes in the emergency department, even though pickleball is classified as low-impact compared to tennis or other racquet sports. Overall, the findings describe pickleball as a recreational activity that is psychosocially beneficial for the elderly but requires awareness of injuries from overuse or falls.

Table 2. Top 10 cited article development of Pickleball research.

No.	Author (Year)	Research objective	Study design	Sample	Main variables	Key findings
1	Heo et al. (2018)	To explore the relationship between serious leisure, financial status, loneliness, and subjective well-being (SWB) in older adults.	Quantitative, cross-sectional	153 older adults (≥50 years) participating in pickleball competitions in the southern US.	SWB (life satisfaction & positive aging experience), serious leisure, financial status, loneliness.	Serious leisure significantly predicted higher SWB. Financial status and loneliness were not significantly related to SWB.
2	(Casper & Jeon, 2019)	To examine the psychological relationship of older adults (≥55 years) toward pickleball regarding behavioural involvement and participation motivation.	Quantitative, cross-sectional (online survey)	690 active pickleball players in North Carolina, US.	Psychological Continuum Model (PCM), playing frequency, playing duration, and motivation (Competition, Diversion, Fitness, Skill Mastery, Socialization).	Fitness & Socialization were the main motivations. At the highest PCM level, Competition & Skill Mastery were rated higher. Higher playing frequency was associated with higher PCM level.
3	Heo et al. (2018)	To explore the relationship between depression, serious leisure, optimism, and social integration in older adult pickleball players.	Quantitative, cross-sectional	153 older adults (≥50 years) participating in pickleball tournaments.	Depression (Major Depression Inventory), serious leisure, optimism, and social integration.	Serious leisure was significantly inversely related to depression (higher commitment associated with lower depression). Optimism and social integration were not significant.
4	(Ryu et al., 2018)	To examine differences in psychosocial benefits (life satisfaction, optimism, social integration) based on demographic characteristics of older adult pickleball players.	Quantitative, cross-sectional	153 older adults (≥50 years) participating in pickleball tournaments.	Life satisfaction, optimism, social integration, age, gender, employment status, and marital status.	Life satisfaction differed significantly based on age and employment status (retirees had higher levels). Social integration was higher in women.
5	Buzzelli and Draper (2020)	To gain insight into the motivations and perceived benefits of pickleball participation in a predominantly older adult community.	Quantitative, cross-sectional (survey)	3,012 USAPA members, mean age 63.17 years.	Sport motivation (Sport Motivation Scale), task-ego orientation, and perceived benefits.	Participants were more task-oriented (personal mastery). "*Competition*" was cited as the highest benefit. Intrinsic motivation (mastering difficult techniques) was highest.
6	Forrester (2020)	To describe pickleball-related injuries treated in US EDs (2001-2017).	Descriptive, cross-sectional (NEISS data)	300 cases (national estimate of 19,012 injuries).	Patient characteristics, injury type, body part, and location of the incident.	Pickleball injuries increased sharply (2013-2017). Patients were predominantly older adults (90.9% ≥50 years, mean age 63 years). Common injuries: strain/sprain (28.7%) and fracture (27.7%).
7	Kim et al. (2021)	To explore the mediating role of social capital in the relationship between pickleball participation and happiness in older adults.	Quantitative, cross-sectional	208 participants in an international pickleball tournament (age 50-83 years).	Pickleball participation (serious leisure), social capital (cognitive & structural), happiness.	Pickleball participation positively predicted happiness. Social capital (trust/safety & neighbourhood connections) mediated this relationship.
8	Changstrom et al. (2022)	To analyse acute racquet and paddle sport injuries (including pickleball) treated in US EDs (2007-2016).	Descriptive epidemiology, cross-sectional (NEISS data)	7,723 cases (estimated 301,038 injuries) for all racquet sports. Pickleball cases are too few (<20).	Injury type, body part, gender, age, and sport.	Most common injuries: strain/sprain (39.8%). Males (60.3%) had more injuries. The lower extremity was most common (34%). Pickleball was not analysed due to too few cases.

9	Weiss et al. (2021)	To describe and compare non-fatal injuries in older adults (≥60 years) playing pickleball vs. tennis in US EDs (2010-2019).	Descriptive, cross-sectional (NEISS data)	429 pickleball cases (estimated 28,984) & 1,109 tennis cases (estimated 58,836) in older adults.	Annual injury trends, injury mechanism (fall), diagnosis, gender, and body part.	Older adult pickleball injuries increased rapidly, equal to tennis by 2018. Dominant mechanism: fall (63.3%). Women were 3.7x more likely to fracture (especially wrist), and men were 3.5x more likely to have a strain/sprain.
10	Webber et al. (2023)	To measure physical activity intensity (heart rate, steps, intensity) in recreational pickleball singles and doubles players in older adults.	Quantitative, cross-sectional	53 pickleball players (22 singles, 31 doubles), mean age 62.1 years.	Heart rate, activity intensity (accelerometer Freedson cut-points), cadence, steps per hour.	Singles and doubles pickleball are moderate-to-vigorous intensity activities (70-71% predicted maximum heart rate). Singles had higher steps per hour (3,322 vs 2,791). Doubles had longer played duration (106 vs 71 minutes).

Conceptual framework

Based on our synthesis, we propose a conceptual framework (Figure 9) that integrates the dual research axes, population demographics, and research domains. This model positions pickleball research along a risk-benefit continuum, with older adults as the primary population of interest, and identifies three intersecting research domains: (1) Psychosocial & Well-being Research, (2) Injury Epidemiology & Prevention, and (3) Participation & Performance Science. The framework highlights gaps where future research is needed (e.g., biomechanical studies, RCTs, cross-cultural comparisons).

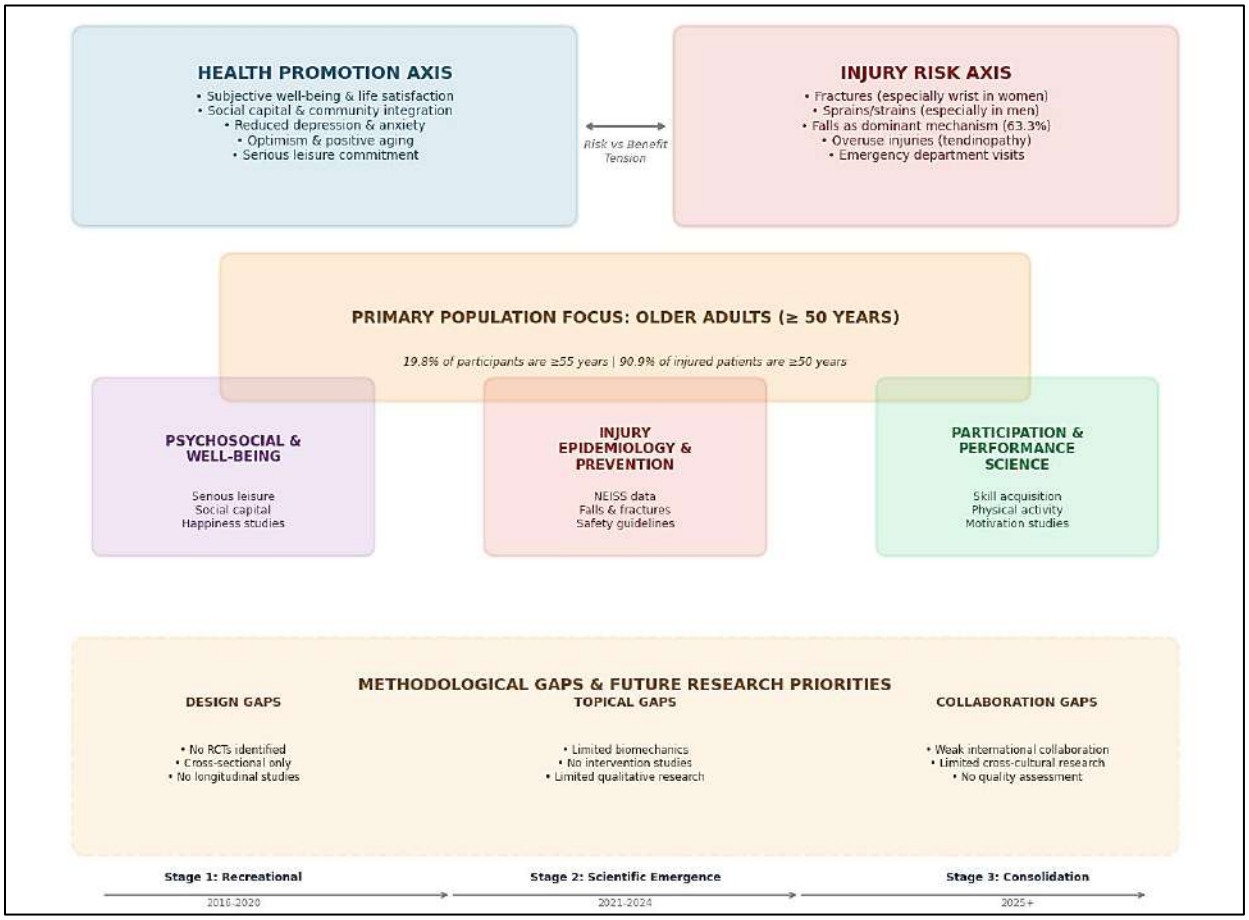


Figure 9. Conceptual framework of pickleball research evolution.

 © 2026 ARD Asociación Española

DISCUSSION

Dynamics of publication development and the impact of citations

The results of the bibliometric analysis show that publications on pickleball have increased significantly, especially since 2016, until its peak in 2025 (45 articles). A sharp surge after 2024 indicates that pickleball has transformed from a purely recreational activity to a serious topic of scientific study in sports science and physical education (Gupta, 2024). This pattern is in line with the growing popularity of sports post-COVID-19 pandemic, where people are looking more for outdoor physical activity that is easy to learn and has a low risk of injury (Sallis et al., 2023). Although the number of articles has soared, the average citations per year have actually decreased after 2021. This phenomenon is natural because the statistically younger documents have not had enough time to accumulate citations. However, these findings also indicate that recent research tends to be more diverse and dispersed, so that a very dominant work has not yet been formed that is a common reference (Specht & Crowston, 2022). In other words, the field of pickleball studies is still in the stage of forming a scientific paradigm, not in the consolidation phase.

U.S. dominance and limited global collaboration

The dominance of the United States (172 publications, 443 total citations) in the scientific map of pickleball is not surprising, given that the sport was born and developed rapidly in the country since the mid-20th century. The presence of Yonsei University (South Korea) as the highest-productivity affiliate is interesting, as it suggests that interest in pickleball has spilled over into Asia, likely driven by the active aging and elderly health programs that are a priority in developed countries. However, the still weak pattern of international collaboration indicates that pickleball research is still very local and dependent on the domestic context (Cerezuela et al., 2023). The lack of involvement of European countries (except Italy and Spain, which will only emerge in 2025–2026) and almost no contributions from Africa and Latin America indicate a large geographical gap. This opens up opportunities for cross-cultural research that compares pickleball's motivations, injury patterns, or psychosocial benefits in sociodemographically distinct populations.

Two main axes: Psychosocial benefits of the elderly versus risk of injury

The most substantive finding of this analysis is the existence of two complementary but contradictory axes of research. The first axis, dominated by the work of Heo, Ryu, Casper, and Kim (2017–2021), consistently shows that pickleball as serious leisure provides real psychosocial benefits for the elderly: improved subjective well-being, life satisfaction, optimism, social integration, and decreased depression. The mechanism of social capital mediation, in which participation in the pickleball community builds trust and support networks, is a key finding that strengthens the theory of activity in social gerontology. In contrast, the second axis, represented by Forrester (2020), Weiss (2021), and Changstrom (2021), highlights the alarming epidemiology of injury. Although pickleball is considered low-impact, data from the U.S. Emergency Department shows that 90.9% of injured patients are ≥50 years old, with fractures (especially wrist in women) and strains/sprains (in men) as the primary diagnoses, as well as the predominant fall mechanism (63.3%). Ironically, activities recommended for the health of the elderly actually carry a significant risk of acute injury. A clear research gap is the lack of intervention studies that test injury prevention programs (e.g., balance exercises, wrist strengthening, equipment modifications) in the elderly pickleball player population.

Generalizable lessons for emerging sports research

Beyond pickleball, our findings offer broader insights into how emerging sports transition into established research domains. We identify three generalizable stages: (1) Recreational phase – dominated by participation growth and descriptive studies; (2) Scientific emergence phase – marked by exponential publication growth, dual risk-benefit narratives, and dominant national productivity; (3) Consolidation phase

– characterized by international collaboration, experimental designs, and evidence-based guidelines. Pickleball currently sits between stages 2 and 3, offering a model for studying other emerging sports (e.g., padel, footgolf, esports). This framework can guide researchers, funders, and policymakers in anticipating research needs and fostering balanced scientific development.

Methodological gaps and future agendas

The majority of the highest-cited articles (top 10 articles) use survey-based or secondary data-driven cross-sectional quantitative design (NEISS). There were no long-term experimental or longitudinal studies on the list. This indicates that the scientific evidence on pickleball is currently still dominated by associative relationships, not causality. For example, it is not yet known for sure whether playing pickleball causes a decrease in depression or whether individuals with low levels of depression are more likely to participate. Similarly, biomechanical studies of the movement patterns that trigger overuse injuries (e.g., epicondylitis, rotator cuff tendinopathy) in elderly players are still very limited. The future research agenda should lead to: (1) randomized controlled trials (RCTs) for pickleball intervention programs on the mental health of the elderly, (2) prospective cohort studies of injury incidence and risk factors, and (3) multidisciplinary collaboration between sports scientists, physiotherapists, and epidemiologists to develop evidence-based safety guidelines. In addition, the keywords "*gender*" and "*adult*" that appear prominently in the word cloud confirm the need for more specific research on gender differences in motivation, injury patterns, and physiological responses to pickleball.

Theoretical implications

Our analysis contributes to sport science theory in three ways. First, it extends the serious leisure framework (Stebbins, 1992) by demonstrating how recreational commitment in later life generates measurable psychosocial outcomes, mediated by social capital. Second, it introduces a dual-paradigm model for emerging sports, where health benefits and injury risks coexist as competing narratives, shaping research agendas and public perception. Third, it proposes a lifecycle model of sport science evolution, providing a heuristic for understanding how recreational activities mature into formal research fields. These theoretical contributions have implications beyond pickleball, offering conceptual tools for analysing other rapidly growing physical activities.

Study limitations and practical implications

The study has some limitations that need to be acknowledged. First, the databases used are limited to Scopus, PubMed, and ScienceDirect, so publications from Google Scholar, the Web of Science (non-Medline index), or international conference proceedings are not included. Second, only English-language articles are analysed, potentially ignoring important findings from non-English-speaking countries such as Japan, Brazil, or Germany. Third, this analysis uses data up to February 2026, so that the current trends after that period are not captured. Fourth, the search strategy employed a single keyword ("*pickleball*"), which may have missed studies where pickleball is mentioned in passing or as a secondary topic. Fifth, grey literature (e.g., theses, government reports, industry white papers) was excluded, potentially overlooking valuable practice-based insights. Sixth, no quality assessment of included studies was performed, meaning that the bibliometric patterns may include studies of variable methodological rigor. Future bibliometric studies could address these limitations by incorporating multiple search terms, including non-English literature, and integrating quality appraisal. Nonetheless, the practical implications of this study are clear: for physical educators, pickleball can be integrated into the curriculum as an inclusive activity to teach motor skills as well as social values. For coaches and public health practitioners, elderly-specific training modules are required that include warm-ups, safe fall techniques, and wrist and lower extremity strengthening before play. For policymakers, these

 © 2026 ARD Asociación Española

results drive the need for pickleball court safety standards as well as national injury surveillance systems, such as NEISS, to be replicated in developing countries.

CONCLUSION

Based on the results of the bibliometric analysis that has been carried out, it can be concluded that research on pickleball has experienced very rapid growth, especially since 2016, until it reached its peak in 2025, which reflects the increasing global interest in this racquet sport post-pandemic. The dominance of the United States is highly visible in terms of the number of publications, citations, and affiliations, although international collaboration is still relatively weak, while the main focus of research is divided into two contradictory axes: on the one hand, pickleball has been shown to provide significant psychosocial benefits for the elderly as a form of serious leisure that improves subjective well-being, life satisfaction, and reduces depression; But on the other hand, this activity also carries a risk of injury that cannot be ignored, such as fractures (especially wrists in women), strains/sprains, and fall injuries that dominate emergency department visits in the population aged 50 years and above. Although the number of publications has soared, the average citations per year have actually decreased in recent publications due to the young age of the document, which is a natural pattern in the growing field of study. This study fills a bibliometric gap in the pickleball literature while recommending the need for more experimental and longitudinal studies, biomechanics research, injury prevention interventions, and strengthening international collaborations to mature this field of study going forward.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualization: Dio Alif Airlangga Daulay, Abdul Rachman Syam Tuasikal, Syed Kamaruzaman Syed Ali, Ainun Zulfikar Rizki. Methodology: Agus Hariyanto, Novadri Ayubi, Fifit Yeti Wulandari. Formal Analysis: Ainun Zulfikar Rizki, Muhammad Charis Fajar, Rene Mediana Babiera. Investigation: Dio Alif Airlangga Daulay, Basyaruddin Daulay, Fifit Yeti Wulandari. Data Curation: Basyaruddin Daulay, Muhammad Charis Fajar, Rene Mediana Babiera, Novadri Ayubi. Writing – Original Draft: Dio Alif Airlangga Daulay, Ainun Zulfikar Rizki, Basyaruddin Daulay. Writing – Review & Editing: Dio Alif Airlangga Daulay, Agus Hariyanto, Fifit Yeti Wulandari, Rene Mediana Babiera, Syed Kamaruzaman Syed Ali, Novadri Ayubi. Supervision: Abdul Rachman Syam Tuasikal, Syed Kamaruzaman Syed Ali.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Buzzelli, A. A., & Draper, J. A. (2020). Examining the motivation and perceived benefits of pickleball participation in older adults. *Journal of Aging and Physical Activity, 28*(2). https://doi.org/10.1123/japa.2018-0413

Casper, J. M., & Jeon, J. H. (2019). Psychological connection to pickleball: Assessing motives and participation in older adults. *Journal of Aging and Physical Activity, 27*(1). https://doi.org/10.1123/japa.2017-0381

Cerezuela, J. L., Lirola, M. J., & Cangas, A. J. (2023). Pickleball and mental health in adults: A systematic review. *Frontiers in Psychology, 14*. https://doi.org/10.3389/fpsyg.2023.1137047

Changstrom, B., McBride, A., & Khodaee, M. (2022). Epidemiology of racket and paddle sports-related injuries treated in the United States emergency departments, 2007–2016. *The Physician and Sportsmedicine, 50*(3). https://doi.org/10.1080/00913847.2021.1892467

Chidiebere Anugwolu. (2025). Literature review: An economic overview of the U.S. pickleball boom and tourism. *World Journal of Advanced Research and Reviews, 26*(2). https://doi.org/10.30574/wjarr.2025.26.2.1929

Forrester, M. B. (2020). Pickleball-related injuries treated in emergency departments. *Journal of Emergency Medicine, 58*(2). https://doi.org/10.1016/j.jemermed.2019.09.016

Gupta, K. (2024). Understanding the fundamental reasons for the growth of pickleball. *Journal of Student Research, 13*(2). https://doi.org/10.47611/jsrhs.v13i2.6795

Heo, J., Ryu, J., Yang, H., Kim, A. C. H., & Rhee, Y. (2018). Importance of playing pickleball for older adults' subjective well-being: A serious leisure perspective. The Journal of Positive Psychology, 13(1). https://doi.org/10.1080/17439760.2017.1374438

Heo, J., Ryu, J., Yang, H., & Kim, K. M. (2018). Serious leisure and depression in older adults: A study of pickleball players. *Leisure Studies, 37*(5). https://doi.org/10.1080/02614367.2018.1477977

Kim, A. C. H., Ryu, J., Lee, C., Kim, K. M., & Heo, J. (2021). Sport participation and happiness among older adults: A mediating role of social capital. *Journal of Happiness Studies, 22*(4). https://doi.org/10.1007/s10902-020-00288-8

Lauxtermann, L., & Stubbs, B. (2025). Padel, pickleball and wellbeing: A systematic review. *Frontiers in Psychology, 16*. https://doi.org/10.3389/fpsyg.2025.1614448

Lee, P. M., Nishi, R., Obana, K. K., Chan, S. M., You, J. K., Weiss, J. M., Levine, W. N., & Trofa, D. P. (2025). Pickleball-related geriatric fractures and pediatric equipment-related injuries are increasing in emergency departments across the United States. *Arthroscopy, Sports Medicine, and Rehabilitation, 7*(5). https://doi.org/10.1016/j.asmr.2025.101228

Moreno-Torres, J. M., García-Roca, J. A., Abellan-Aynes, O., & Diaz-Aroca, A. (2025). Effects of supervised strength training on physical fitness in children and adolescents: A systematic review and meta-analysis. *Journal of Functional Morphology and Kinesiology, 10*(2). https://doi.org/10.3390/jfmk10020162

 © 2026 ARD Asociación Española

Ryu, J., Yang, H., Kim, A. C. H., Kim, K. M., & Heo, J. (2018). Understanding pickleball as a new leisure pursuit among older adults. *Educational Gerontology, 44*(2–3). https://doi.org/10.1080/03601277.2018.1424507

Sallis, J. F., Adlakha, D., Oyeyemi, A., & Salvo, D. (2023). Public health research on physical activity and COVID-19: Progress and updated priorities. *Journal of Sport and Health Science, 12*(5). https://doi.org/10.1016/j.jshs.2023.04.002

Specht, A., & Crowston, K. (2022). Interdisciplinary collaboration from diverse science teams can produce significant outcomes. PLoS ONE, 17(11). https://doi.org/10.1371/journal.pone.0278043

Stroesser, K., Mulcaster, A., & Andrews, D. M. (2024). Pickleball participation and the health and well-being of adults: A scoping review. *Journal of Physical Activity and Health, 21*(9). https://doi.org/10.1123/jpah.2024-0092

Sun, S., & Chen, C. (2024). The effect of sports game intervention on children's fundamental motor skills: A systematic review and meta-analysis. *Children,* 11(2). https://doi.org/10.3390/children11020254

Webber, S. C., Anderson, S., Biccum, L., Jin, S., Khawashki, S., & Tittlemier, B. J. (2023). Physical activity intensity of singles and doubles pickleball in older adults. *Journal of Aging and Physical Activity, 31*(3). https://doi.org/10.1123/japa.2022-0194

Weiss, H., Dougherty, J., & DiMaggio, C. (2021). Non-fatal senior pickleball and tennis-related injuries treated in United States emergency departments, 2010–2019. *Injury Epidemiology, 8*(1). https://doi.org/10.1186/s40621-021-00327-9

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

REVIEW ARTICLE

Virtual reality for enhancing athletic performance: A systematic review of evidence, mechanisms, and future directions

Irma Febriyanti. *State University of Surabaya. Surabaya, Indonesia.*
Dwi Lorry Juniarisca. *State University of Surabaya. Surabaya, Indonesia.*
Sri Wicahyani. *State University of Surabaya. Surabaya, Indonesia.*
Mochamad Ridwan . *State University of Surabaya. Surabaya, Indonesia.*
Ainun Zulfikar Rizki. *State University of Surabaya. Surabaya, Indonesia.*
Farruh Ahmedov. *Samarkand State University. Samarkand, Uzbekistan.*

ABSTRACT

This systematic review evaluates the effectiveness of Virtual Reality (VR) technology in enhancing athletic performance across physical, technical, and psychological domains, including injury rehabilitation contexts, through a comprehensive search of Scopus, PubMed, and Science Direct databases from inception to October 10, 2025, following PRISMA 2020 guidelines, which identified 793 articles, of which 7 experimental studies met the inclusion criteria after duplicate removal (n = 304), title and abstract screening (n = 489), and full-text eligibility assessment. The included studies demonstrated heterogeneous designs, samples, and outcome measures, yet consistently showed promising VR effects on physical performance outcomes (increased power output during HIIT by +5–19W, improved sprint and shuttle run performance), technical and motor skills (enhanced shooting performance, imagery skills, motor response time, and joint stability), and psychological outcomes (reduced cognitive and somatic anxiety, increased self-confidence, lower perceived pain, and higher enjoyment). However, methodological quality varied considerably, and the small number of studies, short intervention durations, and diverse sport contexts preclude strong generalizations, indicating that while VR is a promising supplementary training tool for controlled, psychologically demanding, and rehabilitation-focused environments, the field remains nascent, and this review provides a conceptual framework and structured research agenda to guide future investigations toward more rigorous, standardized, and ecologically valid studies.

Keywords: Virtual reality, Athletic performance, Sports training, Motor skills, Performance enhancement.

Cite this article as:
Febriyanti, I., Juniarisca, D. L., Wicahyani, S., Ridwan, M., Rizki, A. Z., & Ahmedov, F. (2026). Virtual reality for enhancing athletic performance: A systematic review of evidence, mechanisms, and future directions. *Journal of Human Sport and Exercise, 21*(4), 1336-1349. https://doi.org/10.55860/9nxkdr46

Corresponding author. *Universitas Negeri Surabaya, Surabaya, Indonesia.*
E-mail: mochamadridwan@unesa.ac.id
Submitted for publication May 12, 2026.
Accepted for publication July 21, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/9nxkdr46

© 2026 ARD Asociación Española

INTRODUCTION

In contemporary competitive sports, athletes face escalating demands for continuous performance optimization across physical, technical, and psychological domains (Bashir et al., 2022; Li & Smith, 2021). Soccer players, for instance, require high cardiorespiratory endurance, and interval training has demonstrated promise in enhancing this physical fitness component (Haleva & Meckel, 2020). Interval training has been shown to positively affect the cardiovascular system, improve aerobic capacity, and enhance overall physical performance (Franceschi et al., 2023; Oliveira et al., 2017; Panice et al., 2020). Physiological markers such as running economy, maximal oxygen uptake, and anaerobic threshold are typically used to assess aerobic fitness and guide training prescription (Strauss et al., 2014; Urquhart & Saynor, 2018). Notably, the anaerobic threshold has been identified as a particularly sensitive indicator of training effects, potentially outperforming maximal oxygen uptake in discerning performance variations among players of different competitive levels (Salvadori et al., 2021). Interval training regimens, characterized by short bursts of intensive activity interspersed with recovery intervals, have been shown to generate comparable or even greater physiological changes than moderate-intensity continuous training (Atakan et al., 2021; Collins et al., 2023; Liu et al., 2020; Tadiotto et al., 2023). The advantages of interval training are particularly pertinent for soccer players, whose demanding schedules often limit available training time (Krustrup & Bangsbo, 2015; Kunz et al., 2019).

In parallel with advances in training methodology, Virtual Reality (VR) technology has experienced rapid development and found wide applications across medical, educational, and entertainment domains (Fan et al., 2023; Kuna et al., 2023). However, one area that shows significant potential but remains relatively underexplored is its utility in improving sports performance. VR offers an innovative and interactive training method capable of simulating realistic competition conditions without injury risk (Ochi et al., 2022; Pastel et al., 2023). Additionally, VR provides a controlled training environment that can be tailored to individual athletes' needs a feature difficult to achieve through conventional methods (Radhakrishnan et al., 2023). In the context of performance enhancement, injury recovery, and mental preparation, VR represents a potentially transformative tool that opens new opportunities for coaches and athletes (Bui & Alaei, 2022; LeMarshall et al., 2023; Li Pira et al., 2023).

VR technology utilizes hardware and software to create immersive artificial environments. In sports contexts, devices such as headsets, motion sensors, and controllers generate three-dimensional simulations that respond to user movements and interactions in real-time (Loetscher et al., 2023). This technology enables athletes to perceive and react to situations resembling actual competition conditions without being physically present on the field or court. Furthermore, VR can integrate analytical data to provide detailed performance feedback, helping athletes identify improvement areas and formulate more effective training strategies (Doré et al., 2023). Applications also extend to mental training, where athletes can practice visualization and mental strategies in controlled environments, potentially enhancing mental endurance and focus during competition (Corrigan et al., 2023).

Despite growing interest, the evidence base for VR's effectiveness in sport performance enhancement remains fragmented and insufficiently synthesized. Previous literature has primarily focused on rehabilitation applications and basic skill acquisition (Aufegger et al., 2017; Choi et al., 2023), with limited systematic integration of findings across diverse performance domains. This fragmentation presents a significant gap, as practitioners and researchers lack a coherent framework for understanding how, for which outcomes, and under what conditions VR training is most effective (Akbaş et al., 2019).

Therefore, this systematic review aims to address this gap by synthesizing current evidence on VR effectiveness in enhancing athletic performance. Specifically, the review is guided by the following research questions: (1) What are the effects of VR-based interventions on physical performance outcomes in athletic populations? (2) What evidence exists for VR's effectiveness in improving technical and motor skills? (3) What are the psychological and perceptual outcomes associated with VR training? (4) What is the evidence for VR applications in injury rehabilitation contexts? (5) What are the current limitations and future research priorities for VR in sport performance enhancement?

METHODS

Study design

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). Due to the heterogeneity of included studies, quantitative meta-analysis was not feasible.

Search strategy

A comprehensive electronic search was conducted across three databases: Scopus, PubMed, and Science Direct. The search included studies published from database inception through October 10, 2025. Search terms were developed using Medical Subject Headings (MeSH) and free-text terms, combining concepts related to "*virtual reality*" and "*sport performance*." The detailed search strategies for each database are presented in Table 1. Search strategies were adapted iteratively to ensure sensitivity and specificity across databases. No manual reference screening was conducted to maintain systematic rigor.

Table 1. The detailed overview of the complete search strategy.

Database	Search term
Scopus	TITLE-ABS-KEY ("*virtual reality*" OR "*VR*") AND TITLE-ABS-KEY ("*sport performance*" OR "*athletic performance*" OR "*sports training*") AND PUBYEAR > 2015 AND (LIMIT-TO (DOCTYPE, "*ar*") OR LIMIT-TO (DOCTYPE, "*cp*")) AND (LIMIT-TO (LANGUAGE, "*English*"))
Pub Med	"*KEY*"("*virtual reality*"[MeSH Terms] OR ("*virtual*"[All Fields] AND "*reality*"[All Fields]) OR "*virtual reality*"[All Fields]) AND ("*athletic performance*"[MeSH Terms] OR ("*athletic*"[All Fields] AND "*performance*"[All Fields]) OR "*athletic performance*"[All Fields] OR ("*sport*"[All Fields] AND "*performance*"[All Fields]) OR "*sport performance*"[All Fields])
Science Direct	("*virtual reality*" OR VR) AND ("*sports performance*" OR "*athletic performance*" OR "*motor skill learning*")

Eligibility criteria

Studies were included if they met the following criteria: (1) original research investigating the effects of virtual reality on sports performance outcomes; (2) experimental or quasi-experimental study designs; (3) involved human athlete or physically active populations; (4) reported quantitative outcome data; (5) published in English; and (6) peer-reviewed journal articles.

Studies were excluded if they: (1) were review articles, conference proceedings, book chapters, or laboratory studies involving animals; (2) were duplicate publications; (3) lacked complete or adequate data for extraction; (4) were limited to abstracts or conference presentations only; or (5) focused solely on non-athletic populations or clinical rehabilitation without performance outcomes.

 © 2026 ARD Asociación Española

Study selection and screening process

Two independent reviewers (I.F. and D.L.J.) conducted the screening process. In the first stage, titles and abstracts of all identified records were screened against eligibility criteria. Potentially relevant records proceeded to full-text assessment. In the second stage, full texts were independently assessed for eligibility. Disagreements between reviewers were resolved through discussion and consensus, with a third reviewer (M.R.) available for arbitration when necessary. The screening process was documented and managed using Mendeley reference management software.

Data extraction

Data were systematically extracted from included studies using a standardized data extraction form. Extracted information included: author(s) and year, sample characteristics (size, age, sex, sport), study design, intervention details (VR modality, duration, frequency, intensity), outcome measures, and main findings. Data extraction was performed independently by two reviewers and verified for accuracy.

Quality and risk of bias assessment

Methodological quality and risk of bias of included studies were assessed using the Physiotherapy Evidence Database (PEDro) scale, which is appropriate for experimental studies in sports science (de Morton, 2009). The PEDro scale comprises 11 items evaluating internal validity, statistical reporting, and external validity. Studies were rated as "*excellent*" (9–10), "*good*" (6–8), "*fair*" (4–5), or "*poor*" (≤3) based on established criteria (Cashin & McAuley, 2020). Quality assessment was performed independently by two reviewers, with disagreements resolved through consensus.

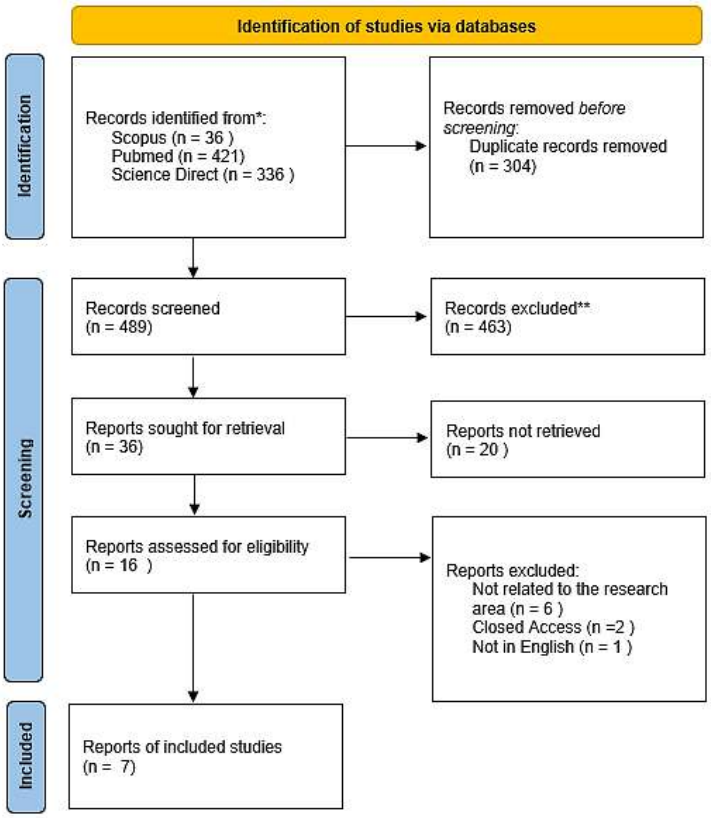


Figure 1. PRISMA 2020 flowchart of the article selection process.

RESULTS

Study selection

The systematic search identified 793 records from the three databases (Scopus: n = 36; PubMed: n = 421; Science Direct: n = 336). After removing duplicate records (n = 304), 489 articles remained for title and abstract screening. Following screening, 36 reports were sought for retrieval. Of these, 20 reports could not be retrieved. The remaining 16 reports underwent full-text eligibility assessment. At this stage, reports were excluded for the following reasons: not related to the research area (n = 6), closed access/unavailable (n = 2), not in English (n = 1). The final synthesis included 7 studies that met all inclusion criteria. The PRISMA flowchart illustrating the study selection process is presented in Figure 1.

Study characteristics

The seven included studies were all experimental designs, published between 2018 and 2022. Total sample sizes ranged from 13 to 45 participants (total across studies: N = 196). Participant populations included cyclists, football players, ice hockey players, wrestlers, and target-based sport athletes. Sample characteristics were predominantly young adults (mean age range: 20.5–21 years). Interventions varied considerably, including VR-HIIT exergaming, cycling with perceptual load manipulation, mixed-reality cycling competitions, VR motion analysis, VR training for injury rehabilitation, VR presence interventions, and VR-based imagery training. Intervention durations ranged from single sessions to 4-week programs. A summary of study characteristics is presented in Table 2.

Table 2. Summary of study characteristics, findings, and quality assessment.

Author (Year)	Sample characteristics	Study design	Intervention	Key results	PEDro Score (Quality)
Farrow et al. (2018)	16 (8 M, 8 F)	Experimental, cross-over	4 VR-HIIT conditions: blank, track, ghost, hard	Enjoyment higher for track vs. blank (diff: 0.9; 95% CI: 0.6–1.3). Mean power higher for track vs. ghost (+5 W) and hard vs. ghost (+19 W)	6/10 (Good)
Wender et al. (2022)	43 healthy (20 F, mean age 21)	Experimental, within-subjects	Cycling at "*hard*" intensity: no VR (NPL), VR low (LPL) & high (HPL) perceptual load	Significant main effects: condition ($F = 13.46$, $p < .001$) and time ($F = 113.05$, $p < .001$) on quadriceps pain	5/10 (Fair)
Westmatte lmann et al. (2022)	Virtual Tour de France 2020 riders	Experimental	6 stages (hilly, high mountains, bumpy, etc.)	Relative power output explains most performance differences	4/10 (Fair)
Polikanova et al. (2022)	20 (13 hockey, 7 wrestlers)	Experimental	VR motion analysis: joint angles, stick speed, response time, hits/misses	Hockey players showed more stable joint patterns & fewer head movements (0.66 vs. 1.25, $p = .043$)	5/10 (Fair)
Nambi et al. (2020)	45 (15 per group)	Experimental, RCT	VR training (VRT) vs. IKT & control; outcomes: sprint, jump, shuttle run	VRT group improved pain, wellness, & sports performance vs. IKT & control	7/10 (Good)
Harrison et al. (2021)	13 female footballers (age 20.5 ± 1.1)	Experimental	VR presence questionnaire (spatial, involvement, realism)	Cognitive anxiety differed significantly ($\chi^2 = 18.63$, $p < .001$). VR vs. baseline ($p = .002$)	5/10 (Fair)
Bedir & Erhan (2021)	34 athletes	Experimental	VRBI training vs. VMBR+VM; shot performance & imagery skills	VRBI group showed greater improvement in shot performance & imagery over 4 weeks ($p < .05$)	6/10 (Good)

 © 2026 ARD Asociación Española

Physical performance outcomes

Farrow et al. (2018) investigated VR-HIIT exergaming in 16 participants (8 male, 8 female). The study compared four VR conditions (blank, track, ghost, and hard) during high-intensity interval training. Results demonstrated significantly higher enjoyment for the track condition compared to the blank condition (difference: 0.9; 95% CI: 0.6–1.3). Importantly, mean power output was higher for track compared to ghost (+5 W) and for hard compared to ghost (+19 W), suggesting that VR can enhance both affective responses and physical performance during HIIT.

Wender et al. (2022) examined VR-based distraction during cycling at "*hard*" intensity in 43 healthy young adults (20 female, mean age 21 years). The within-subjects design compared three conditions: no VR (NPL), VR with low perceptual load (LPL), and VR with high perceptual load (HPL). Significant main effects were found for condition ($F = 13.46$, $p < .001$) and time ($F = 113.05$, $p < .001$) on quadriceps pain. Notably, individuals cycling with immersive VR while performing a lower perceptual load task chose to exercise at higher intensity despite greater quadriceps pain. Conversely, those performing a higher perceptual load task did not increase training intensity but reported higher pain, possibly reflecting greater mental effort requirements.

Westmattelmann et al. (2022) analysed performance data from the Virtual Tour de France 2020 on the Zwift platform. The study identified that relative power output explained most performance differences across six stages. This research highlighted performance-outcome gaps that require consideration of competition strategy and equipment use, with important implications for emerging mixed-reality sports.

Nambi et al. (2020) conducted a three-arm randomized controlled trial involving 45 university football players (15 per group) with chronic low back pain. The VR training group demonstrated superior improvements in pain, wellness, and sports performance outcomes (40m sprint, 4×5m sprint, and shuttle run) compared to both isokinetic training and conventional exercise control groups.

Technical and motor skill outcomes

Polikanova et al. (2022) employed VR motion analysis to examine joint angles, stick speed, response time, and hits/misses in 20 athletes (13 hockey players, 7 wrestlers). Hockey players showed more stable joint patterns and fewer head movements compared to wrestlers (0.66 vs. 1.25, $p = .043$). The study demonstrated that VR can successfully train individual parameters necessary for high performance in hockey, including motor response time to puck arrival, stick response time, puck catching, and movement analysis.

Bedir & Erhan (2021) investigated VR-based imagery (VRBI) training compared to video-modelling with imagery (VMBR+VM) and control conditions in 34 athletes. The VRBI group showed significantly greater improvements in shot performance and imagery skills over 4 weeks ($p < .05$). The VRBI program demonstrated superior efficiency in terms of both shooting performance and imagination skills compared to the traditionally used VMBR+VM approach.

Psychological and perceptual outcomes

Harrison et al. (2021) assessed VR presence interventions in 13 female footballers (age 20.5 ± 1.1 years). Cognitive anxiety differed significantly across conditions ($\chi^2 = 18.63$, $p < .001$), with VR interventions showing significant reductions compared to baseline ($p = .002$). The VR intervention significantly reduced cognitive and somatic anxiety, increased self-confidence, and reduced heart rate. However, the authors noted that future research is needed to understand the relationship between VR relaxation, kinematics, and performance.

Overall evidence summary

Across the seven included studies, VR-based interventions demonstrated promising but heterogeneous effects across performance domains. The evidence suggests that VR may be particularly effective for: (a) enhancing enjoyment and motivation during high-intensity exercise; (b) improving specific technical parameters such as response time and joint stability; (c) reducing anxiety and increasing confidence; and (d) supporting rehabilitation outcomes. However, the small number of studies, limited sample sizes, short intervention durations, and diverse sport contexts preclude robust generalizations. Furthermore, the absence of long-term follow-up assessments and limited ecological validity represent significant gaps in the current evidence base.

DISCUSSION

Summary of main findings

This systematic review synthesized evidence from seven experimental studies investigating VR effectiveness for enhancing athletic performance across physical, technical, and psychological domains. The findings indicate that VR-based interventions show promise in improving several aspects of sports performance, including increased enjoyment and power output during HIIT (Farrow et al., 2018), enhanced motor response time and joint stability (Polikanova et al., 2022), improved shooting performance and imagery skills (Bedir & Erhan, 2021), reduced cognitive and somatic anxiety (Harrison et al., 2021), and better pain management and sports performance in athletes with chronic low back pain (Nambi et al., 2020). However, the evidence base remains limited, heterogeneous, and insufficient to support broad, context-independent conclusions about VR's efficacy across all sports and performance domains.

Interpretation of findings through theoretical lenses

The observed effects can be interpreted through established theoretical frameworks in motor learning and cognitive psychology. First, VR provides rich multisensory stimulation combining visual, auditory, and proprioceptive feedback that may accelerate motor learning and skill adaptation through enhanced neural plasticity (Juliano et al., 2022; Salvadori et al., 2021). This aligns with motor learning theory, which emphasizes the importance of varied, context-rich practice environments for robust skill acquisition (Schmidt & Lee, 2023).

Second, the immersive and realistic nature of VR supports cognitive theories of mental practice and imagery (Kweon et al., 2023; Le Franc et al., 2021). By simulating realistic game situations, VR enables athletes to experience high-pressure scenarios, potentially improving decision-making, focus, and performance under stress (Le Noury et al., 2022; Palidis et al., 2017). This aligns with the broader literature on simulation training across diverse domains (Aufegger et al., 2017).

Third, the observed improvements in psychological outcomes reduced anxiety, increased confidence, and enhanced enjoyment can be understood through attentional control theory (Eysenck et al., 2007). VR may serve as an attentional distraction, redirecting focus away from pain or anxiety toward task-relevant stimuli, thereby improving performance and reducing perceived exertion (Wender et al., 2022).

Conceptual framework for VR in athletic performance

Based on the synthesized evidence and theoretical interpretations, we propose a conceptual framework illustrating the pathways through which VR may influence athletic performance (Figure 2).

 © 2026 ARD Asociación Española

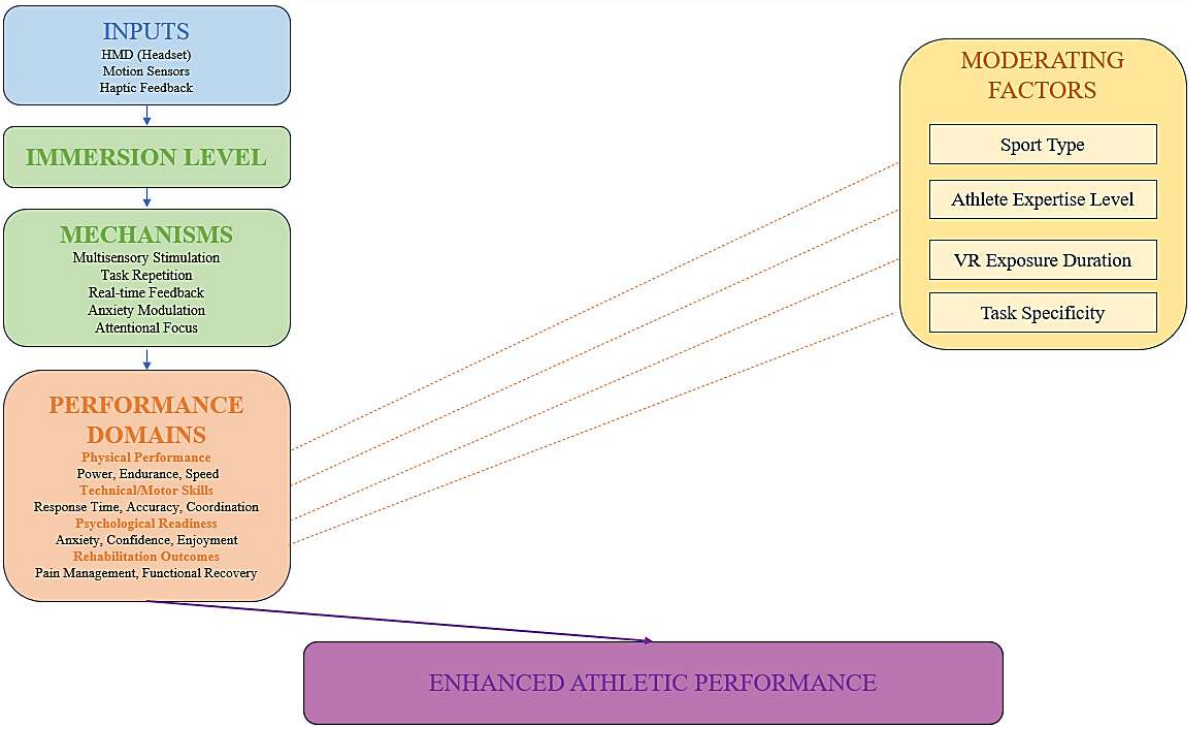


Figure 2. Conceptual framework: VR effect in athletic performance.

This framework positions VR as a multi-modal intervention operating through distinct yet interconnected pathways to influence performance outcomes.

Implications for theory and practice

The findings of this review have several implications for both theoretical development and practical application. For theory, this review underscores the importance of considering multisensory stimulation in motor learning research and highlights the need for integrative models that incorporate technological interventions into established performance frameworks. The conceptual framework proposed here offers a starting point for such integration, organizing the complex relationships between VR characteristics, mediating mechanisms, and performance outcomes. For practice, the findings suggest that VR can be a valuable supplementary training tool, particularly in contexts where: (a) physical training is limited by injury or logistical constraints; (b) psychological preparation is a priority; (c) specific technical parameters require isolated practice; and (d) performance monitoring and feedback are essential. Coaches and sports scientists should consider VR as part of a comprehensive training program rather than a replacement for traditional methods (Masiello et al., 2022). The personalized feedback and real-time monitoring capabilities of VR also present opportunities for individualized training prescription (Fusco & Tieri, 2022; Shah et al., 2023).

Social and ethical implications

The integration of VR into sports training raises several social and ethical considerations that warrant attention. Socially, the accessibility of this technology may be limited to athletes from developed countries or those with sufficient financial resources, potentially exacerbating existing performance inequalities (Arora et al., 2023). Ethically, it is important to ensure that VR does not replace the essential human interactions in training, such as emotional support and nuanced feedback from coaches (Arora et al., 2023). Additionally, the collection of personal data during VR training sessions raises privacy concerns that require appropriate

safeguards. As VR adoption in sports expands, these social and ethical dimensions must be addressed proactively through policy development, equitable access initiatives, and ethical guidelines.

Contextualizing findings within the broader literature

The findings of this review align with emerging evidence across related fields. For instance, research on simulation training for musicians has demonstrated the value of mental practice and simulation for performance enhancement (Aufegger et al., 2017). Similarly, studies on VR rehabilitation have shown benefits for motor recovery in clinical populations (Choi et al., 2023). The application of VR to social skills training for autism spectrum disorders further illustrates the technology's versatility (Tan et al., 2022). Together, these diverse applications suggest that VR's potential extends beyond sport-specific outcomes to encompass broader human performance enhancement.

However, this review also reveals that the sport performance literature lags behind other domains in terms of methodological rigor, standardization, and evidence synthesis. While clinical and educational applications have benefited from established protocols, outcome measures, and quality standards, sport performance research remains fragmented, with considerable variability in study designs, VR modalities, and performance assessments.

Strengths and limitations

Strengths of this review include the systematic approach to literature search and selection following PRISMA guidelines, the inclusion of studies from multiple databases, and the application of quality assessment procedures. The narrative synthesis approach allowed for meaningful integration despite methodological heterogeneity.

Limitations include: (1) the small number of studies (n = 7) meeting inclusion criteria, limiting the generalizability of findings; (2) substantial heterogeneity in study designs, populations, interventions, and outcomes, precluding meta-analysis; (3) the lack of long-term follow-up assessments in included studies, limiting conclusions about sustained effects; (4) potential publication bias, as positive findings are more likely to be published; (5) limited representation of diverse sports populations, with most studies focusing on cycling, football, and hockey; and (6) the absence of formal assessment of ecological validity in the included studies. These limitations should be considered when interpreting the findings and planning future research.

Future research directions

Based on the findings and limitations of this review, we propose a structured research agenda to advance the field, emphasizing the need for future studies to move beyond generalized inquiries of VR effectiveness toward performance-specific trials that investigate which particular outcomes and under what conditions VR yields optimal benefits, requiring clearly defined and sport-specific measures. Long-term longitudinal studies with follow-up periods of at least six months are essential to establish the durability of VR training effects, including skill retention, transfer to real-world competition, and the sustainability of psychological benefits, thereby distinguishing between acute and lasting performance improvements. Furthermore, research must prioritize ecological validity by designing interventions that bridge the gap between virtual training environments and actual competition settings, addressing the critical gap in evidence regarding transferability. Concurrently, investigators should examine the social and ethical implications of VR adoption, including barriers to access, equity issues, data privacy concerns, and the development of ethical frameworks for informed consent and appropriate implementation. The field would also benefit from consensus on standardized outcome measures, protocols, and reporting guidelines specific to VR sport performance research to facilitate cross-study comparisons and meta-analytic syntheses. Finally, interdisciplinary

 © 2026 ARD Asociación Española

collaboration among sports scientists, technologists, psychologists, and ethicists is imperative, as is systematic investigation of psychological and motivational factors such as individual differences in presence, immersion, and engagement that may moderate VR training effectiveness (Akbaş et al., 2019; Denche-Zamorano et al., 2023).

Research limitations

Several limitations of this review should be acknowledged. First, the sample of included studies may not represent the full population of athletes across various sports due to the limited number and diversity of studies. Second, the observed duration of VR use in training may have been too short to measure long-term impacts, as most studies employed brief interventions. Third, contextual factors such as individual psychological states, motivation, and prior experience with technology may influence outcomes but were not fully considered in the included studies. Fourth, the heterogeneity of outcome measures limited the ability to conduct quantitative synthesis. Finally, the quality assessment revealed methodological limitations in the included studies, suggesting that future research should prioritize rigorous experimental designs with appropriate controls, blinding, and sample size justification.

CONCLUSSION

This systematic review synthesizes the current, albeit limited, evidence on VR effectiveness for enhancing athletic performance across physical, technical, and psychological domains, indicating that VR shows promise as a supplementary training tool, particularly in controlled environments prioritizing multisensory stimulation, task repetition, and feedback, with demonstrated potential for improving power output, sprint performance, response time, joint stability, shooting accuracy, anxiety reduction, confidence enhancement, and enjoyment. However, the field remains nascent and the evidence base too heterogeneous to support broad generalizations, as the seven included studies exhibit considerable variability in design, intervention, and outcomes, while the absence of long-term follow-up and limited evidence for transfer to real competition represent critical gaps. This review provides a conceptual framework identifying three primary pathways motor skill enhancement, cognitive load modulation, and psychological readiness alongside a structured research agenda addressing performance-specific trials, longitudinal studies, ecological validity, equity and ethics, and outcome measurement standardization. Ultimately, realizing VR's potential as an essential component of modern sports training requires rigorous investigation, interdisciplinary collaboration, and careful attention to ethical and social implications to complement traditional methods and optimize athletic performance.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualization: Irma Febriyanti, Mochamad Ridwan, Ainun Zulfikar Rizki, Farruh Ahmedov. Methodology: Dwi Lorry Juniarisca, Sri Wicahyani, Mochamad Ridwan. Formal Analysis: Ainun Zulfikar Rizki, Farruh Ahmedov, Dwi Lorry Juniarisca. Investigation: Irma Febriyanti, Sri Wicahyani, Mochamad Ridwan. Data Curation: Dwi Lorry Juniarisca, Sri Wicahyani, Ainun Zulfikar Rizki. Writing – Original Draft: Irma Febriyanti, Ainun Zulfikar Rizki, Dwi Lorry Juniarisca. Writing – Review & Editing: Irma Febriyanti, Sri Wicahyani, Mochamad Ridwan, Farruh Ahmedov, Ainun Zulfikar Rizki. Supervision: Mochamad Ridwan, Farruh Ahmedov.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Akbaş, A., Marszałek, W., Kamieniarz, A., Polechoński, J., Słomka, K. J., & Juras, G. (2019). Application of virtual reality in competitive athletes: A review. *Journal of Human Kinetics*, *69*(1), 5-16. https://doi.org/10.2478/hukin-2019-0023

Arora, N. K., Roehrken, G., Crumbach, S., Phatak, A., Labott, B. K., Nicklas, A., Wicker, P., & Donath, L. (2023). Good scientific practice and ethics in sports and exercise science: A brief and comprehensive hands-on appraisal for sports research. *Sports*, *11*(2), Article 47. https://doi.org/10.3390/sports11020047

Atakan, M. M., Li, Y., Koşar, Ş. N., Turnagöl, H. H., & Yan, X. (2021). Evidence-based effects of high-intensity interval training on exercise capacity and health: A review with historical perspective. *International Journal of Environmental Research and Public Health*, *18*(13), Article 7201. https://doi.org/10.3390/ijerph18137201

Aufegger, L., Perkins, R., Wasley, D., & Williamon, A. (2017). Musicians' perceptions and experiences of using simulation training to develop performance skills. *Psychology of Music*, *45*(3). https://doi.org/10.1177/0305735616666940

Bashir, M., Soh, K. G., Samsudin, S., Akbar, S., Luo, S., & Sunardi, J. (2022). Effects of functional training on sprinting, jumping, and functional movement in athletes: A systematic review. *Frontiers in Physiology*, *13*, Article 1045870. https://doi.org/10.3389/fphys.2022.1045870

Bedir, D., & Erhan, S. E. (2021). The effect of virtual reality technology on the imagery skills and performance of target-based sports athletes. *Frontiers in Psychology*, *11*, Article 2073. https://doi.org/10.3389/fpsyg.2020.02073

Bui, V., & Alaei, A. (2022). Virtual reality in training artificial intelligence-based systems: A case study of fall detection. *Multimedia Tools and Applications*, *81*(22). https://doi.org/10.1007/s11042-022-13080-y

Cashin, A. G., & McAuley, J. H. (2020). Clinimetrics: Physiotherapy Evidence Database (PEDro) scale. *Journal of Physiotherapy*, *66*(1). https://doi.org/10.1016/j.jphys.2019.08.005

Choi, J. Y., Yi, S. H., Shim, D., Yoo, B., Park, E. S., & Rha, D. W. (2023). Home-based virtual reality-enhanced upper limb training system in children with brain injury: A randomized controlled trial. *Frontiers in Pediatrics, 11*. https://doi.org/10.3389/fped.2023.1131573

 © 2026 ARD Asociación Española

Collins, B. E. G., Donges, C., Robergs, R., Cooper, J., Sweeney, K., & Kingsley, M. (2023). Moderate continuous- and high-intensity interval training elicit comparable cardiovascular effect among middle-aged men regardless of recovery mode. *European Journal of Sport Science*, 23(8). https://doi.org/10.1080/17461391.2023.2171908

Corrigan, N., Păsărelu, C. R., & Voinescu, A. (2023). Immersive virtual reality for improving cognitive deficits in children with ADHD: A systematic review and meta-analysis. *Virtual Reality*, *27*(4). https://doi.org/10.1007/s10055-023-00768-1

Denche-Zamorano, A., Rodriguez-Redondo, Y., Barrios-Fernandez, S., Mendoza-Muñoz, M., Castillo-Paredes, A., Rojo-Ramos, J., Garcia-Gordillo, M. A., & Adsuar, J. C. (2023). Rehabilitation is the main topic in virtual and augmented reality and physical activity research: A bibliometric analysis. *Sensors*, 23(6), Article 2987. https://doi.org/10.3390/s23062987

Doré, B., Gaudreault, A., Everard, G., Ayena, J. C., Abboud, A., Robitaille, N., & Batcho, C. S. (2023). Acceptability, feasibility, and effectiveness of immersive virtual technologies to promote exercise in older adults: A systematic review and meta-analysis. *Sensors*, 23(5), Article 2506. https://doi.org/10.3390/s23052506

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion*, 7(2), 336-353. https://doi.org/10.1037/1528-3542.7.2.336

Fan, T., Wang, X., Song, X., Zhao, G., & Zhang, Z. (2023). Research status and emerging trends in virtual reality rehabilitation: Bibliometric and knowledge graph study. *JMIR Serious Games, 11*. https://doi.org/10.2196/41091

Farrow, M., Lutteroth, C., Rouse, P. C., & Bilzon, J. L. J. (2019). Virtual-reality exergaming improves performance during high-intensity interval training. *European Journal of Sport Science*, 19(6), 719-727. https://doi.org/10.1080/17461391.2018.1542459

Franceschi, A., Robinson, M. A., Owens, D., Brownlee, T., Ferrari Bravo, D., & Enright, K. (2023). Reliability and sensitivity to change of post-match physical performance measures in elite youth soccer players. *Frontiers in Sports and Active Living, 5*. https://doi.org/10.3389/fspor.2023.1173621

Fusco, A., & Tieri, G. (2022). Challenges and perspectives for clinical applications of immersive and non-immersive virtual reality. *Journal of Clinical Medicine*, *11*(15), Article 4540. https://doi.org/10.3390/jcm11154540

Haleva, Y., & Meckel, Y. (2020). The effect of basic technical training on performance capabilities of young soccer players. *Advances in Physical Education*, *10*(1). https://doi.org/10.4236/ape.2020.101003

Harrison, K., Potts, E., King, A. C., & Braun-Trocchio, R. (2021). The effectiveness of virtual reality on anxiety and performance in female soccer players. *Sports*, *9*(12). https://doi.org/10.3390/sports9120167

Juliano, J. M., Schweighofer, N., & Liew, S. L. (2022). Increased cognitive load in immersive virtual reality during visuomotor adaptation is associated with decreased long-term retention and context transfer. *Journal of NeuroEngineering and Rehabilitation*, *19*(1). https://doi.org/10.1186/s12984-022-01084-6

Krustrup, P., & Bangsbo, J. (2015). Recreational football is effective in the treatment of non-communicable diseases. *British Journal of Sports Medicine*, *49*(22). https://doi.org/10.1136/bjsports-2015-094955

Kuna, P., Hašková, A., & Borza, Ľ. (2023). Creation of virtual reality for education purposes. *Sustainability*, *15*(9). https://doi.org/10.3390/su15097153

Kunz, P., Engel, F. A., Holmberg, H. C., & Sperlich, B. (2019). A meta-comparison of the effects of high-intensity interval training to those of small-sided games and other training protocols on parameters related to the physiology and performance of youth soccer players. *Sports Medicine - Open*, *5*(1). https://doi.org/10.1186/s40798-019-0180-5

Kweon, J., Vigne, M. M., Jones, R. N., Carpenter, L. L., & Brown, J. C. (2023). Practice makes plasticity: 10-Hz rTMS enhances LTP-like plasticity in musicians and athletes. *Frontiers in Neural Circuits, 17*. https://doi.org/10.3389/fncir.2023.1124221

Le Franc, S., Fleury, M., Jeunet, C., Butet, S., Barillot, C., Bonan, I., Cogne, M., & Lecuyer, A. (2021). Influence of the visuo-proprioceptive illusion of movement and motor imagery of the wrist on EEG cortical excitability among healthy participants. *PLoS ONE*, *16*(9 September). https://doi.org/10.1371/journal.pone.0256723

Le Noury, P., Polman, R., Maloney, M., & Gorman, A. (2022). A narrative review of the current state of extended reality technology and how it can be utilised in sport. *Sports Medicine*, *52*(7). https://doi.org/10.1007/s40279-022-01669-0

LeMarshall, S. J., Stevens, L. M., Ragg, N. P., Barnes, L., Foster, J., & Canetti, E. F. D. (*202*3). Virtual reality-based interventions for the rehabilitation of vestibular and balance impairments post-concussion: A scoping review. *Journal of NeuroEngineering and Rehabilitation*, 20(1). https://doi.org/10.1186/s12984-023-01145-4

Li, L., & Smith, D. M. (2021). Neural efficiency in athletes: A systematic review. *Frontiers in Behavioral Neuroscience, 15*. https://doi.org/10.3389/fnbeh.2021.698555

Li Pira, G., Aquilini, B., Davoli, A., Silvana, G., & Ruini, C. (2023). The use of virtual reality interventions to promote positive mental health: Systematic literature review. *JMIR Mental Health, 10*. https://doi.org/10.2196/44998

Liu, J., Zhu, L., & Su, Y. (2020). Comparative effectiveness of high-intensity interval training and moderate-intensity continuous training for cardiometabolic risk factors and cardiorespiratory fitness in childhood obesity: A meta-analysis of randomized controlled trials. *Frontiers in Physiology, 11*. https://doi.org/10.3389/fphys.2020.00214

Loetscher, T., Barrett, A. M., Billinghurst, M., & Lange, B. (2023). Immersive medical virtual reality: Still a novelty or already a necessity? *Journal of Neurology, Neurosurgery & Psychiatry, 94*(7). https://doi.org/10.1136/jnnp-2022-330207

Masiello, I., Herault, R., Mansfeld, M., & Skogqvist, M. (2022). Simulation-based VR training for the nuclear sector: A pilot study. *Sustainability*, *14*(13). https://doi.org/10.3390/su14137984

Nambi, G., Abdelbasset, W. K., Elsayed, S. H., Alrawaili, S. M., Abodonya, A. M., Saleh, A. K., & Elnegamy, T. E. (2020). Comparative Effects of Isokinetic Training and Virtual Reality Training on Sports Performances in University Football Players with Chronic Low Back Pain-Randomized Controlled Study. *Evidence-Based Complementary and Alternative Medicine, 2020*(1), 2981273. https://doi.org/https://doi.org/10.1155/2020/2981273

Ochi, G., Kuwamizu, R., Fujimoto, T., Ikarashi, K., Yamashiro, K., & Sato, D. (2022). The effects of acute virtual reality exergaming on mood and executive function: Exploratory crossover trial. *JMIR Serious Games*, *10*(3). https://doi.org/10.2196/38200

Oliveira, C. C., Ferreira, D., Caetano, C., Granja, D., Pinto, R., Mendes, B., & Sousa, M. (2017). Nutrition and supplementation in soccer. *Sports*, *5*(2). https://doi.org/10.3390/sports5020028

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*. https://doi.org/10.1136/bmj.n71

Palidis, D. J., Wyder-Hodge, P. A., Fooken, J., & Spering, M. (2017). Distinct eye movement patterns enhance dynamic visual acuity. *PLoS ONE*, *12*(2). https://doi.org/10.1371/journal.pone.0172061

Panice, L., Deprá, P. P., de Oliveira Jaime, M., da Costa, J. C., Avelar, A., Kravchychyn, C., Junior, S. F., & Borges, P. H. (2020). Which defensive tactical indicators are associated with victory in the semifinals and finals of the 2014 FIFA World Cup? *Motriz: Revista de Educação Física, 26*(3). https://doi.org/10.1590/s1980-6574202000030100

 © 2026 ARD Asociación Española

Pastel, S., Petri, K., Chen, C. H., Wiegand Cáceres, A. M., Stirnatis, M., Nübel, C., Schlotter, L., & Witte, K. (2023). Training in virtual reality enables learning of a complex sports movement. *Virtual Reality*, *27*(2). https://doi.org/10.1007/s10055-022-00679-7

Polechoński, J., Zwierzchowska, A., Makioła, Ł., Groffik, D., & Kostorz, K. (2022). Handheld weights as an effective and comfortable way to increase exercise intensity of physical activity in virtual reality: Empirical study. *JMIR Serious Games*, *10*(4), Article e39932. https://doi.org/10.2196/39932

Polikanova, I., Yakushina, A., Leonov, S., Kruchinina, A., Chertopolokhov, V., & Liutsko, L. (2022). What differences exist in professional ice hockey performance using virtual reality (VR) technology between professional hockey players and freestyle wrestlers? A pilot study. *Sports*, *10*(8), Article 116. https://doi.org/10.3390/sports10080116

Radhakrishnan, U., Chinello, F., & Koumaditis, K. (2023). Investigating the effectiveness of immersive VR skill training and its link to physiological arousal. *Virtual Reality*, *27*(2). https://doi.org/10.1007/s10055-022-00699-3

Salvadori, A., Fanari, P., Marzullo, P., Codecasa, F., Tovaglieri, I., Cornacchia, M., Terruzzi, I., Ferrulli, A., Palmulli, P., Brunani, A., Lanzi, S., & Luzi, L. (2021). Playing around the anaerobic threshold during COVID-19 pandemic: Advantages and disadvantages of adding bouts of anaerobic work to aerobic activity in physical treatment of individuals with obesity. *Acta Diabetologica*, *58*(10). https://doi.org/10.1007/s00592-021-01747-1

Schmidt, R. A., & Lee, T. D. (2023). *Motor learning and performance: From principles to application* (7th ed.). Human Kinetics.

Shah, S. H. H., Karlsen, A. S. T., Solberg, M., & Hameed, I. A. (2023). A social VR-based collaborative exergame for rehabilitation: codesign, development and user study. *Virtual Reality*, *27*(4). https://doi.org/10.1007/s10055-022-00721-8

Strauss, A., Jacobs, S., & Van Den Berg, L. (2014). The influence of anaerobic and aerobic fitness on the technical skill ability of national elite male under-18 african soccer players. *Mediterranean Journal of Social Sciences*, *5*(27). https://doi.org/10.5901/mjss.2014.v5n27p1704

Tadiotto, M. C., Corazza, P. R. P., Menezes-Junior, F. J. de, Moraes-Junior, F. B. de, Tozo, T. A. A., Purim, K. S. M., Mota, J., & Leite, N. (2023). Effects and individual response of continuous and interval training on adiponectin concentration, cardiometabolic risk factors, and physical fitness in overweight adolescents. *European Journal of Pediatrics*, *182*(6). https://doi.org/10.1007/s00431-023-04974-6

Tan, B. L., Shi, J., Yang, S., Loh, H., Ng, D., Choo, C., & Medalia, A. (2022). The use of virtual reality and augmented reality in psychosocial rehabilitation for adults with neurodevelopmental disorders: A systematic review. *Frontiers in Psychiatry*, *13*, Article 1055204. https://doi.org/10.3389/fpsyt.2022.1055204

Urquhart, D. S., & Saynor, Z. L. (2018). Exercise testing in cystic fibrosis: Who and why? *Paediatric Respiratory Reviews, 27*. https://doi.org/10.1016/j.prrv.2018.01.004

Wender, C. L. A., Tomporowski, P. D., Ahn, S. J. G., & O'Connor, P. J. (2022). Virtual reality-based distraction on pain, performance, and anxiety during and after moderate-vigorous intensity cycling. *Physiology & Behavior*, *250*, Article 113779. https://doi.org/10.1016/j.physbeh.2022.113779

Westmattelmann, D., Stoffers, B., Sprenger, M., Grotenhermen, J. G., & Schewe, G. (2022). The performance-result gap in mixed-reality cycling: Evidence from the Virtual Tour de France 2020 on Zwift. *Frontiers in Physiology*, *13*, Article 868902. https://doi.org/10.3389/fphys.2022.868902

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Predictive value of creatinine/cystatin C ratio and physical activity for all-cause mortality risk in hypertensive patients: A cohort study based on NHANES data

Zhujun Mao. *Wudang Mountain Branch. Taihe Hospital Affiliated to Hubei University of Medicine. Shiyan, China. School of Basic Medical Sciences. China Three Gorges University. Yichang, China.*
Jiahe Zhang. *School of Basic Medical Sciences. China Three Gorges University. Yichang, China.*
Peng Zhang . *Wudang Mountain Branch. Taihe Hospital Affiliated to Hubei University of Medicine. Shiyan, China.*

ABSTRACT

Physical activity (PA) is a cornerstone of hypertension management, but whether muscle mass influences its survival benefits remains unclear. The serum creatinine-to-cystatin C ratio (CCR) has been proposed as a surrogate marker of muscle mass, although it is also affected by renal function, nutritional status, and inflammation. This study examined the association between CCR and mortality in hypertensive adults and explored the role of PA intensity. This retrospective cohort study included 2,432 adults with essential hypertension from the National Health and Nutrition Examination Survey (NHANES). Hypertension was defined as systolic blood pressure ≥140 mmHg, diastolic blood pressure ≥90 mmHg, or use of antihypertensive medication. Muscle mass was estimated using CCR, and PA was classified as inactive, moderate, or vigorous. All-cause mortality was obtained through linkage with the National Death Index. Covariates included age, sex, race/ethnicity, education, smoking status, body mass index (BMI), albumin, C-reactive protein (CRP), lipid profile, and estimated glomerular filtration rate (eGFR). Kaplan–Meier analyses and multivariable Cox regression models were used. Low CCR was associated with older age, female sex, higher CRP, and lower albumin levels. In multivariable analyses, low CCR independently predicted all-cause mortality and outperformed indicators such as BMI and lipid measures. Stratified analyses suggested a stronger association between low CCR and mortality among participants performing vigorous PA (HR 1.95) than among those with moderate PA (HR 1.20) or inactivity (HR 1.29), although the interaction between CCR and PA was not significant (*p*-interaction = .21). Exercise was associated with survival in those with higher CCR. CCR is an independent predictor of mortality in hypertensive adults and adds value beyond conventional markers. Low CCR may be associated with reduced survival benefits from vigorous PA, although this finding requires confirmation. Incorporating CCR into risk assessment may help identify patients who could benefit from muscle-preserving strategies and resistance training.
Keywords: sport medicine; hypertension; creatinine-to-cystatin c ratio (CCR); muscle mass; physical activity; all-cause mortality; sarcopenia; national health and nutrition examination survey (NHANES); risk stratification; nomogram; survival analysis.

Cite this article as:
Mao, Z., Zhang, J., & Zhang, P. (2026). Predictive value of creatinine/cystatin C ratio and physical activity for all-cause mortality risk in hypertensive patients: A cohort study based on NHANES data. *Journal of Human Sport and Exercise, 21*(4), 1350-1368. https://doi.org/10.55860/1spaax18

Corresponding author. *Wudang Mountain Branch, Taihe Hospital Affiliated to Hubei University of Medicine, Shiyan, 442714, China.*
E-mail: 15872756406@163.com
Submitted for publication April 15, 2026.
Accepted for publication June 16, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/1spaax18

© 2026 ARD Asociación Española

INTRODUCTION

Hypertension is a major risk factor for cardiovascular morbidity and premature mortality, highlighting the importance of its management worldwide (Mills et al., 2020). Regular PA is a foundational non-pharmacological approach to blood pressure regulation (Whelton et al., 2018) and cardiovascular risk mitigation, but its survival benefits may also be conditioned by skeletal muscle integrity, which is an important element of glucose homeostasis and systemic inflammation (Pedersen & Febbraio, 2012). Sarcopenia, a syndrome characterized by progressive loss of muscle mass and function, is especially prone to occur in patients with hypertension, driven by chronic inflammation, oxidative stress, and excessive activation of the renin-angiotensin-aldosterone system (RAAS) (Springer et al., 2017). This loss of muscle can reduce exercise capacity, making conventional measures such as BMI, which cannot differentiate lean mass from fat mass, less useful in the accurate classification of risks (Srikanthan & Karlamangla, 2014). Serum CCR may provide a more valid assessment of muscle reserve, as it is a biomarker combining muscle-derived creatinine and cystatin C (Tabara et al., 2020), where a lower CCR value may indicate muscle wasting and frailty (Chen et al., 2022). Though PA and muscle mass are correlated with longevity independently, it is not clear how muscle mass influences the survival advantage of PA among hypertensive patients (Liao et al., 2025). Using NHANES data, this study tested the relationship between CCR and all-cause mortality and further identified the interaction between muscle mass and PA with the aim of guiding muscle-centred exercise interventions to help manage hypertension.

MATERIALS AND METHODS

Data source and study population

The present study used NHANES data. NHANES is a program conducted by the National Center for Health Statistics (NCHS) at the Centers for Disease Control and Prevention (CDC). NHANES uses a stratified, multistage, complex probability sampling design to determine the health and nutrition of the non-institutionalized US civilian population. The research protocol was approved by the NCHS Research Ethics Review Board, and written informed consent was obtained from all participants. Adults with essential hypertension were selected for inclusion in the study if they had a mean systolic blood pressure ≥140 mmHg or ≥90 mmHg diastolic blood pressure measured in the Mobile Examination Center (MEC), or if they reported a physician diagnosis of hypertension with current use of antihypertensive medication.

Data cleaning

To ensure analytical rigor, an exclusion process was followed strictly. Individuals were excluded if they were: (1) below the age of 18 years or pregnant; (2) lacking laboratory data on serum creatinine or cystatin C needed to estimate the primary exposure; (3) lacking verifiable information on mortality status or duration of follow-up through probabilistic linkage with the NDI; or (4) lacking one of the main sociodemographic or clinical covariates: education, marital status, BMI, or smoking history. After applying these criteria, the final analytic cohort included 2,432 hypertensive adults, of whom 1,179 were men and 1,253 were women.

Variable definitions

The main exposure, serum CCR, was calculated using standardized laboratory values (serum creatinine [mg/dL]/cystatin C [mg/L]) and was used as a proxy indicator that primarily reflects skeletal muscle mass but is also influenced by renal function, nutritional status, and inflammatory state. The major outcome was all-cause mortality; survival status and follow-up time were determined by probabilistic linkage with NDI records. A detailed covariate list was taken into consideration to control potential confounding: sociodemographic variables (age, sex, race/ethnicity, education, marital status), lifestyle variables (smoking, alcohol

consumption), anthropometric variables (body mass index [BMI]), and biochemical variables (albumin, C-reactive protein [CRP], total cholesterol, high-density lipoprotein cholesterol [HDL-C], and estimated glomerular filtration rate [eGFR]). PA was assessed using structured questionnaires, whereby participants were classified into inactive, moderate-intensity, and vigorous-intensity groups according to self-reported frequency and duration.

Statistical analysis

The statistical tests were carried out with standard statistical software. Baseline characteristics were reported as mean ± standard deviation (SD) for continuous data and frequencies (expressed as percentages) for categorical data, with intergroup comparisons using Student's t-test or Mann–Whitney U test for continuous data and the chi-square test for categorical variables. Kaplan–Meier curves were used to visualize survival curves, and the log-rank test was used to compare them. Multivariable Cox proportional hazards regression models were used to estimate hazard ratios with 95% confidence intervals (CIs), especially the interaction between CCR levels and physical activity levels on mortality risk. A prognostic nomogram was then constructed using identified independent predictors, and its performance was assessed by discrimination using the area under the receiver operating characteristic curve (AUC), calibration plots to assess agreement between predicted and observed survival, and decision curve analysis (DCA) to measure net clinical benefit over a range of threshold probabilities. All statistical tests were two-sided, and statistical significance was set at $p < .05$.

RESULTS

Comparison of baseline characteristics

The final analytic cohort included 2,432 adults with hypertension, comprising 1,253 women and 1,179 men. Women were slightly older than men (68.1 ± 13.4 vs. 65.8 ± 14.3 years) and had lower weight and height, but a slightly higher BMI (29.6 ± 6.6 vs. 28.8 ± 5.4 kg/m²). Women also exhibited higher mean systolic blood pressure (149.1 ± 22.5 mmHg) and elevated lipid parameters, including total, high-density lipoprotein (HDL), and non-HDL cholesterol, whereas men had higher serum albumin, creatinine, and cystatin C levels. The CCR, a surrogate marker of skeletal muscle mass, was significantly lower in women (0.77 ± 0.18 vs. 0.99 ± 0.23), and the prevalence of low CCR was higher among women (26.1% vs. 23.7%), despite similar eGFR between sexes. Women had a longer follow-up duration (161 ± 71 months vs. 149 ± 76 months in men). Sociodemographic and lifestyle patterns also differed: men were more likely to be married or cohabiting (69.0%) and reported higher rates of smoking and physical activity (49.8% overall, with 22.1% engaging in vigorous activity), whereas women were more often widowed or divorced (53.4%), predominantly never-smokers (62.8%), and had a slightly higher rate of antihypertensive medication use (64.6% vs. 60.3% in men). These baseline differences indicate a female phenotype characterized by older age, dyslipidaemia, and lower muscle reserve, while men exhibited larger body size and higher levels of smoking and exercise, providing a heterogeneous basis for prognostic modelling.

Correlation between CCR and clinical characteristics

CCR-based stratification identified different clinical phenotypes. The low-CCR group was significantly older (mean age 69.8 vs. 64.2 years) and had smaller body size, but BMI was also higher, indicating a sarcopenic obesity phenotype. This population had a distinct hemodynamic and metabolic pattern with increased pulse pressure (greater systolic and reduced diastolic blood pressure), lower serum albumin, and increased inflammatory (CRP) and lipid markers (total cholesterol), although HDL levels were higher. Despite lower serum creatinine levels, eGFR was higher, possibly reflecting creatinine-based overestimation in the context of skeletal muscle loss.

 © 2026 ARD Asociación Española

Table 1. Baseline participant characteristics.

Characteristics	Female (n = 1253)	Male (n = 1179)
Age	68.06 ± 13.41	65.84 ± 14.26
Weight, kg	74.67 ± 18.68	85.90 ± 18.74
Height, cm	158.82 ± 7.22	172.51 ± 7.49
Body Mass Index	29.57 ± 6.57	28.82 ± 5.42
Systolic BP, mmHg	149.10 ± 22.53	143.18 ± 20.41
Diastolic BP, mmHg	70.00 ± 17.28	72.83 ± 18.38
Albumin, g/dL	4.19 ± 0.30	4.32 ± 0.33
CRP, mg/dL	0.66 ± 1.18	0.55 ± 1.19
Total Cholesterol, mg/dL	216.06 ± 40.09	200.57 ± 42.21
HDL Cholesterol, mg/dL	56.85 ± 16.66	46.59 ± 14.13
Non-HDL Cholesterol, mg/dL	159.25 ± 40.54	153.62 ± 43.49
Creatinine, mg/dL	0.86 ± 0.75	1.13 ± 0.86
Cystatin C, mg/L	1.11 ± 0.64	1.16 ± 0.69
CCR Ratio	0.77 ± 0.18	0.99 ± 0.23
GFR, mL/min/1.73m²	82.47 ± 24.61	81.86 ± 24.44
Overall Survival, months	161.00 ± 71.31	148.88 ± 75.79
Ethnicity		
Non-Hispanic White	679 (54.2%)	637 (54.0%)
Mexican American	235 (18.8%)	227 (19.3%)
Non-Hispanic Black	252 (20.1%)	254 (21.5%)
Other Race	24 (1.9%)	23 (2.0%)
Other Hispanic	63 (5.0%)	38 (3.2%)
Education level		
Less than 9th grade	126 (10.1%)	221 (18.7%)
9-11th grade	283 (22.6%)	297 (25.2%)
High school graduate/GED	327 (26.1%)	245 (20.8%)
Some college/AA	241 (19.2%)	207 (17.6%)
College graduate or above	271 (21.6%)	208 (17.6%)
Unknown	5 (0.4%)	1 (0.1%)
Marital status		
Married or living with partner	520 (41.5%)	814 (69.0%)
Widowed, divorced or separated	669 (53.4%)	325 (27.6%)
Never married	64 (5.1%)	40 (3.4%)
Hypertension medication		
No	444 (35.4%)	468 (39.7%)
Yes	809 (64.6%)	711 (60.3%)
Diabetes		
No	1031 (82.3%)	947 (80.3%)
Yes	221 (17.6%)	232 (19.7%)
Unknown	1 (0.1%)	0 (0.0%)
Low CCR		
No	926 (73.9%)	900 (76.3%)
Yes	327 (26.1%)	279 (23.7%)
Smoking status		
Never smoked	787 (62.8%)	404 (34.3%)
Former smoker	329 (26.3%)	579 (49.1%)
Current smoker	137 (10.9%)	196 (16.6%)
Exercise habits		
No exercise	754 (60.2%)	592 (50.2%)
Exercise	499 (39.8%)	587 (49.8%)
Exercise intensity		
Light	754 (60.2%)	592 (50.2%)
Moderate	324 (25.9%)	327 (27.7%)
Vigorous	175 (14.0%)	260 (22.1%)

Table 2. Association between CCR and clinical characteristics.

Variable	Low CCR	High CCR	*p*-value
Age	69.80 ± 12.64	64.18 ± 14.47	<.001
Weight (kg)	77.30 ± 19.71	82.93 ± 18.94	<.001
Height (cm)	161.59 ± 9.15	169.33 ± 9.39	<.001
BMI	29.57 ± 6.50	28.84 ± 5.54	.003
SBP (mmHg)	148.94 ± 21.63	143.53 ± 21.50	<.001
DBP (mmHg)	68.92 ± 18.52	73.82 ± 16.85	<.001
Albumin (g/dL)	4.23 ± 0.33	4.27 ± 0.32	<.001
CRP (mg/dL)	0.71 ± 1.40	0.51 ± 0.91	<.001
TC (mg/dL)	210.25 ± 42.09	206.85 ± 41.54	.045
HDL (mg/dL)	53.18 ± 16.48	50.57 ± 16.04	<.001
Non-HDL (mg/dL)	157.11 ± 42.11	155.93 ± 42.07	.488
Creatinine (mg/dL)	0.80 ± 0.38	1.19 ± 1.05	<.001
Cystatin C (mg/L)	1.15 ± 0.49	1.11 ± 0.80	.192
eGFR (mL/min/1.73m²)	87.77 ± 23.24	76.58 ± 24.51	<.001
Follow-up time (months)	147.97 ± 74.94	162.27 ± 71.86	<.001
Gender			**<.001**
Female	883 (72.6%)	370 (30.4%)	
Male	333 (27.4%)	846 (69.6%)	
Ethnicity			**<.001**
Non-Hispanic White	697 (57.3%)	619 (50.9%)	
Mexican American	286 (23.5%)	176 (14.5%)	
Non-Hispanic Black	146 (12.0%)	360 (29.6%)	
Other Race	22 (1.8%)	25 (2.1%)	
Other Hispanic	65 (5.3%)	36 (3.0%)	
Education level			**<.001**
Less than 9th grade	128 (10.5%)	219 (18.0%)	
9-11th grade	332 (27.3%)	248 (20.4%)	
High school graduate/GED	301 (24.8%)	271 (22.3%)	
Some college/AA	219 (18.0%)	229 (18.8%)	
College graduate or above	233 (19.2%)	246 (20.2%)	
Unknown	3 (0.2%)	3 (0.2%)	
Marital status			**<.001**
Married/Living with partner	574 (47.2%)	760 (62.5%)	
Widowed/Divorced/Separated	566 (46.5%)	428 (35.2%)	
Never married	76 (6.2%)	28 (2.3%)	
Hypertension medication			**.402**
No	446 (36.7%)	466 (38.3%)	
Yes	770 (63.3%)	750 (61.7%)	
Diabetes			**.598**
No	987 (81.2%)	991 (81.5%)	
Yes	228 (18.8%)	225 (18.5%)	
Unknown	1 (0.1%)	0 (0.0%)	
Low CCR indicator			**<.001**
No	610 (50.2%)	1216 (100.0%)	
Yes	606 (49.8%)	0 (0.0%)	
Smoking status			**<.001**
Never	661 (54.4%)	530 (43.6%)	
Former	391 (32.2%)	517 (42.5%)	
Current	164 (13.5%)	169 (13.9%)	
Exercise habit			**<.001**
No	761 (62.6%)	585 (48.1%)	
Yes	455 (37.4%)	631 (51.9%)	
Exercise intensity			**<.001**
Light	761 (62.6%)	585 (48.1%)	
Moderate	300 (24.7%)	351 (28.9%)	
Vigorous	155 (12.7%)	280 (23.0%)	
Age binary			**<.001**
Low Age	490 (40.3%)	705 (58.0%)	
High Age	726 (59.7%)	511 (42.0%)	

 © 2026 ARD Asociación Española

The low-CCR group was predominantly female (around two-thirds) and included more non-Hispanic Whites or Mexican Americans, lower education levels, and higher rates of widowhood or divorce. The lifestyle features reflected a sedentary profile, with a higher percentage of never-smokers and a much lower percentage of moderate and vigorous physical activity. By contrast, the high-CCR group was predominantly younger and male, with larger body size, higher socioeconomic status, and active lifestyles, including increased rates of smoking and exercise intensity. Such results imply that low CCR is an indicator of low muscle mass and also suggests the presence of a susceptible hypertensive subgroup in terms of aging, systemic inflammation, physical inactivity, and social disadvantage.

The CCR distribution was highly sexually dimorphic, with a much higher median value in males than in females (~1.0 vs. .8, $p < .001$), which is suggestive of greater physiological muscle reserve. In line with the pathophysiology of sarcopenic aging, an age-related reduction in CCR was noted ($p < .001$), whereas physical activity intensity exhibited a positive gradient against CCR ($p < .001$), indicating that vigorous physical exercise may have protective effects on muscle preservation. Smoking status was statistically significant but may not be clinically meaningful, whereas diabetes status was not significantly associated with CCR distribution. Correlation-based studies showed that CCR had negative correlations with systolic blood pressure (r = -.138, $p < .001$) and positive correlations with diastolic blood pressure (r = .140, $p < .001$), suggesting that muscle depletion is connected to the expansion of pulse pressure. There was a negative relationship between CCR and inflammatory markers (CRP) and a positive relationship with nutritional markers (albumin), indicating that systemic inflammation and malnutrition could be involved in muscle wasting. The strongest inverse relationship was observed with eGFR (r = −.329, $p < .001$), reflecting the mathematical dependence of CCR on serum creatinine levels. The stratification into low- versus high-CCR phenotypes further demonstrated the presence of a high-risk profile: the low-CCR group comprised mostly (72.6%) elderly women with a sarcopenic-obese anthropometric appearance (lower weight and height and slightly higher BMI), lower socioeconomic attainment, and inactive lifestyles. Together, these results suggest that CCR is not only a proxy biomarker of muscle mass but a complex biomarker that expresses the interactions between aging, inflammatory burden, and physical frailty in hypertensive patients.

Survival analysis and Cox regression

In this hypertensive cohort, univariate Cox regression analysis showed that several continuous variables were significantly associated with all-cause mortality: each additional year of age increased the hazard by approximately 9% (HR = 1.09, 95% CI 1.08-1.09, $p < .001$); BMI was inversely associated with risk, with a 4% reduction per unit increase (HR = 0.96, 95% CI 0.95-0.97, $p < .001$); systolic blood pressure (SBP) increased risk by about 1% per mmHg (HR = 1.01, 95% CI 1.01-1.01, $p < .001$); higher serum albumin was protective (HR = 0.53, 95% CI 0.45-0.62, $p < .001$), whereas elevated CRP indicated increased risk (HR = 1.05, 95% CI 1.02-1.08, $p < .001$). Higher eGFR modestly reduced mortality (HR = 0.98, 95% CI 0.98-0.98, $p < .001$). Among categorical variables, men had a 17% higher risk than women (HR = 1.17, 95% CI 1.06-1.30, $p = .002$), and widowed or divorced individuals had a 33% higher risk (HR = 1.33, 95% CI 1.20-1.47, $p < .001$). Diabetes, smoking, and low CCR were each important risk factors, and regular physical activity was associated with a 35% reduction in mortality risk (HR = 0.65, 95% CI 0.58-0.72, $p = .001$). After multivariable adjustment, age, BMI, SBP, albumin, HDL cholesterol, CCR, eGFR, male sex, smoking, diabetes, and physical inactivity were independent predictors. It is important to note that CCR had a hazard ratio of 0.13 (95% CI 0.09-0.18), and a lower creatinine-to-cystatin C ratio, indicating lower muscle mass, was a powerful independent risk factor. These findings were confirmed by Kaplan–Meier survival curves: participants aged 69 or older with low BMI, high SBP, albumin of less than 4.30 g/dL, low CCR, and low eGFR had significantly worse survival outcomes, and smokers and individuals with diabetes showed poorer outcomes compared with those who exercised regularly. Taken together, these results indicate that CCR is not a simple reflection

of skeletal muscle mass but rather a composite marker influenced by age, nutritional status, and renal function, such that people with low CCR are older, frailer, and more susceptible to death.

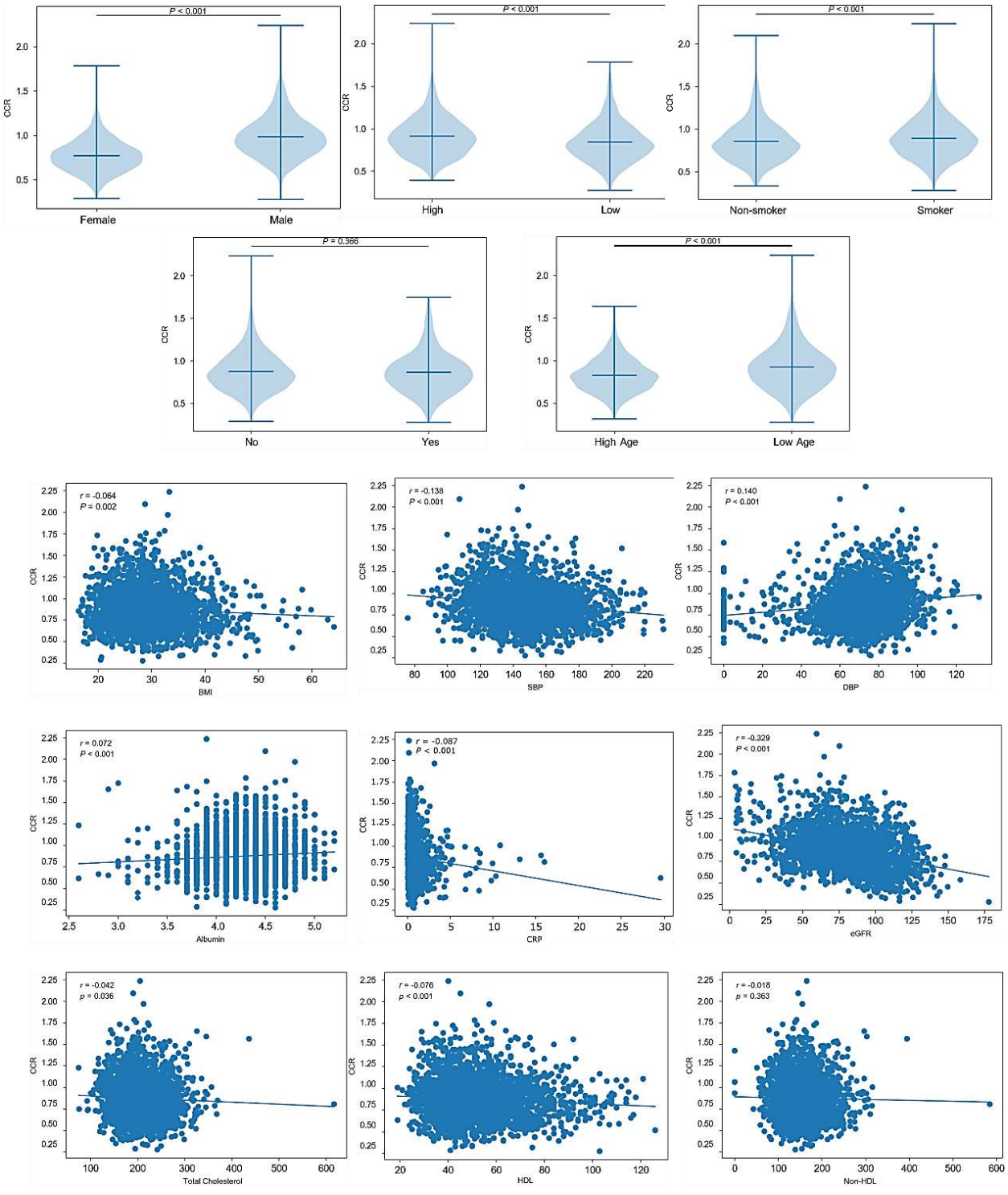


Figure 1. Stratified distribution and correlation analyses of CCR across baseline subject characteristics.

 © 2026 ARD Asociación Española

Table 3. Univariate Cox proportional hazards analysis of variables associated with all-cause mortality.

Numerical variable	**HR (95% CI)**	***p*-value**
Age	1.09 (1.08-1.09)	<.001
Weight (kg)	0.99 (0.98-0.99)	<.001
Height (cm)	0.99 (0.99-1.00)	.005
BMI	0.96 (0.95-0.97)	<.001
Systolic blood pressure (mmHg)	1.01 (1.01-1.01)	<.001
Albumin (g/dL)	0.53 (0.45-0.62)	<.001
CRP (mg/dL)	1.05 (1.02-1.08)	<.001
TC (mg/dL)	1.00 (1.00-1.00)	.023
HDL (mg/dL)	1.00 (1.00-1.01)	.124
Cystatin C (mg/L)	0.37 (0.3-0.46)	<.001
eGFR (mL/min/1.73m²)	0.98 (0.98-0.98)	<.001
Categorical variable		
Gender	1.17 (1.06-1.3)	.002
Ethnicity	0.69 (0.62-0.76)	<.001
Education level	0.96 (0.86-1.06)	.396
Marital status	1.33 (1.2-1.47)	<.001
Hypertension medication	1.31 (1.18-1.46)	<.001
Diabetes	1.51 (1.34-1.71)	<.001
Low CCR indicator	1.48 (1.33-1.65)	<.001
Smoking status	1.28 (1.16-1.42)	<.001
Exercise habit	0.65 (0.58-0.72)	<.001

Table 4. Multivariate Cox proportional hazards analysis of independent prognostic factors for all-cause mortality.

Numerical variable	**HR (95% CI)**	***p*-value**
Age	1.06 (1.05-1.07)	<.001
BMI	0.99 (0.98-1.00)	.013
Systolic blood pressure (mmHg)	1.00 (1.00-1.01)	.013
Albumin (g/dL)	0.62 (0.52-0.73)	<.001
HDL (mg/dL)	1.01 (1.00-1.01)	<.001
CCR Ratio	0.13 (0.09-0.18)	<.001
eGFR (mL/min/1.73m²)	0.98 (0.98-0.98)	<.001
Categorical variable		
Gender	2.25 (1.98-2.57)	<.001
Smoking status	1.36 (1.22-1.51)	<.001
Diabetes	1.39 (1.23-1.57)	<.001
Exercise habit	0.78 (0.70-0.87)	<.001

Subgroup analysis of exercise intensity and interaction

In this cohort, we examined the interaction between CCR and exercise on all-cause mortality. No significant interaction was observed between CCR status and exercise (*p*-interaction = .21), indicating that the adverse effect of low CCR on mortality was consistent regardless of exercise participation. Among non-exercisers, individuals with low CCR had a hazard ratio (HR) of 1.30 (95% CI 1.14-1.48) compared with those with high CCR, whereas among exercisers, the HR was 1.48 (95% CI 1.26-1.74). Stratification by exercise intensity revealed HRs for low versus high CCR of 1.29 (95% CI 1.13-1.47) for non-exercisers, 1.20 (95% CI 0.98-1.45, $p = .072$) for moderate-intensity exercisers, and 1.95 (95% CI 1.46-2.60, $p < .001$) for vigorous exercisers. Although the point estimates suggest a gradient of risk across exercise intensities, the lack of significant interaction ($p = .21$) precludes definitive conclusions about effect modification. Receiver operating characteristic (ROC) analysis showed that predictive performance was higher for selected variables: age (area under the curve or AUC = 0.835) had the highest predictive power, whereas systolic blood pressure, BMI, albumin, CCR, and eGFR had lower predictive value. Although CCR had a small AUC, it still had independent prognostic value when included in multivariable models. Forest plots and Kaplan–Meier curves repeatedly established that increased CCR correlated with improved survival regardless of exercise status

and that exercise resulted in relatively small benefits among individuals with low CCR, consistent with the possibility that muscle depletion may limit exercise benefits, though this interpretation is speculative given the non-significant interaction. The intensity-based analysis revealed the greatest risk in the vigorous exercise group, and the moderate-activity association was non-significant, potentially due to sample size constraints or selection bias. Overall, these results suggest that CCR, as a surrogate marker of muscle mass, has a close relationship with mortality in hypertensive patients, and its prognostic value remains consistent across different exercise behaviours. Although moderate exercise can have some overall health benefits, further studies with larger sample sizes are needed to clarify whether moderate exercise differentially affects survival in low-CCR individuals.

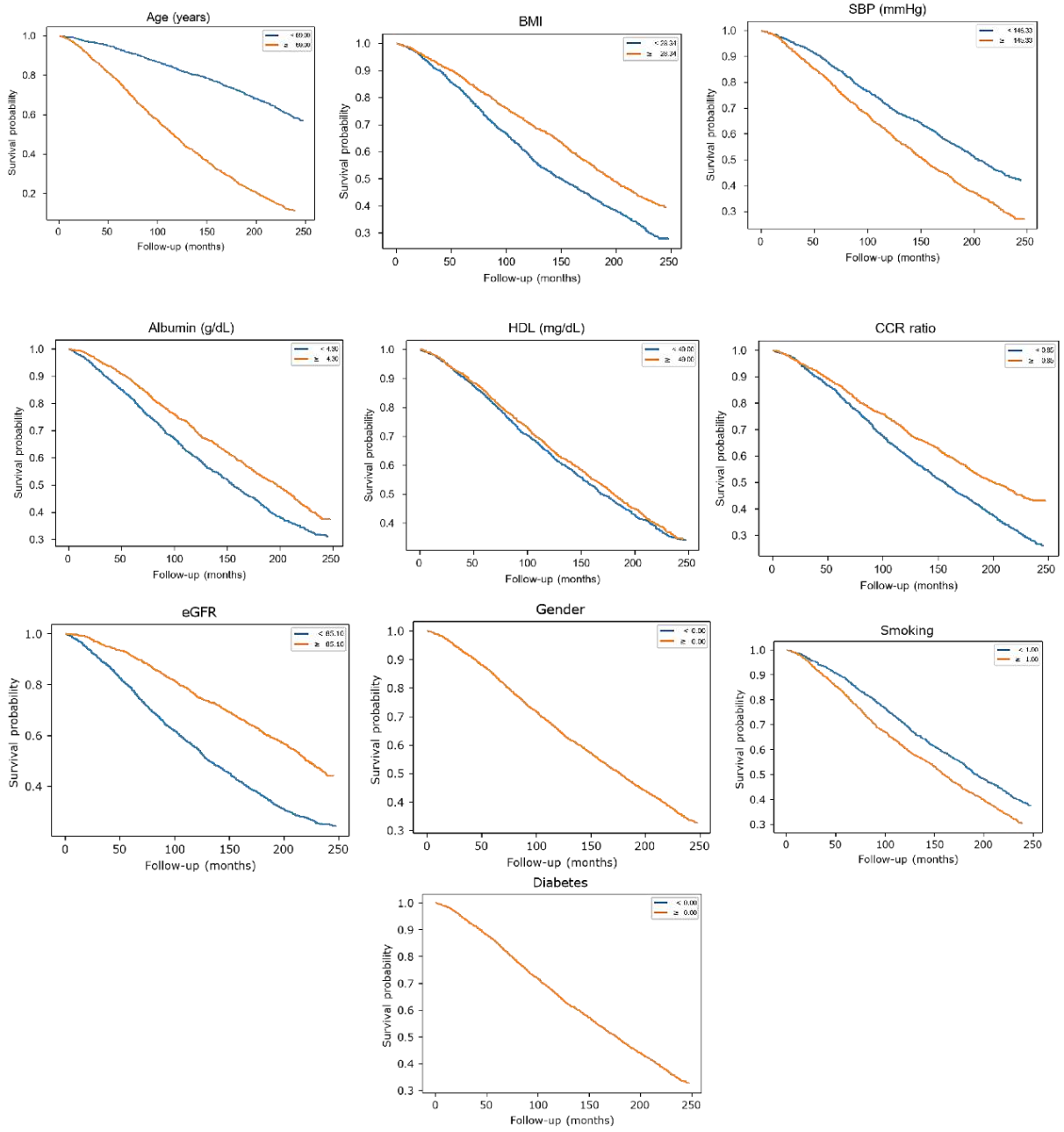


Figure 2. Kaplan-Meier survival analyses of significant predictive factors for survival outcome.

 © 2026 ARD Asociación Española

Table 5. Interaction analysis between CCR status and physical activity.

Exercise intensity	HR (95% CI)	*p*-value
No exercise	1.29 (1.13 - 1.47)	<.001
Moderate intensity	1.2 (0.98 - 1.45)	.072
Vigorous intensity	1.95 (1.46 - 2.6)	<.001

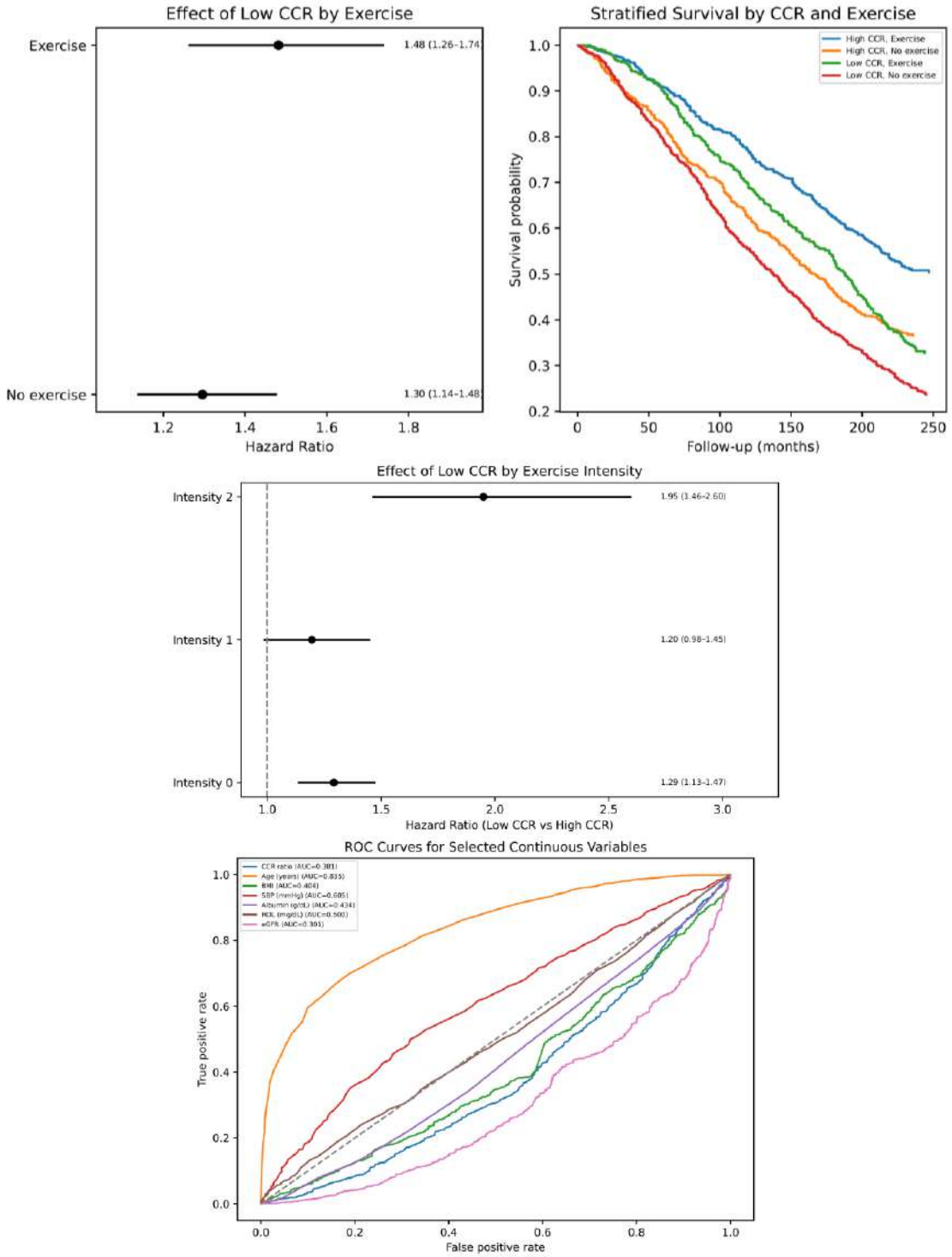


Figure 3. Interaction analysis of CCR and exercise, stratified survival curves, and ROC prediction curves.

Construction and validation of the prognostic nomogram

Specific risk scores were calculated using eleven predictors: age, BMI, SBP, albumin, HDL cholesterol, CCR, eGFR, sex, smoking, diabetes, and exercise in the nomogram. The highest range of points was exhibited by variables such as age, eGFR, and CCR, implying that age, poor kidney function, and muscle depletion had the greatest influence on mortality risk. The scale can predict 3-, 5-, and 10-year survival rates, with higher total scores indicating poorer predicted survival. Time-varying AUCs did not indicate any notable difference between the nomogram and a model based only on traditional cardiovascular risk factors (AUCs of 0.749 vs. 0.747 at 3 years, 0.753 vs. 0.744 at 5 years, and 0.789 vs. 0.785 at 10 years), suggesting limited additional prognostic information with the introduction of CCR and other variables. Calibration plots showed close agreement between predicted and observed survival at 3 and 5 years, as well as moderate deviation at 10 years. Decision curve analysis indicated that the nomogram had a larger net benefit than the basic model across various threshold probabilities (0.05-0.40) and was superior to treat-all and treat-none strategies, supporting its clinical utility. Risk stratification based on estimated 5-year risk showed a clear distinction between high- and low-risk groups, with significantly poorer survival in the former. A combined consideration of these results implies that inclusion of an indicator of muscle mass (CCR) into a multivariate nomogram may offer modest improvements in calibration and decision-analytic characteristics, though the incremental discriminative value appears limited relative to conventional risk-factor models.

Nomogram for predicting all-cause mortality in hypertensive patients

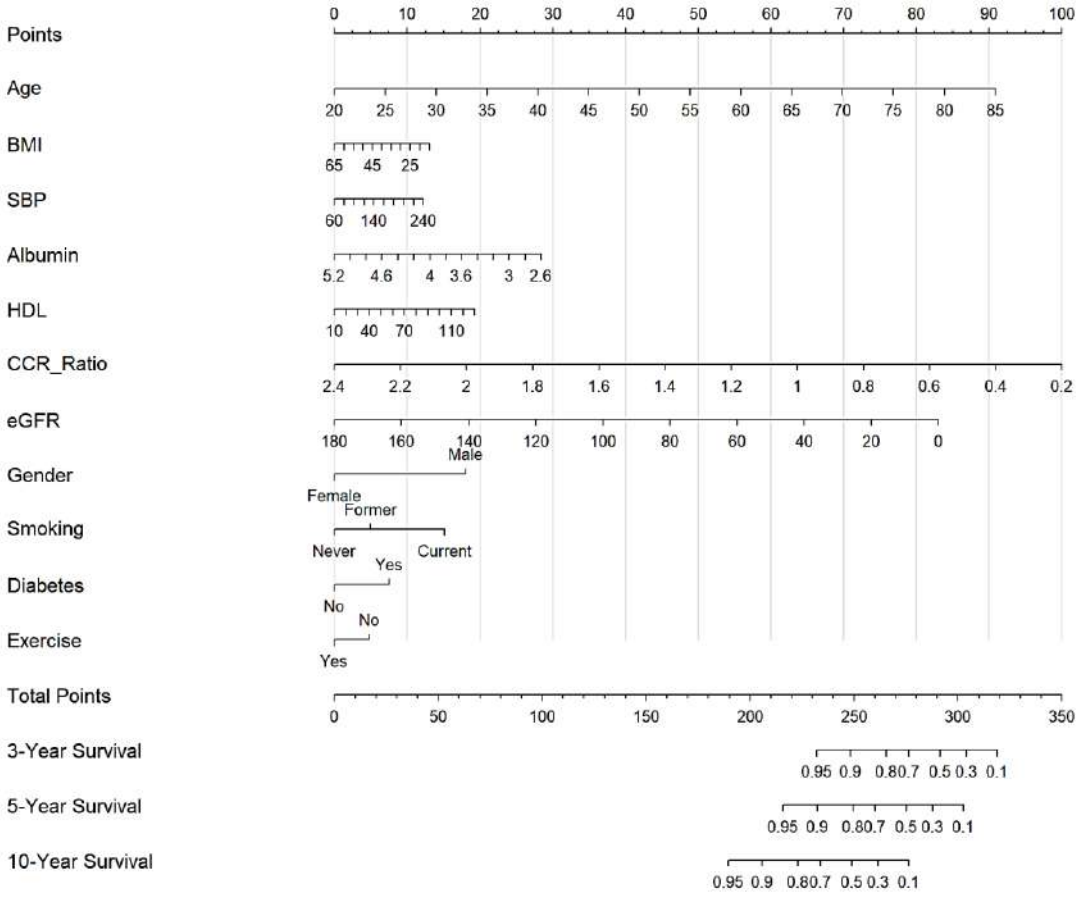


Figure 4. A prognostic nomogram to estimate long-term survival rates for patients with hypertension.

 © 2026 ARD Asociación Española

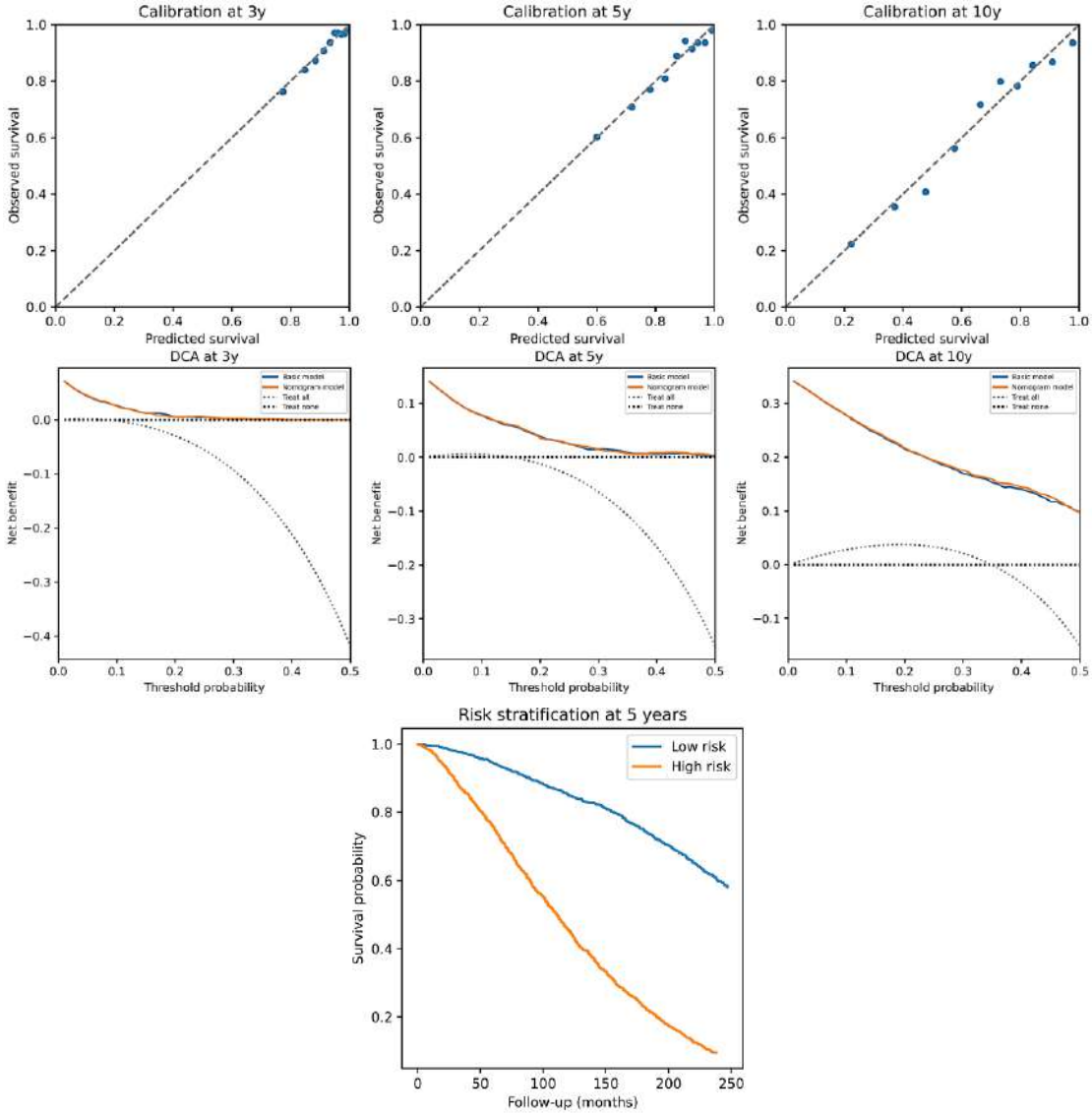


Figure 5. Calibration curves, decision curve analysis and risk-stratified survival curves for validating the prognostic nomogram.

DISCUSSION

Main findings

This is, to our knowledge, one of the larger studies examining the relationship between serum CCR and all-cause mortality in individuals with hypertension and one of the first to quantify the modifying influence of physical activity intensity using the nationally representative NHANES cohort (Osaka et al., 2018; Ren et al., 2025). In our analysis, lower CCR was identified as an independent predictor of mortality with a substantial effect size (Kirkman et al., 2021), though direct comparisons with BMI should consider their different biological meanings (Batsis & Villareal, 2018; Wannamethee & Atkins, 2015). Notably, we also found that the survival advantages of physical activity were not uniformly distributed, and poor skeletal muscle health may have reduced the potential benefit of vigorous exercise, implying that sufficient physiological muscle reserve is a major requirement for achieving the cardiovascular advantages of physical exercise (McPhee et al., 2016;

Reid & Fielding, 2012; Wolfe, 2006). Furthermore, the combined nomogram demonstrated modest incremental value beyond traditional risk factors, primarily through improved calibration and net benefit on decision curve analysis rather than substantial gains in discrimination (Pencina et al., 2008), supporting the incorporation of muscle-mass assessment into routine risk stratification of hypertensive patients (Sayer & Kirkwood, 2015).

Effect modification of muscle mass on exercise benefits

The second important study finding is that there may be skeletal muscle mass-related effect heterogeneity in the universal survival benefits of vigorous physical exercise, a finding that contrasts with the widely held assumption. Our results suggest that among those with low CCR, indicating possible sarcopenic frailty, vigorous exercise was not clearly associated with survival benefit and may even have been associated with worse outcomes, possibly because it exceeded physiological capacity (Eijsvogels et al., 2016; Mons et al., 2014). The observation is in line with the recent phenomenon of the so-called physical activity paradox (Powers et al., 2020), according to which, under conditions of pathological muscle depletion, the ability of the musculoskeletal system to counteract exercise-induced oxidative stress and hemodynamic load is compromised, resulting in maladaptive instead of adaptive responses (Radak et al., 2008; Viña et al., 2000). This significant heterogeneity was likely masked by previous aggregate studies that did not take into consideration muscle mass (Bouchard et al., 2012; Pickering & Kiely, 2019). These exploratory findings suggest that CCR might serve as a potential safety indicator, pending validation in prospective studies (Franklin et al., 2020), to guide the prescription of high-intensity exercise and to support cautious approaches in potentially susceptible subpopulations (Fragala et al., 2019; Izquierdo et al., 2021).

Putative pathophysiological mechanisms

The pathophysiological interpretation of CCR is complex. While it partially reflects skeletal muscle anabolism, it is also mathematically dependent on serum creatinine and influenced by renal function, nutritional status, and systemic inflammatory load. Therefore, CCR should be understood as a composite biomarker of physiological reserve rather than a specific measure of muscle mass alone (Knight et al., 2004; Shlipak et al., 2013). High CCR may indicate adequate musculoskeletal reserve and a favourable anabolic environment. Skeletal muscle is a locomotor organ but also the largest endocrine organ in the body, which secretes protective myokines (e.g., IL-6, irisin) (Severinsen & Pedersen, 2020) that enhance insulin sensitivity and reduce endothelial dysfunction induced by hypertension (Boström et al., 2012). On the other hand, a low CCR indicates a maladaptive condition of loss of metabolic plasticity (Smith et al., 2018) and chronic low-grade inflammation, including inflammaging (Ferrucci & Fabbri, 2018; Visser et al., 2002), with stimulation of vascular stiffness and augmentation of oxidative stress (Piotrowicz et al., 2022; Simioni et al., 2018). Such a biological background may help explain the impaired exercise response observed in our study: in the context of sarcopenic depletion, intensive exercise may fail to trigger a hormetic compensatory response and could potentially impose hemodynamic strain and metabolic stress that surpass already impaired compensatory capacity, thereby nullifying the desired cardiovascular advantages (Ji et al., 2016).

Clinical implications, strengths, and limitations

These results may have potential implications for the management of hypertension, and it may be necessary to move away from a blood pressure-based model to a more holistic one that includes musculoskeletal assessment (Benetos et al., 2019; Richter et al., 2022). We suggest that serum CCR could be considered in routine risk stratification procedures to detect subclinical sarcopenia and frailty. Our findings support personalized exercise prescriptions, i.e., patients with intact CCR may achieve cardiovascular benefits from moderate-vigorous aerobic exercise (Bull et al., 2020), whereas patients with low CCR, particularly older or frail individuals, might consider muscle-preserving interventions, such as nutritional optimization and

 © 2026 ARD Asociación Española

resistance training, as a preparatory step before progressive increases in exercise intensity. These are hypothesis-generating suggestions rather than prescriptive recommendations (Bauer et al., 2013; Cadore & Izquierdo, 2015). This is one of the strategies that can be used to counter the risks of intense exercise among muscle-depleted patients. Moreover, CCR helps improve the assessment of renal function, particularly in individuals with increased muscle mass, where healthy individuals may be incorrectly classified as having renal impairment because of increased serum creatinine (Delanaye et al., 2017; Rule et al., 2004). The strengths of this study include the use of a nationally representative NHANES dataset (Ahluwalia et al., 2016), high statistical power and generalizability, and thorough adjustment for possible confounders of renal function and systemic inflammation. Limitations are that this is an observational cohort study and therefore does not allow causal inference (Sedgwick, 2015); there is the possibility of residual confounding by unmeasured variables; and the study used self-reported physical activity, which may introduce recall bias (Prince et al., 2008; Troiano, 2008). There is also a lack of longitudinal detailed dietary data that could be used to evaluate nutritional effects (Beasley et al., n.d.). Future prospective and interventional studies are warranted to determine whether interventions that improve CCR can enhance survival among hypertensive patients (Yoshimura et al., 2017).

CONCLUSION

This study suggests that serum CCR is a marker of skeletal muscle mass and skeletal muscle physiological reserve with prognostic ability beyond conventional indices for predicting long-term mortality in hypertensive patients (Tang et al., 2020). We suggest that low CCR, potentially reflecting sarcopenia, may serve as a predictor of unfavourable outcomes and challenge the assumption that exercise uniformly benefits all individuals regardless of muscle status, though this requires confirmation in interventional studies. Particularly, we demonstrate that the cardiovascular benefits of moderate-intensity exercise may be attenuated in individuals with insufficient muscle reserve, and vigorous exercise in this subgroup warrants careful consideration (O'Keefe et al., 2012). These findings emphasize the importance of skeletal muscle as a potential mechanistic effector and a key metabolic basis for buffering disease burden (Argilés et al., 2016). The nomogram developed in the current study may provide a useful instrument for individualized risk stratification.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Peng Zhang. Methodology: Zhujun Mao, Peng Zhang. Formal analysis: Zhujun Mao. Investigation: Jiahe Zhang. Data curation: Zhujun Mao. Writing – original draft: Zhujun Mao, Jiahe Zhang. Writing – review & editing: Peng Zhang. Supervision: Peng Zhang.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Ahluwalia, N., Dwyer, J., Terry, A., Moshfegh, A., & Johnson, C. (2016). Update on NHANES dietary data: Focus on collection, release, analytical considerations, and uses to inform public policy. *Advances in Nutrition, 7*(1), 121–134. https://doi.org/10.3945/an.115.009258

Argilés, J. M., Campos, N., Lopez-Pedrosa, J. M., Rueda, R., & Rodriguez-Mañas, L. (2016). Skeletal muscle regulates metabolism via interorgan crosstalk: Roles in health and disease. *Journal of the American Medical Directors Association, 17*(9), 789–796. https://doi.org/10.1016/j.jamda.2016.04.019

Batsis, J. A., & Villareal, D. T. (2018). Sarcopenic obesity in older adults: Aetiology, epidemiology and treatment strategies. *Nature Reviews Endocrinology, 14*(9), 513–537. https://doi.org/10.1038/s41574-018-0062-9

Bauer, J., Biolo, G., Cederholm, T., Cesari, M., Cruz-Jentoft, A. J., Morley, J. E., Phillips, S., Sieber, C., Stehle, P., Teta, D., Visvanathan, R., Volpi, E., & Boirie, Y. (2013). Evidence-based recommendations for optimal dietary protein intake in older people: A position paper from the PROT-AGE Study Group. *Journal of the American Medical Directors Association, 14*(8), 542–559. https://doi.org/10.1016/j.jamda.2013.05.021

Beasley, J. M., Shikany, J. M., & Thomson, C. A. (2013). The role of dietary protein intake in the prevention of sarcopenia of aging. *Nutrition in Clinical Practice, 28*(6), 684–690. https://doi.org/10.1177/0884533613507607

Benetos, A., Petrovic, M., & Strandberg, T. (2019). Hypertension management in older and frail older patients. *Circulation Research, 124*(7), 1045–1060. https://doi.org/10.1161/CIRCRESAHA.118.313236

Boström, P., Wu, J., Jedrychowski, M. P., Korde, A., Ye, L., Lo, J. C., Rasbach, K. A., Boström, E. A., Choi, J. H., Long, J. Z., Kajimura, S., Zingaretti, M. C., Vind, B. F., Tu, H., Cinti, S., Højlund, K., Gygi, S. P., & Spiegelman, B. M. (2012). A PGC1-α-dependent myokine that drives brown-fat-like development of white fat and thermogenesis. *Nature, 481*(7382), 463–468. https://doi.org/10.1038/nature10777

Bouchard, C., Blair, S. N., Church, T. S., Earnest, C. P., Hagberg, J. M., Häkkinen, K., Jenkins, N. T., Karavirta, L., Kraus, W. E., Leon, A. S., Rao, D. C., Sarzynski, M. A., Skinner, J. S., Slentz, C. A., & Rankinen, T. (2012). Adverse metabolic response to regular exercise: Is it a rare or common occurrence? *PLOS ONE, 7*(5), e37887. https://doi.org/10.1371/journal.pone.0037887

Bull, F. C., Al-Ansari, S. S., Biddle, S., Borodulin, K., Buman, M. P., Cardon, G., Carty, C., Chaput, J.-P., Chastin, S., Chou, R., Dempsey, P. C., DiPietro, L., Ekelund, U., Firth, J., Friedenreich, C. M., Garcia, L., Gichu, M., Jago, R., Katzmarzyk, P. T., … Willumsen, J. F. (2020). World Health Organization

 © 2026 ARD Asociación Española

2020 guidelines on physical activity and sedentary behaviour. *British Journal of Sports Medicine, 54*(24), 1451–1462. https://doi.org/10.1136/bjsports-2020-102955

Cadore, E. L., & Izquierdo, M. (2015). Exercise interventions in polypathological aging patients that coexist with diabetes mellitus: Improving functional status and quality of life. *AGE, 37*(3), 64. https://doi.org/10.1007/s11357-015-9800-2

Chen, D. C., Shlipak, M. G., Scherzer, R., Bauer, S. R., Potok, O. A., Rifkin, D. E., Ix, J. H., Muiru, A. N., Hsu, C., & Estrella, M. M. (2022). Association of intraindividual difference in estimated glomerular filtration rate by creatinine vs cystatin C and end-stage kidney disease and mortality. *JAMA Network Open, 5*(2), e2148940. https://doi.org/10.1001/jamanetworkopen.2021.48940

Delanaye, P., Cavalier, E., & Pottel, H. (2017). Serum creatinine: Not so simple! *Nephron, 136*(4), 302–308. https://doi.org/10.1159/000469669

Eijsvogels, T. M. H., Molossi, S., Lee, D., Emery, M. S., & Thompson, P. D. (2016). Exercise at the Extremes. *JACC, 67*(3), 316-329. https://doi.org/10.1016/j.jacc.2015.11.034

Ferrucci, L., & Fabbri, E. (2018). Inflammageing: Chronic inflammation in ageing, cardiovascular disease, and frailty. *Nature Reviews Cardiology, 15*(9), 505-522. https://doi.org/10.1038/s41569-018-0064-2

Fragala, M. S., Cadore, E. L., Dorgo, S., Izquierdo, M., Kraemer, W. J., Peterson, M. D., & Ryan, E. D. (2019). Resistance training for older adults: Position statement from the national strength and conditioning association. *The Journal of Strength & Conditioning Research, 33*(8), 2019. https://doi.org/10.1519/JSC.0000000000003230

Franklin, B. A., Thompson, P. D., Al-Zaiti, S. S., Albert, C. M., Hivert, M.-F., Levine, B. D., Lobelo, F., Madan, K., Sharrief, A. Z., Eijsvogels, T. M. H., & On behalf of the American Heart Association Physical Activity Committee of the Council on Lifestyle and Cardiometabolic Health; Council on Cardiovascular and Stroke Nursing; Council on Clinical Cardiology; and Stroke Council. (2020). Exercise-Related Acute Cardiovascular Events and Potential Deleterious Adaptations Following Long-Term Exercise Training: Placing the Risks Into Perspective-An Update: A Scientific Statement From the American Heart Association. Circulation, 141(13), e705-e736. https://doi.org/10.1161/CIR.0000000000000749

Izquierdo, M., Merchant, R. A., Morley, J. E., Anker, S. D., Aprahamian, I., Arai, H., Aubertin-Leheudre, M., Bernabei, R., Cadore, E. L., Cesari, M., Chen, L.-K., de Souto Barreto, P., Duque, G., Ferrucci, L., Fielding, R. A., García-Hermoso, A., Gutiérrez-Robledo, L. M., Harridge, S. D. R., Kirk, B., … Singh, M. F. (2021). International exercise recommendations in older adults (ICFSR): Expert consensus guidelines. *The Journal of Nutrition, Health & Aging, 25*(7), 824-853. https://doi.org/10.1007/s12603-021-1665-8

Ji, L. L., Kang, C., & Zhang, Y. (2016). Exercise-induced hormesis and skeletal muscle health. Free Radical Biology and Medicine, 98, 113-122. https://doi.org/10.1016/j.freeradbiomed.2016.02.025

Kattan, M. W. (2003). Nomograms are superior to staging and risk grouping systems for identifying high-risk patients: Preoperative application in prostate cancer. *Current Opinion in Urology, 13*(2), 111. https://doi.org/10.1097/00042307-200303000-00005

Kirkman, D. L., Bohmke, N., Carbone, S., Garten, R. S., Rodriguez-Miguelez, P., Franco, R. L., Kidd, J. M., & Abbate, A. (2021). Exercise intolerance in kidney diseases: Physiological contributors and therapeutic strategies. *American Journal of Physiology-Renal Physiology, 320*(2), F161-F173. https://doi.org/10.1152/ajprenal.00437.2020

Knight, E. L., Verhave, J. C., Spiegelman, D., Hillege, H. L., De Zeeuw, D., Curhan, G. C., & De Jong, P. E. (2004). Factors influencing serum cystatin C levels other than renal function and the impact on renal function measurement. *Kidney International, 65*(4), 1416-1421. https://doi.org/10.1111/j.1523-1755.2004.00517.x

Liao, Y., Hu, H. Fei, & Song, H. (2025). Association between the haemoglobin glycation index and risk of cardiovascular disease in the CKM syndrome stage 0-3 (SSRN Scholarly Paper No. 5527825). *Social Science Research Network*. https://doi.org/10.2139/ssrn.5527825

McPhee, J. S., French, D. P., Jackson, D., Nazroo, J., Pendleton, N., & Degens, H. (2016). Physical activity in older age: Perspectives for healthy ageing and frailty. *Biogerontology, 17*(3), 567-580. https://doi.org/10.1007/s10522-016-9641-0

Mills, K. T., Stefanescu, A., & He, J. (2020). The global epidemiology of hypertension. *Nature Reviews Nephrology, 16*(4), 223-237. https://doi.org/10.1038/s41581-019-0244-2

Mons, U., Hahmann, H., & Brenner, H. (2014). A reverse J-shaped association of leisure time physical activity with prognosis in patients with stable coronary heart disease: evidence from a large cohort with repeated measurements. *Heart, 100*(13), 1043–1049. https://doi.org/10.1136/heartjnl-2013-305242

O'Keefe, J. H., Patil, H. R., Lavie, C. J., Magalski, A., Vogel, R. A., & McCullough, P. A. (2012). Potential adverse cardiovascular effects from excessive endurance exercise. *Mayo Clinic Proceedings, 87*(6), 587-595. https://doi.org/10.1016/j.mayocp.2012.04.005

Osaka, T., Hamaguchi, M., Hashimoto, Y., Ushigome, E., Tanaka, M., Yamazaki, M., & Fukui, M. (2018). Decreased the creatinine to cystatin C ratio is a surrogate marker of sarcopenia in patients with type 2 diabetes. *Diabetes Research and Clinical Practice, 139*, 52-58. https://doi.org/10.1016/j.diabres.2018.02.025

Pedersen, B. K., & Febbraio, M. A. (2012). Muscles, exercise and obesity: Skeletal muscle as a secretory organ. *Nature Reviews Endocrinology, 8*(8), 457-465. https://doi.org/10.1038/nrendo.2012.49

Pencina, M. J., D' Agostino Sr, R. B., D' Agostino Jr, R. B., & Vasan, R. S. (2008). Evaluating the added predictive ability of a new marker: From area under the ROC curve to reclassification and beyond. *Statistics in Medicine, 27*(2), 157-172. https://doi.org/10.1002/sim.2929

Pickering, C., & Kiely, J. (2019). Do non-responders to exercise exist-And if so, what should we do about them? *Sports Medicine, 49*(1), 1-7. https://doi.org/10.1007/s40279-018-01041-1

Piotrowicz, K., Klich-Rączka, A., Skalska, A., Gryglewska, B., Grodzicki, T., Gąsowski, J., Piotrowicz, K., Klich-Rączka, A., Skalska, A., Gryglewska, B., Grodzicki, T., & Gąsowski, J. (2022). Pulse wave velocity and sarcopenia in older persons-A systematic review and meta-analysis. International *Journal of Environmental Research and Public Health, 19*(11). https://doi.org/10.3390/ijerph19116477

Powers, S. K., Deminice, R., Ozdemir, M., Yoshihara, T., Bomkamp, M. P., & Hyatt, H. (2020). Exercise-induced oxidative stress: Friend or foe? *Journal of Sport and Health Science, 9*(5), 415-425. https://doi.org/10.1016/j.jshs.2020.04.001

Prince, S. A., Adamo, K. B., Hamel, M. E., Hardt, J., Gorber, S. C., & Tremblay, M. (2008). A comparison of direct versus self-report measures for assessing physical activity in adults: A systematic review. *International Journal of Behavioral Nutrition and Physical Activity, 5*(1), 56. https://doi.org/10.1186/1479-5868-5-56

Radak, Z., Chung, H. Y., Koltai, E., Taylor, A. W., & Goto, S. (2008). Exercise, oxidative stress and hormesis. *Ageing Research Reviews, 7*(1), 34-42. https://doi.org/10.1016/j.arr.2007.04.004

Reid, K. F., & Fielding, R. A. (2012). Skeletal muscle power: A critical determinant of physical functioning in older adults. *Exercise and Sport Sciences Reviews, 40*(1), 4. https://doi.org/10.1097/JES.0b013e31823b5f13

Ren, C., Hu, T., Zhu, J., Chu, H., & Guo, Q. (2025). Sarcopenia index is associated with alzheimer's disease, mild cognitive impairment and their mortality in chinese adults aged 65 and older. *BMC Public Health, 25*, 2277. https://doi.org/10.1186/s12889-025-23512-7

Richter, D., Guasti, L., Walker, D., Lambrinou, E., Lionis, C., Abreu, A., Savelieva, I., Fumagalli, S., Bo, M., Rocca, B., Jensen, M. T., Pierard, L., Sudano, I., Aboyans, V., & Asteggiano, R. (2022). Frailty in

 © 2026 ARD Asociación Española

cardiology: Definition, assessment and clinical implications for general cardiology. A consensus document of the council for cardiology practice (CCP), association for acute cardio vascular care (ACVC), association of cardiovascular nursing and allied professions (ACNAP), european association of preventive cardiology (EAPC), european heart rhythm association (EHRA), council on valvular heart diseases (VHD), council on hypertension (CHT), council of cardio-oncology (CCO), working group (WG) aorta and peripheral vascular diseases, WG e-cardiology, WG thrombosis, of the european society of cardiology, european primary care cardiology society (EPCCS). *European Journal of Preventive Cardiology, 29*(1), 216-227. https://doi.org/10.1093/eurjpc/zwaa167

Rule, A. D., Larson, T. S., Bergstralh, E. J., Slezak, J. M., Jacobsen, S. J., & Cosio, F. G. (2004). Using serum creatinine to estimate glomerular filtration rate: Accuracy in good health and in chronic kidney disease. *Annals of Internal Medicine, 141*(12), 929-937. https://doi.org/10.7326/0003-4819-141-12-200412210-00009

Sayer, A. A., & Kirkwood, T. B. L. (2015). Grip strength and mortality: A biomarker of ageing? *The Lancet, 386*(9990), 226-227. https://doi.org/10.1016/S0140-6736(14)62349-7

Sedgwick, P. (2015). Bias in observational study designs: cross sectional studies. *BMJ, 350*. https://doi.org/10.1136/bmj.h1286

Severinsen, M. C. K., & Pedersen, B. K. (2020). Muscle-organ crosstalk: The emerging roles of myokines. *Endocrine Reviews, 41*(4), 594-609. https://doi.org/10.1210/endrev/bnaa016

Shlipak, M. G., Matsushita, K., Ärnlöv, J., Inker, L. A., Katz, R., Polkinghorne, K. R., Rothenbacher, D., Sarnak, M. J., Astor, B. C., Coresh, J., Levey, A. S., & Gansevoort, R. T. (2013). Cystatin C versus creatinine in determining risk based on kidney function. *New England Journal of Medicine, 369*(10), 932-943. https://doi.org/10.1056/NEJMoa1214234

Simioni, C., Zauli, G., Martelli, A. M., Vitale, M., Sacchetti, G., Gonelli, A., & Neri, L. M. (2018). Oxidative stress: Role of physical exercise and antioxidant nutraceuticals in adulthood and aging. *Oncotarget, 9*(24), 17181-17198. https://doi.org/10.18632/oncotarget.24729

Smith, R. L., Soeters, M. R., Wüst, R. C. I., & Houtkooper, R. H. (2018). Metabolic flexibility as an adaptation to energy resources and requirements in health and disease. *Endocrine Reviews, 39*(4), 489-517. https://doi.org/10.1210/er.2017-00211

Springer, J., Springer, J.-I., & Anker, S. D. (2017). Muscle wasting and sarcopenia in heart failure and beyond: Update 2017. *ESC Heart Failure, 4*(4), 492-498. https://doi.org/10.1002/ehf2.12237

Srikanthan, P., & Karlamangla, A. S. (2014). Muscle mass index As a predictor of longevity in older adults. *The American Journal of Medicine, 127*(6), 547-553. https://doi.org/10.1016/j.amjmed.2014.02.007

Tabara, Y., Kohara, K., Okada, Y., Ohyagi, Y., & Igase, M. (2020). Creatinine-to-cystatin C ratio as a marker of skeletal muscle mass in older adults: J-SHIPP study. *Clinical Nutrition, 39*(6), 1857-1862. https://doi.org/10.1016/j.clnu.2019.07.027

Tang, T., Zhuo, Y., Xie, L., Wang, H., & Yang, M. (2020). Sarcopenia index based on serum creatinine and cystatin C is associated with 3-year mortality in hospitalized older patients. *Scientific Reports, 10*(1), 1260. https://doi.org/10.1038/s41598-020-58304-z

Tieland, M., Trouwborst, I., & Clark, B. C. (2018). Skeletal muscle performance and ageing. *Journal of Cachexia, Sarcopenia and Muscle, 9*(1), 3-19. https://doi.org/10.1002/jcsm.12238

Troiano, R., Berrigan, D., Dodd, K., Mâsse, L., Tilert, T., & Mcdowell, M. (2008). Physical Activity in the United States Measured by Accelerometer. *Medicine & Science in Sports & Exercise, 40*(1), 181–188. https://doi.org/10.1249/mss.0b013e31815a51b3

VinÑa, J., Gomez-Cabrera, M.-C., Lloret, A., Marquez, R., Miñana, J. B., Pallardó, F. V., & Sastre, J. (2000). Free Radicals in Exhaustive Physical Exercise: Mechanism of Production, and Protection by Antioxidants. *IUBMB Life, 50*(4-5), 271-277. https://doi.org/10.1080/713803729

Visser, M., Pahor, M., Taaffe, D. R., Goodpaster, B. H., Simonsick, E. M., Newman, A. B., Nevitt, M., & Harris, T. B. (2002). Relationship of interleukin-6 and tumor necrosis factor-α with muscle mass and muscle strength in elderly men and women: The health ABC study. *The Journals of Gerontology: Series A, 57*(5), M326-M332. https://doi.org/10.1093/gerona/57.5.M326

Wannamethee, S. G., & Atkins, J. L. (2015). Muscle loss and obesity: The health implications of sarcopenia and sarcopenic obesity. *Proceedings of the Nutrition Society, 74*(4), 405-412. https://doi.org/10.1017/S002966511500169X

Whelton, P. K., Carey, R. M., Aronow, W. S., Casey, D. E., Collins, K. J., Himmelfarb, C. D., DePalma, S. M., Gidding, S., Jamerson, K. A., Jones, D. W., MacLaughlin, E. J., Muntner, P., Ovbiagele, B., Smith, S. C., Spencer, C. C., Stafford, R. S., Taler, S. J., Thomas, R. J., Williams, K. A., … Wright, J. T. (2018). 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA Guideline for the Prevention, Detection, Evaluation, and Management of High Blood Pressure in Adults. *JACC, 71*(19), e127–e248. https://doi.org/10.1016/j.jacc.2017.11.006

Wolfe, R. R. (2006). The underappreciated role of muscle in health and disease. *The American Journal of Clinical Nutrition, 84*(3), 475-482. https://doi.org/10.1093/ajcn/84.3.475

Yoshimura, Y., Wakabayashi, H., Yamada, M., Kim, H., Harada, A., & Arai, H. (2017). Interventions for treating sarcopenia: A systematic review and meta-analysis of randomized controlled studies. *Journal of the American Medical Directors Association, 18*(6), 553.e1-553.e16. https://doi.org/10.1016/j.jamda.2017.03.019

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

ORIGINAL ARTICLE

Physiological and anthropometric characteristics of Croatian national football team players

Ahmet Naci Dilek. *Faculty of Sport Science. Bartın University. Türkiye.*
Parham Jalali. *Wellness, Sport and Health Program. University of Bologna. Rimini Campus, Italy.*
Aida Mohammadi. *Sport and Health Promotion Program. Department of Experimental Medicine and Surgery. University of Rome Tor Vergata. Italy.*
Hadi Nobari. *LFE Research Group. Department of Health and Human Performance. Faculty of Physical Activity and Sport Science (INEF). Polytechnic University of Madrid. Spain.*
Adem Preljević. *Faculty of Sport and Physical Education. University of Novi Pazar. Serbia.*
Boriss Bazanov. *School of Natural Sciences and Health. Tallinn University. Estonia.*
Ivana Grle. *Department of Physical Medicine and Rehabilitation. University Clinical Hospital Mostar. Mostar, Bosnia and Herzegovina.*
Maki Grle. *Department of Orthopaedics. University Clinical Hospital Mostar. Bosnia and Herzegovina.*
Ernest Šabić. *Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Naim Ćeleš. *Deparment of Physical Education and Sport. Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Nijaz Skender. *Deparment of Physical Education and Sport. Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Goran Sporiš ✉ **.** *Department of General and Applied Kinesiology. Faculty of Kinesiology. University of Zagreb. Croatia.*
Jerko Prlić. *Department of Orthopaedics. University Clinical Hospital Mostar. Mostar, Bosnia and Herzegovina.*
Dejan Tiric. *Department of Obstetrics and Gynecology. University Clinical Hospital Mostar. Mostar, Bosnia and Herzegovina.*
Bozenka Galic Tiric. *Chair of Occupational Medicine. Faculty of Medicine. University of Mostar. Mostar, Bosnia and Herzegovina.*
Natalija Kurtović. *Deparment of Physical Education and Sport. Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Davorin Antonić. *Larus Sport d.o.o. Croatia.*
Dražen Čular. *Faculty of Kinesiology. University of Split. Croatia.*
Ivica Franjko. *Faculty of Kinesiology. Josip Juraj Srossmayer University in Osijek. Croatia.*
Ivan Duroci. *Faculty of Kinesiology. University of Zagreb. Croatia.*
Davor Ljesević. *Faculty of Kinesiology. University of Zagreb. Croatia.*
Hrvoje Ajman. *Faculty of Kinesiology. Josip Juraj Srossmayer University in Osijek. Croatia.*
Željko Širić. *Faculty of Kinesiology. Josip Juraj Srossmayer University in Osijek. Croatia.*
Fredi Fiorentini. *Faculty of Kinesiology. University of Split. Croatia.*
Zeljko Kovacevic. *Faculty of Health Sciences. University of Split. Croatia.*
Besnik Morina. *Faculty of Physical Education and Sport. University of Pristina "Hasan Pristina". Kosovo.*
Milan Milošević. *Ribnjak Polyclinic. Croatia.*
Veljko Vukicevic. *Faculty of Sport and Physical Education. University of Novi Sad. Serbia.*

ABSTRACT

The aim of this study was to analyse physiological and anthropometric characteristics of Croatian national football team players, with particular focus on blood lactate concentration, relative oxygen consumption, body height, body mass, body fat percentage, and playing position. The sample consisted of 17 elite football players. Descriptive statistical analysis was performed for all analysed variables. The average blood lactate concentration was 10.46 ± 1.12 mmol/L, while the average relative oxygen consumption was 60.91 ± 3.15 mL/kg/min. The players demonstrated highly developed aerobic and anaerobic capacities characteristic of elite football populations. Anthropometric and physiological profiles differed according to playing position, reflecting specific tactical and physical demands in modern football.

Keywords: sport medicine; football; blood lactate; oxygen consumption; body fat; anthropometry; elite football.

Cite this article as:
Dilek, A. N., Jalali, P., Mohammadi, A., Nobari, H., Preljević, A., Bazanov, B., Grle, I., Grle, M., Šabić, E., Ćeleš, N., Skender, N., Sporiš, G., Prlić, J., Tiric, D., Galic Tiric, B., Kurtović, N., Antonić, D., Čular, D., Franjko, I., Duroci, I., Ljesević, D., Ajman, H., Širić, Ž., Fiorentini, F., Kovacevic, Z., Morina, B., Milošević, M., & Vukicevic, V. (2026). Physiological and anthropometric characteristics of Croatian national football team players. *Journal of Human Sport and Exercise, 21*(4), 1369-1379. https://doi.org/10.55860/xhy7m957

✉ **Corresponding author.** *Department of General and Applied Kinesiology. Faculty of Kinesiology. University of Zagreb. Croatia.*
E-mail: goran.sporis@kif.unizg.hr

Submitted for publication May 25, 2026.
Accepted for publication July 27, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/xhy7m957

INTRODUCTION

Modern football requires players to possess highly developed physiological, anthropometric, technical, and tactical characteristics. Elite football players perform repeated high-intensity activities including sprinting, jumping, accelerations, decelerations, and rapid changes of direction during matches (Bangsbo et al., 2022). Consequently, football performance depends heavily on aerobic endurance, anaerobic power, body composition, and recovery capacity.

Blood lactate concentration is commonly used as an indicator of exercise intensity and anaerobic glycolytic activity. During high-intensity exercise, lactate production increases due to accelerated glycolysis and muscular energy demands (Brooks, 2023). Elite football players generally demonstrate higher lactate tolerance and improved clearance capacity compared with non-athletes.

Relative oxygen consumption (VO_{2max} relative) represents one of the most important indicators of aerobic fitness and endurance performance. Higher VO_2 values enable players to sustain repeated high-intensity efforts and recover more efficiently during matches (Bassett & Howley, 2023). Midfield players often demonstrate particularly elevated aerobic capacities due to extensive running demands during competition.

Anthropometric characteristics such as body height, body mass, and body fat percentage are also important performance determinants in football. Body composition influences sprint ability, agility, movement economy, and duel performance. Lower body fat percentages are generally associated with improved athletic performance due to better power-to-weight ratio and movement efficiency (Reilly et al., 2022).

Positional specialization additionally influences anthropometric and physiological profiles. Goalkeepers are usually taller and heavier, defenders possess strong physical characteristics for duels, midfielders demonstrate exceptional aerobic endurance, while forwards combine speed, agility, and anaerobic power (Castagna et al., 2022).

Croatian football has achieved remarkable international success during the last decade. Players such as Luka Modrić, Ivan Rakitić, and Mario Mandžukić are internationally recognized for their technical quality and physical preparedness.

Modern football is characterized by extremely high physiological and tactical demands. Elite football players are required to repeatedly perform sprinting, accelerations, decelerations, jumps, rapid changes of direction, technical actions under pressure, and continuous transitions between offensive and defensive phases during competition. Due to these demands, contemporary football increasingly relies on sports science methods for monitoring physiological, anthropometric, and performance-related characteristics of players (Sporis et al., 2009).

Football performance depends on the interaction of aerobic endurance, anaerobic power, muscular strength, agility, speed, technical skills, and tactical intelligence. The physical demands of modern football have substantially increased during recent decades, with elite players performing greater numbers of high-intensity actions and covering longer running distances during matches than previously observed (Sporis et al., 2011a). Consequently, physiological conditioning has become one of the key determinants of success in elite football.

 © 2026 ARD Asociación Española

Aerobic endurance represents a fundamental physiological component in football because it enables players to sustain repeated high-intensity efforts throughout the duration of the match. Relative oxygen consumption (VO_{2max} relative) is commonly used as an indicator of aerobic fitness and exercise capacity. Higher VO_{2max} values allow players to recover more efficiently between sprint actions and maintain technical and tactical performance during prolonged competition (Sporis et al., 2009).

Research conducted on elite football players demonstrated that players with superior aerobic capacities also achieve better movement efficiency and greater tolerance to match intensity (Sporis et al., 2009). Midfield players in particular frequently demonstrate exceptionally high aerobic capacities due to their extensive movement demands and constant involvement in offensive and defensive play.

Anaerobic metabolism also plays an essential role in football performance. High-intensity actions such as sprinting, pressing, tackling, and explosive accelerations rely heavily on anaerobic glycolytic energy pathways. Blood lactate concentration is widely used as an indicator of anaerobic exercise intensity and glycolytic activity (Sporis et al., 2008). Elite football players demonstrate improved lactate tolerance and more efficient lactate clearance mechanisms compared with recreational athletes.

Research by Sporis, Ruzic, and Leko (2008) demonstrated that high-intensity conditioning programs can significantly improve anaerobic endurance in elite soccer players. Their findings highlighted the importance of structured conditioning programs for developing football-specific physiological capacities. The authors concluded that repeated high-intensity exercise training improves the ability to tolerate metabolic stress associated with competitive football.

Anthropometric characteristics also represent important determinants of football performance. Variables such as body height, body mass, and body composition influence sprinting ability, agility, strength, movement economy, and duel efficiency (Sporis et al., 2011b). Modern football increasingly favours players with optimized body composition and high relative power output.

Body fat percentage is particularly important because excessive fat mass may negatively affect locomotor efficiency and increase physiological demands during repeated high-intensity exercise. Elite football players generally demonstrate relatively low body fat percentages compared with non-athletic populations (Sporis et al., 2009). Lower body fat values are associated with improved acceleration, sprinting performance, and agility.

Positional specialization additionally influences anthropometric and physiological profiles among football players. Goalkeepers are generally taller and heavier due to the specific demands of aerial duels and goal coverage, while midfield players often demonstrate superior aerobic capacities and lower body fat percentages (Sporis et al., 2011b). Defenders require physical strength and duel capacity, whereas forwards combine speed, agility, and anaerobic power.

Agility and quickness are also considered critical performance determinants in modern football. Research by Sporis et al. (2010a) investigated the reliability and validity of agility tests in soccer players and confirmed the importance of multidirectional movement abilities in football-specific performance. The ability to rapidly change direction while maintaining speed and balance is essential during match situations.

In addition to aerobic and anaerobic capacities, repeated sprint ability has become increasingly important in elite football. Football players frequently perform repeated maximal sprint actions with limited recovery

periods. Consequently, conditioning programs are designed to simultaneously develop aerobic recovery capacity and anaerobic power production (Sporis et al., 2008).

Research conducted by Sporis et al. (2011a) also suggested that official football matches themselves contribute significantly to maintaining player fitness levels due to the exceptionally high physiological demands experienced during competition. Match play includes intermittent periods of high-intensity activity combined with tactical and technical complexity, making football-specific conditioning particularly unique.

Croatian football has achieved remarkable international success over the last decade. The Croatian national football team consistently demonstrates high technical quality, tactical organization, and physical preparedness at major international competitions. Players such as Luka Modrić, Ivan Rakitić, Mario Mandžukić, and Ivan Perišić are internationally recognized for their endurance capacities, tactical intelligence, and technical abilities.

Physiological and anthropometric profiling therefore represents an important component of sports diagnostics in football. Monitoring blood lactate concentration, relative oxygen consumption, body composition, and positional differences may contribute to optimization of training processes, talent identification, injury prevention, and performance enhancement.

Therefore, the aim of this study was to analyse physiological and anthropometric characteristics of Croatian national football team players, with particular focus on blood lactate concentration, relative oxygen consumption, body height, body mass, body fat percentage, and positional specialization.

Therefore, the aim of this study was to analyse physiological and anthropometric characteristics of Croatian national football team players.

METHODS

Sample

The sample consisted of 17 Croatian national football team players. The relatively small sample size reflects the exclusive nature of senior national-team selection. Although statistical generalization is limited, studies involving world-class athletes inevitably include smaller samples because access to elite populations is highly restricted. All measurements were collected during the pre-competition training camp of the Croatian senior national football team between May and June 2022. All players belonged to the same competitive squad. Written informed consent form was signed according to the Declaration of Helsinki and subjects agreed to participate in the experiment which was approved by the University Ethics Committee.

Variables

Blood lactate concentration (mmol/L)

Blood lactate concentration was measured from capillary blood samples collected from the fingertip using a portable lactate analyser (manufacturer, model). Samples were obtained immediately (or 3 min) after completion of the exercise protocol according to the manufacturer's recommendations.

Relative oxygen consumption (VO_{2max}, $mL \cdot kg^{-1} \cdot min^{-1}$)

Relative oxygen consumption was assessed using (direct breath-by-breath gas analysis with manufacturer/model "*ili"* estimated from the Yo-Yo Intermittent Recovery Test Level 1, treadmill test, Bruce protocol itd., ovisno o stvarnoj metodi).

 © 2026 ARD Asociación Española

Body height (cm)
Body height was measured to the nearest 0.1 cm using a calibrated wall-mounted stadiometer.

Body mass (kg)
Body mass was measured to the nearest 0.1 kg using a calibrated digital scale, with participants wearing light sports clothing and no shoes.

Body fat percentage (%)
Body fat percentage was assessed using (bioelectrical impedance analysis, skinfold thickness, DXA, InBody, Tanita, itd.), following standardized testing procedures.

Playing position
Players were classified according to their primary playing position within the Croatian national team (goalkeepers, defenders, midfielders, forwards).

Statistical analysis
Descriptive statistical indicators were calculated, including arithmetic mean (M), standard deviation (SD), minimum value (Min), and maximum value (Max): Anthropometry (height, weight, body fat); aerobic capacity (VO_{2max}); recovery ability; repeated high intensity running; football performance; anaerobic capacity (blood lactate); position-specific demands.

RESULTS

Table 1. Physiological and anthropometric characteristics of Croatian national football team players.

Player	Position	Lactate (mmol/L)	Relative oxygen consumption	Height (cm)	Weight (kg)	Body fat (%)
S.P	Goalkeeper	9.3	50.2	193	88	12.1
D.Š	Goalkeeper	9.9	51.3	191	84	11.8
V.Č	Defender	10.5	59.2	192	87	10.5
D.L	Defender	11.0	60.1	188	84	9.8
Š.V	Defender	11.2	61.1	181	73	8.7
I.R	Midfielder	12.0	62.2	184	78	8.1
L.M	Midfielder	11.0	63.1	172	66	7.4
D.S	Midfielder	10.3	61.4	172	70	8.9
M.K	Midfielder	10.0	59.9	177	78	8.0
I.P	Winger	11.0	62.5	186	80	7.9
I.O	Forward	10.3	61.3	182	72	8.2
M.M	Forward	11.5	61.9	190	85	8.5
M.B	Midfielder	12.0	62.1	181	75	8.3
A.R	Forward	9.0	60.5	185	78	8.8
D.V	Defender	8.0	59.1	184	76	9.7
I.S	Defender	10.0	61.6	186	77	8.9
A.K	Forward	11.0	62.1	177	73	7.8

Table 2. Descriptive statistics.

Variable	Mean ± SD	Min	Max
Blood lactate (mmol/L)	10.46 ± 1.12	8.0	12.0
Relative oxygen consumption	60.91 ± 3.15	50.2	63.1
Height (cm)	183.6 ± 6.5	172	193
Weight (kg)	78.8 ± 6.4	66	88
Body fat (%)	9.0 ± 1.4	7.4	12.1

The results indicate highly developed physiological and anthropometric profiles among Croatian national football team players. Midfield players demonstrated the highest relative oxygen consumption values, while goalkeepers possessed the highest body mass and body fat percentages.

DISCUSSION

The novelty of this study lies in providing one of the few comprehensive physiological and anthropometric profiles of Croatian senior national team players, a population that has consistently achieved outstanding international success despite the relatively small player pool available. The results suggest that Croatian elite players combine exceptionally high aerobic capacity with low body fat and position-specific anthropometric optimization, representing an efficient physiological model for modern elite football.

The findings of this study demonstrate that Croatian national football team players possess highly developed aerobic and anaerobic capacities alongside optimal anthropometric characteristics for elite football performance. The average relative oxygen consumption value above 60 mL/kg/min reflects exceptional aerobic endurance capacity characteristic of elite-level football players (Stølen et al., 2022).

Midfield players such as Luka Modrić and Ivan Rakitić demonstrated particularly elevated aerobic values, which corresponds with the extensive running demands associated with midfield positions. Midfielders typically cover the greatest total distance during matches and perform continuous transitions between attacking and defensive phases.

Blood lactate values observed in this study indicate strong anaerobic glycolytic capacity and tolerance to high-intensity exercise. Elite football players repeatedly perform explosive actions including sprinting, pressing, and accelerations, all of which contribute to increased lactate production (Brooks, 2023).

Compared with elite players from the English Premier League (VO_{2max} 58–61 $mL \cdot kg^{-1} \cdot min^{-1}$), Spanish La Liga players (59–62), and Bundesliga professionals (58–63), Croatian national team players demonstrated comparable or slightly higher aerobic capacities.

Body fat percentages were relatively low across all players, reflecting excellent conditioning and optimized body composition. Lower body fat contributes to improved movement economy, acceleration ability, and sprint performance (Reilly et al., 2022). Goalkeepers demonstrated slightly higher body fat percentages and body mass values compared with outfield players, which is consistent with positional demands emphasizing reach, stability, and strength rather than continuous running.

The relatively homogeneous profiles observed in this study suggest that elite football environments favour highly standardized physiological and anthropometric characteristics. Modern football increasingly requires players to simultaneously develop aerobic endurance, anaerobic power, speed, strength, and tactical intelligence (Impellizzeri et al., 2023).

The aim of this study was to analyse physiological and anthropometric characteristics of Croatian national football team players, with particular emphasis on blood lactate concentration, relative oxygen consumption, body height, body mass, body fat percentage, and positional specialization. The obtained results indicate highly developed aerobic and anaerobic capacities together with favourable anthropometric profiles characteristic of elite football players.

 © 2026 ARD Asociación Española

The average relative oxygen consumption observed in this study was exceptionally high, indicating superior aerobic endurance capacity among analysed players. Aerobic endurance is considered one of the fundamental physiological requirements in modern football because players are required to sustain repeated high-intensity efforts throughout the entire duration of the match (Sporis et al., 2009). Elite football players frequently cover distances exceeding 10 kilometres during competition while simultaneously performing sprinting actions, accelerations, and tactical transitions.

Midfield players demonstrated the highest relative oxygen consumption values in the present study. This finding corresponds with previous research showing that midfielders typically possess superior aerobic endurance due to their continuous involvement in both attacking and defensive phases of play (Sporis et al., 2009). Players such as Luka Modrić and Ivan Rakitić are internationally recognized for exceptional movement capacities and endurance performance during matches.

High aerobic fitness contributes to improved recovery between repeated sprint actions and allows players to maintain tactical and technical performance under fatigue conditions. Sporis et al. (2009) emphasized that elite football players with superior aerobic capacities demonstrate greater movement efficiency and better tolerance to match intensity. Consequently, aerobic conditioning remains one of the primary objectives of modern football training programs.

Blood lactate concentration values obtained in this study also indicate highly developed anaerobic capacity among Croatian national football team players. Football is characterized by intermittent high-intensity exercise involving repeated sprinting, pressing, jumping, tackling, and rapid directional changes. Such activities strongly activate anaerobic glycolytic pathways and result in elevated lactate production (Sporis et al., 2008).

The highest lactate values were recorded among players occupying demanding transitional and midfield roles. This finding may reflect greater exposure to repeated high-intensity actions during both training and competition. Research conducted by Sporis, Ruzic, and Leko (2008) demonstrated that structured high-intensity conditioning programs significantly improve anaerobic endurance and tolerance to metabolic stress in elite soccer players.

Modern sports physiology no longer considers lactate solely as a by-product of fatigue. Instead, lactate is recognized as an important metabolic substrate involved in energy transport and muscular adaptation processes. Elite football players demonstrate enhanced buffering capacity and faster lactate clearance compared with recreational athletes, allowing them to repeatedly perform high-intensity actions with reduced performance decline (Sporis et al., 2008).

Anthropometric characteristics observed in this study were also consistent with profiles commonly described in elite football populations. The average body height and body mass values reflected positional specialization and the physical demands of modern football. Goalkeepers and central defenders demonstrated larger body dimensions compared with midfield players and forwards, which corresponds with previous football research findings (Sporis et al., 2011b).

Body height represents an important factor in football because it influences aerial duel performance, defensive coverage, jumping ability, and physical dominance during set-piece situations. Taller players are frequently preferred for defensive and goalkeeping positions due to advantages in reach and heading ability.

However, excessive body mass may negatively affect agility and acceleration performance if not accompanied by optimal conditioning levels.

Body fat percentage values in the present study were relatively low across all players, indicating excellent conditioning status and optimized body composition. Low body fat percentage is associated with improved sprinting performance, movement economy, agility, and acceleration capacity (Sporis et al., 2009). Elite football players generally maintain low fat mass in order to optimize power-to-weight ratio and reduce unnecessary physiological load during repeated high-intensity activity.

The observed positional differences additionally confirm the importance of individualized conditioning approaches in football training. Goalkeepers demonstrated slightly higher body mass and body fat percentages compared with outfield players, reflecting positional demands focused on explosive actions, jumping, and reaction performance rather than continuous locomotor activity. Midfield players demonstrated the highest aerobic values and lower fat percentages, while forwards combined high anaerobic capacities with relatively low body fat.

Agility and multidirectional movement abilities are also essential components of football performance. Research conducted by Sporis et al. (2010a) demonstrated high reliability and validity of agility tests specifically designed for football players. Modern football requires athletes to rapidly change direction while maintaining balance, speed, and technical precision under pressure conditions.

Repeated sprint ability has become increasingly important due to the rising tempo of elite football competition. Football players are frequently exposed to short recovery intervals between maximal sprint efforts. Therefore, contemporary conditioning programs integrate aerobic and anaerobic training methods in order to simultaneously improve endurance, sprint capacity, and recovery efficiency (Sporis et al., 2008).

The relatively homogeneous physiological and anthropometric profiles observed in this study suggest that elite football environments favour highly standardized conditioning and body composition characteristics. Talent identification and player development systems increasingly utilize physiological testing, anthropometric monitoring, and performance diagnostics in order to optimize long-term athlete development.

One important limitation of this study is the relatively small sample size and cross-sectional design. Although the analysed players represent elite-level football performers, larger samples would improve statistical reliability and allow more detailed positional comparisons. Another limitation concerns the absence of direct laboratory measurements for certain variables such as body fat percentage and maximal aerobic power.

Future research should include longitudinal monitoring across competitive seasons, direct physiological laboratory testing, sprint performance analysis, maximal aerobic speed assessment, and biochemical recovery markers. Additionally, future studies should investigate the relationship between physiological variables and match performance indicators such as running distance, sprint frequency, accelerations, and technical efficiency.

Despite these limitations, the present study provides valuable insight into the physiological and anthropometric characteristics of Croatian national football team players. The findings confirm that elite football performance depends on the interaction between aerobic endurance, anaerobic power, body composition, and position-specific physical demands.

 © 2026 ARD Asociación Española

Overall, Croatian national football players demonstrated exceptionally high physiological preparedness and optimized anthropometric profiles consistent with the demands of modern elite football. These characteristics likely contribute significantly to the international competitive success achieved by Croatian football in recent years.

One limitation of this study is the relatively small sample size and the use of estimated body fat percentages. Future research should include direct laboratory measurements, sprint tests, maximal aerobic speed, and longitudinal monitoring across competitive seasons.

The present findings suggest that the international success of Croatian football may be supported by a distinctive physiological profile characterized by high aerobic fitness, efficient body composition, and position-specific specialization. Integrating these physiological characteristics with modern external-load monitoring and match-performance analytics may provide a comprehensive framework for talent development and long-term performance optimization in elite football.

CONCLUSION

Croatian national football team players demonstrated highly developed physiological and anthropometric characteristics appropriate for elite football performance. The players exhibited excellent aerobic endurance, elevated anaerobic capacity, optimal body composition, and position-specific anthropometric profiles. These characteristics represent important prerequisites for success in modern elite football. Physiological profiling alone should no longer be viewed as sufficient. Modern football performance emerges from the interaction between physiological capacity, external-load monitoring, tactical behaviour, and longitudinal player tracking.

Practical application

- Efference values for Croatian academies,
- Talent identification,
- Monitoring player readiness,
- Individualized conditioning,
- Return-to-play benchmarks,
- National federation databases,
- Position-specific training design.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Boriss Bazanov, Ivica Franjko, Veljko Vukicevic. Methodology: Maki Grle, Goran Sporiš, Besnik Morina, Milna Milošević. Formal analysis: Davorin Antonić. Investigation: Ernest Šabić, Davor Lješević, Fredi Fiorentini, Zeljko Kovačević. Data curation: Naim Ćeleš, Davorin Antonić, Ivan Duroci, Hrvoje Ajman, Zeljko Širič. Writing – original draft: Ivana Grle, Goran Sporiš, Bozenka Galic Tiric. Nijaz Skender, Jerko Prlić, Aida Mohammadi, Ahmet Naci Dilek, Hadi Nobari, Adem Preljević. Supervision: Goran Sporiš, Dejan Tiric, Natalija Kurtović, Parham Jalali.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

Individuals who contributed to the research through support, acknowledgements, funding, and donations: Vjekoslav Radovčić, Željko Kovačević, Adnan Mustedanagić, Štefan Modrić, Ivan Stevura, Josip Lepeš, Igor Sabo, Ivan Đuroci, Miloš Maravić, Marko Žigman, Miloš Stojković, Željko Širić, Agim Hasani, Darko Dumančić, Stjepan Babić, Robert Citozi, Jakov Gogić, Veljko Vukičević, Marin Nikolić, Mario Anić Kremić, Krešimir Maronić, Tomislav Brlečić, Dino Kluk, Davor Lješević, Dominik Pick, Mladen Muškovac, Deni Hajdarović, Josip Zornjak, Štefan Modrić, Karlo Zornjak, Željko Ostrman, Baltazar Bogulin, Marijan Spehnjak, Baltazar Bogulin, Nijaz Skender, Perica Vidak, Marko Žigman, Krševan Santini, Željko Širić, Goran Špaleta, Darko Dumančić, Damir Benedeković, Robert Citozi, Dominik Mohorocić, Veljko Vukičević, Goran Vučković, Mario Anić Kremić, Nic Jamec, Tomislav Brlečić, Besim Morina, Davor Lješević, Bojan Šestan, Mladen Muškovac, Mladen Muškovac, Josip Zornjak, Hrvoje Ajman, Karlo Zornjak, Ivana Grle, Baltazar Bogulin, Maki Grle, Zoran Bogulin, Jerko Prlić, Perica Vidak, Dejan Tiric, Krševan Santini, Bozenka Galic Tiric, Goran Špaleta, Vedran Režić, Lazar Zaknić, Jose Antonio Perez Turpin, Damir Benedeković, Boriss Bazanov, Dominik Mohorocić, Davor Bučević, Bojan Šestan, Sandra Kerim, Jakov Gogić, Marko Čurković, Deni Hajdarović, Haris Ćoćić, Marin Nikolić, Ivan Žižić, Hrvoje Ajman, Zlatko Triplat, Mate Vukoja, Robet Čović, Zvezdan Stefanović, Josip Zekić, Faisal Osama Mohamed Hasan Mohamed, Tomas Marczinka, Ahmed Kamal Ahmed Hasan Ali, Juraj Govorčin, Ivan Pavić, Vatroslav Horvat, Andrej Radić, Anto Aračić, Dino Bartoluci, Jasmin Ičanović, Milan Milošević, Vlatka Tomić, Dalija Kuvačić, Petra Špaleta, Vid Kučko, Miroslav Hrženjak, Goran Jelaska, Srđan Prodanović, Peruško Manuel, Šutić Danijel, Vlašić Jan, Petra Mandić, Damir Jurko, Ante Vukoja, Mauro Carvalho, Tomislav Lopac, Haris Alić, Ahmed Kamal, Marijan Jozić, Marko Erceg, Ahmet Naci Dilek, Gaetano Raiola, Deniss Dunik, Fjodor Dunik, Ilja Jazev, Mindaugas Balčiūnas, Arūnas Emeljanovas, Brigita Miežiene, Balčiuniene Vaiva, Tolga Tek, Perez Aleixandre Pablo, Sport Sapiens OU, Milan Milošević, Andrej Radić, Poliklinika Ribnjak.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

ETHICAL APPROVAL

Ethical approval for this study was obtained within the framework of the Croatian Science Foundation project (IP-2020-02-3366), which was approved by the relevant Ethics Committee and conducted in accordance with the Croatian Science Foundation's Code of Ethics. The study was carried out in accordance with the ethical principles of the Declaration of Helsinki.

DATA AVAILABILITY STATEMENT

All data generated or analysed during this study are included in this published article and its Supplementary Materials. The datasets generated during the current study are available from the corresponding author upon reasonable request.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

 © 2026 ARD Asociación Española

REFERENCES

Bangsbo, J., Mohr, M., & Krustrup, P. (2022). Physical and metabolic demands of football. *Journal of Sports Sciences, 40*(5), 523–536.

Bassett, D. R., Jr., & Howley, E. T. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Medicine & Science in Sports & Exercise, 32*(1), 70–84. https://doi.org/10.1097/00005768-200001000-00012

Brooks, G. A. (2023). Lactate metabolism in exercise physiology. *Cell Metabolism, 35*(4), 567–580.

Castagna, C., Impellizzeri, F., & Rampinini, E. (2022). Anthropometric and physiological characteristics in elite football players. *Journal of Sports Sciences, 40*(11), 1204–1213.

Impellizzeri, F., Marcora, S., & Castagna, C. (2023). Physiological conditioning in elite football. *Sports Medicine, 53*(6), 1111–1125.

Jovanović, M., Sporiš, G., Omrčen, D., & Fiorentini, F. (2011). Effects of speed, agility, quickness training method on power performance in elite soccer players. *Journal of Strength and Conditioning Research, 25*(5), 1285–1292. https://doi.org/10.1519/JSC.0b013e3181d67c65

Milanović, Z., Pantelić, S., Čović, N., Sporiš, G., & Krustrup, P. (2015). Is recreational soccer effective for improving physical fitness? A systematic review and meta-analysis. *Sports Medicine, 45*(9), 1339–1353. https://doi.org/10.1007/s40279-015-0361-4

Milanović, Z., Sporiš, G., Trajković, N., James, N., & Šamija, K. (2013). Effects of a 12 week SAQ training programme on agility with and without the ball among young soccer players. *Journal of Sports Science and Medicine, 12*(1), 97–103. https://www.jssm.org/jssm-12-97.xml-Fulltext

Reilly, T., Bangsbo, J., & Franks, A. (2022). Anthropometric predispositions for elite football performance. *European Journal of Sport Science, 22*(8), 1181–1192.

Sporiš, G., Čanaki, M., & Barišić, V. (2007). Morphological differences of elite Croatian female soccer players according to team position. *Hrvatski Športskomedicinski Vjesnik, 22*(2), 91–96. https://hrcak.srce.hr/20122

Sporiš, G., Jovanović, M., Omrčen, D., & Matković, B. (2011a). Can the official soccer game be considered the most important contribution to player physical fitness level? *Journal of Sports Medicine and Physical Fitness, 51*(3), 374–380.

Sporiš, G., Jukić, I., Milanović, L., & Vučetić, V. (2010a). Reliability and factorial validity of agility tests for soccer players. *Journal of Strength and Conditioning Research, 24*(3), 679–686. https://doi.org/10.1519/JSC.0b013e3181c4d324

Sporiš, G., Jukić, I., Ostojić, S. M., & Milanović, D. (2009). Fitness profiling in soccer: Physical and physiologic characteristics of elite players. *Journal of Strength and Conditioning Research, 23*(7), 1947–1953. https://doi.org/10.1519/JSC.0b013e3181b3e141

Sporiš, G., Milanović, Z., Trajković, N., & Joksimović, A. (2011b). Correlation between speed, agility and quickness performance and anthropometric characteristics in elite young soccer players. *Collegium Antropologicum, 35*(2), 599–605.

Sporiš, G., Ružić, L., & Leko, G. (2008). The anaerobic endurance of elite soccer players improved after a high-intensity training intervention in the 8-week conditioning program. *Journal of Strength and Conditioning Research, 22*(2), 559–566. https://doi.org/10.1519/JSC.0b013e3181660401

Sporiš, G., Vučetić, V., Milanović, L., Milanović, Z., Krespi, M., & Krakan, I. (2014). A comparison anaerobic endurance capacity in elite soccer, handball and basketball players. *Kinesiology, 46*(Suppl. 1), 52–59. https://hrcak.srce.hr/127843

Stølen, T., Chamari, K., Castagna, C., & Wisløff, U. (2022). Physiology of football: Updated perspectives. *European Journal of Sport Science, 22*(7), 1045–1058.

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

When extra-role becomes expected: Organizational citizenship behaviour as a boundary condition in the coach–athlete interaction–burnout link

Acelya Telli . *Department of Business Administration. Istanbul Esenyurt University. Istanbul, Türkiye.*
Serdar Bozkurt. *Department of Business Administration. Yildiz Technical University. Istanbul, Türkiye.*

ABSTRACT

Coach–athlete interaction represents a central relational resource in team sports and is closely linked to athletes' motivation, psychological well-being, and sustained engagement. Yet, athletes often operate in climates where 'going above and beyond' for the team can be experienced not only as a voluntary contribution but also as an implicit expectation. Building on Leader–Member Exchange (LMX) Theory and research on organizational citizenship behaviour in sport (OCB-S), this study examines (a) whether higher-quality coach–athlete interaction is associated with lower athlete burnout, and (b) whether athletes' OCB functions as a boundary condition in this relationship. Survey data were collected from 250 adult athletes participating in team sports in Türkiye. Using PLS-SEM, the results showed that higher-quality coach–athlete interaction was negatively associated with athlete burnout. Moreover, OCB strengthened the negative association between coach–athlete interaction and burnout, such that the relationship was stronger at higher levels of OCB. These findings suggest that higher-quality coach–athlete interaction is associated with lower athlete burnout, particularly when athletes' extra-role involvement remains meaningful and self-endorsed rather than merely compliant with team norms.

Keywords: organizational citizenship behaviour in sport; leader–member exchange; coach–athlete interaction; athlete burnout; team sports; coaching practice.

Cite this article as:
Telli, A., & Bozkurt, S. (2026). When extra-role becomes expected: Organizational citizenship behaviour as a boundary condition in the coach–athlete interaction–burnout link. *Journal of Human Sport and Exercise, 21*(4), 1380-1394. https://doi.org/10.55860/kzbz2s03

Corresponding author. *Department of Business Administration. Istanbul Esenyurt University. Zafer Mahallesi Adile Naşit Bulvarı No:1. 34510 Istanbul, Türkiye.*
E-mail: acelyatelli@esenyurt.edu.tr
Submitted for publication April 15, 2026.
Accepted for publication July 21, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/kzbz2s03

© 2026 ARD Asociación Española

INTRODUCTION

In the realm of sports, one essential and universal element underpinning success is interaction—the central mechanism through which team members connect, coordinate, and collaborate. Both interactions among athletes and those between athletes and coaches are critical determinants of athletic performance. High-quality coach–athlete interactions are associated with positive outcomes such as satisfaction, commitment, and engagement with the team. In contrast, lower-quality interactions have been associated with diminished motivation (Cahyono et al., 2023), dissatisfaction and withdrawal from sport (Olsson et al., 2022; Shang & Yang, 2021), and burnout (Deci & Ryan, 2012; Standage & Ryan, 2020; Davis et al., 2023). Such circumstances may also reduce athletes' engagement in voluntary, extra-role behaviours that are often driven by intrinsic motivation. Understanding these relationships is therefore crucial for fostering positive psychological and performance outcomes.

In coaching contexts, athletes' discretionary contributions (e.g., helping teammates, taking on extra training tasks, maintaining a positive attitude) may simultaneously serve as a performance-enhancing resource and a potential stressor. Because team sport environments often involve strong normative expectations and hierarchical authority, athletes can experience 'extra-role' behaviours as partly expected rather than purely voluntary. This ambiguity is important for burnout research: when additional contributions are self-endorsed, they may buffer strain, but when they are driven by obligation, they can intensify exhaustion.

Drawing on Leader–Member Exchange (LMX) Theory, we conceptualize coach–athlete interaction quality as a relational mechanism through which coaches provide support, trust, and respect, shaping athletes' psychological experiences in training and competition. High-quality exchange relationships are expected to foster need satisfaction, engagement, and resilience, whereas low-quality exchanges can increase stress and vulnerability to burnout.

Although the coach–athlete relationship has been widely linked to performance and well-being, less is known about when and for whom relational quality is most strongly associated with lower athlete burnout. Athletes' extra-role involvement—captured here as organizational citizenship behaviour in sport (OCB)—may be one such boundary condition. OCB reflects behaviours that support team functioning beyond formal role requirements; however, in sport settings, these behaviours can be intertwined with implicit expectations and moralized commitment. Accordingly, we examine whether OCB strengthens the association between coach–athlete interaction and burnout.

Using survey data from 250 team-sport athletes in Türkiye, this study investigates the relationship between coach–athlete interaction and athlete burnout and tests OCB as a moderator. By integrating a coaching-specific view of relational quality with contemporary work on citizenship behaviour in sport, the study offers applied insights for coaches seeking to better understand factors associated with athlete burnout while sustaining constructive team contributions.

Literature review and hypothesis development

Coach–athlete interaction and athlete burnout

Leader–athlete interactions are central not only in business contexts but also in sports environments, where they influence both individual and team performance (Gu et al., 2023). The theoretical framework for coach–athlete interaction is grounded in Leader–Member Exchange (LMX) Theory, which focuses on the quality of social interactions between leaders and team members (Graen & Uhl-Bien, 1995; Leduc et al., 2024). Coaches and athletes continuously interact within a team setting, and athletes' satisfaction and perceptions of their coaches depend on interaction quality (Lee et al., 2023; Stephen et al., 2022).

The Coach–Athlete Relationship (CAR) is typically conceptualized along three dimensions: closeness, commitment, and complementarity. Closeness refers to trust, respect, liking, and appreciation between athlete and coach (do Nascimento Junior et al., 2020); commitment reflects a harmonious relationship between the two parties (Simons & Bird, 2023); and complementarity indicates cooperative, reciprocal behaviours (Li et al., 2021). High-quality CAR fosters a harmonious environment, increases athlete motivation, and enhances participation in training, ultimately positively influencing athletic performance (Davis et al., 2018; Foulds et al., 2019; Lee et al., 2023).

Although the coach–athlete relationship has been extensively examined using sport-specific frameworks such as Jowett's 3+1Cs model (closeness, commitment, complementarity, and co-orientation)(Jowett, 2007), the present study adopts a Leader–Member Exchange (LMX) perspective to conceptualize coach–athlete interaction quality. While these frameworks originate from different research traditions, they share a common relational core. Specifically, the LMX dimensions of trust, loyalty, contribution, and professional respect conceptually overlap with the affective and behavioural components captured by the 3+1Cs model. In this respect, LMX provides a complementary lens that emphasizes exchange-based relational processes and perceived reciprocity within hierarchical relationships. Given the structured and authority-based nature of coach–athlete dynamics in team sports, LMX offers a suitable framework for capturing how relational quality functions as a resource influencing athlete outcomes such as burnout (Jowett, 2007; Graen & Uhl-Bien, 1995).

Burnout represents a major threat in both individual and team sports, characterized by emotional and physical exhaustion, depersonalization, and reduced accomplishment (Wilczyńska et al., 2022; Raedeke & Smith, 2001). Studies demonstrate that insufficient coach support significantly increases burnout levels, while high-quality interactions help mitigate it (Fan et al., 2023; Brown & Roloff, 2015; Buyukbasmaci, 2024; Dixon, 2021; Li et al., 2024; Nicholls et al., 2022). Based on this evidence, the first hypothesis is proposed:

H_1: Coach–athlete interaction is negatively associated with athlete burnout.

The moderating role of OCB

Organizational Citizenship Behaviour (OCB) refers to discretionary behaviours that are not formally required or rewarded, which also manifest in sports settings (Kim et al., 2022). In sports, OCB includes actions such as sharing knowledge with teammates, participating in extra training sessions, organizing team activities, and supporting team cohesion (Chelladurai, 2006; Podsakoff et al., 2000; Fletcher & Wagstaff, 2009; Jabeen et al., 2021).

Importantly, the meaning of 'citizenship' in sport is not always straightforward. Because coaches hold substantial authority and team cultures may valorise sacrifice, athletes can perceive extra-role behaviours as expected demonstrations of commitment. This can create a grey zone between truly discretionary contribution and compliance with normative demands—an issue with direct implications for burnout and wellbeing.

In sports contexts, a unique OCB dimension—sportsmanship—emerges due to the high authority of coaches and normative expectations for athletes to comply with instructions (Stirling & Kerr, 2009). Unlike employees in non-sport organizations, athletes may experience uncertainty regarding which behaviours are truly voluntary versus expected, creating a "*grey area*" in OCB assessment (Love & Kim, 2019; Kim et al., 2022). Kim et al.'s (2022) OCB-S scale, used in the present study, includes five subdimensions: bonding, community service, encouraging, extra work, and helping, reflecting voluntary behaviours that strengthen team dynamics and performance (Güner & Işık, 2023).

 © 2026 ARD Asociación Española

From an LMX perspective, athletes are more likely to engage in OCB when they have a high-quality relationship with their coach, as relational support exceeds baseline expectations. Prior research confirms that insufficient coach support correlates with lower OCB levels, while transformational, autonomy-supportive, or democratic coaching styles positively affect both CAR and OCB (Dekas et al., 2013; Eby et al., 2015; Ellinger & Cseh, 2007; Jin et al., 2022; Choi et al., 2020). High-quality interactions satisfy athletes' psychological needs, increase positive outcomes, and reduce negative outcomes such as burnout (Davis et al., 2023; Fan et al., 2023).

However, the relationship between OCB and burnout may be contingent on whether extra-role contributions are experienced as self-endorsed or as obligations. When OCB reflects authentic team-oriented engagement, it may function as a resource that amplifies the protective role of coach–athlete interaction. Consistent with a boundary-condition approach, we therefore test whether OCB moderates the link between coach–athlete interaction and athlete burnout.

> *H_2: Athletes' organizational citizenship behaviours moderate the relationship between coach–athlete interaction and athlete burnout, such that the negative association is stronger when OCB is higher.*

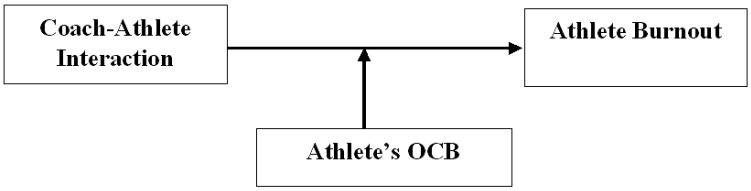


Figure 1. Research model.

METHODOLOGY

Participants

The population of the research consists of individuals aged 18 and above who are involved in team sports in Türkiye. While exact data on the total number of eligible individuals aged 18 and above participating in team sports in Türkiye was not available, the sample size was designed to meet generally accepted adequacy criteria for quantitative studies in the social sciences. Therefore, the sample of the study consists of 250 volunteer athletes (no distinction was made between licensed and unlicensed athletes) from Türkiye who completed the online questionnaire via Google Forms. Participants were selected using the convenience sampling method, as collecting data online via Google Forms voluntarily conflicts with random sampling.

Scales

A survey method was employed for data collection. Survey data were gathered online via Google Forms, following the approval of the Istanbul Esenyurt University Ethics Committee (Approval No. 2025/01). The survey included demographic questions (4 items), items from the Leader–Member Exchange (LMX) Scale, the Athlete Burnout Questionnaire (ABQ), and the Organizational Citizenship Behaviour in Sports (OCB-S) Scale. In total, the survey consisted of 51 items. Detailed information regarding the scales and demographic questions utilized in the research is provided below:

- *Leader–Member Exchange (LMX) Scale*: Developed by Liden and Maslyn (1998), the Turkish reliability and validity study was conducted by Baş et al. (2010). This scale comprises 12 items distributed across four sub-dimensions: Impact, Loyalty, Contribution, and Professional Respect.

- *Athlete Burnout Questionnaire (ABQ):* Developed by Raedeke and Smith (2001, 2009), with its Turkish reliability and validity study conducted by Kelecek et al. (2016). The ABQ contains 13 items across three sub-dimensions: Reduced Sense of Accomplishment, Emotional/Physical Exhaustion, and Devaluation.
- *Organizational Citizenship Behaviour in Sports Scale (OCB-S):* Developed by Kim et al. (2022), and its Turkish adaptation and validity study were conducted by Güner and Işık (2023). This scale consists of 22 items across five sub-dimensions: Bonding, Community Service, Encouraging, Extra Work, and Helping.

These scales were selected due to their established reliability and validity in both international and Türkiye contexts, providing a robust framework to examine coach–athlete interactions, athlete burnout, and OCB in sports settings.

RESULTS

Of the 250 individuals participating in the research, 56.4% (141) are men and 43.6% (109) are women. Considering the age range, it is evident that the majority of participants in the research (76.8%, 192 people) fall within the 18-27 age group. The sports branches that the participants of the research are most interested in are football, with 31.2% (78 people), volleyball, with 30% (75 people), and basketball, with 20.8% (52 people). When the participants were asked how many years they had been engaged in the type of sports they declared, 27.2% (68 people) said 5-10 years, 26.4% (66 people) said 10 years or more, and 23.2% (58 people) had been engaged in a certain type of sports for 1-3 years.

Reliability and validity analysis

Reliability and validity analyses were conducted for each scale before hypothesis testing. Cronbach's Alpha and composite reliability values (rho_a and rho_c) indicate that the scales demonstrate satisfactory reliability for this study ($\alpha > .70$) (George & Mallery, 2003). Also, AVE values indicated acceptable convergent validity for most constructs. Although the AVE value for Athlete Burnout was slightly below the recommended threshold of 0.50, its composite reliability exceeded 0.90, suggesting that the construct still demonstrates adequate internal consistency and convergent validity (Hair et al., 2021).

Table 1. Construct validity and reliability analysis findings.

	Cronbach Alpha	rho_a	rho_c	AVE
LMX	.947	.951	.954	.636
OCB in sports	.973	.978	.975	.636
Athlete burnout	.901	.914	.909	.439

Discriminant validity was assessed using the Heterotrait-Monotrait (HTMT) ratio. Results indicate a low-to-moderate positive correlation (.283) between Athlete Burnout and LMX, a moderate correlation between OCB in Sports and LMX, and a low correlation between Athlete Burnout and OCB in Sports (Table 2).

Table 2. Discriminant validity (HTMT) analysis.

	Athlete burnout	LMX	OCB in sports
LMX	.283		
OCB in sports	.179	.502	
OCB in sports x LMX	.153	.276	.340

 © 2026 ARD Asociación Española

Factor analysis

Athlete Burnout Questionnaire

Confirmatory factor analysis revealed that the Athlete Burnout Questionnaire retained its three original sub-dimensions, consistent with both the original and Turkish adaptation (Kelecek et al., 2016; Raedeke & Smith, 2001).

Table 3. Factor loadings of the Athlete Burnout Questionnaire.

Factor	Item	Loading	*p*
Decreased sense of accomplishment	20	.712	.000
	22	.737	.000
	27	.621	.000
	28	.509	.000
Emotional/physical exhaustion	17	.479	.000
	19	.631	.000
	23	.763	.000
	25	.667	.000
	26	.670	.000
Depersonalization	18	.680	.000
	21	.731	.000
	24	.652	.000
	29	.629	.000

Leader-Member Exchange (LMX) Scale

Factor analysis confirmed the original four sub-dimensions, with all items loading appropriately (Baş et al., 2010; Dienesch & Liden, 1986).

Table 4. Factor loadings of the LMX Scale.

Factor	Item	Loading	*p*
Impact	5	.852	.000
	6	.832	.000
	7	.880	.000
Loyalty	8	.691	.000
	9	.787	.000
	10	.776	.000
Contribution	11	.775	.000
	12	.703	.000
	13	.723	.000
Professional respect	14	.825	.000
	15	.835	.000
	16	.866	.000

OCB in Sports Scale

Factor loadings confirmed the original five sub-dimensions, with all items appropriately aligned (Güner & Işık, 2023; Kim et al., 2022).

Variance Inflation Factor (VIF) values were calculated to assess multicollinearity. All VIF values were below 10, indicating no concerns about multicollinearity (Hair et al., 2019).

Table 5. Factor loadings of the OCB in sports scale.

Factor	Item	Loading	*p*
Bonding	30	.806	.000
	31	.843	.000
	32	.815	.000
	33	.780	.000
Community service	34	.721	.000
	35	.720	.000
	36	.744	.000
Encouraging	37	.819	.000
	38	.829	.000
	39	.821	.000
	40	.831	.000
	41	.841	.000
Extra-work	42	.720	.000
	43	.796	.000
	44	.801	.000
	45	.836	.000
	46	.783	.000
Helping	47	.881	.000
	48	.893	.000
	49	.898	.000
	50	.903	.000
	51	.780	.000

Table 6. Collinearity statistics (VIF) analysis findings.

	VIF
LMX → Athlete burnout	1.328
OCB in Sports → Athlete burnout	1.390
OCB in Sports x LMX → Athlete burnout	1.151

Table 7. Model fit.

	Saturated model	Estimated model
SRMR	.083	.085
Chi-square	3.549.410	3.550.601
NFI	.692	.692

Model fit indices indicate an acceptable fit. SRMR values between 0.05 and 0.10 indicate a good model fit, while NFI values below the conventional threshold of 0.90 suggest room for improvement (Hu & Bentler, 1999). Although the NFI value is below the conventional threshold, PLS-SEM studies have noted that model fit indices should be interpreted cautiously, as prediction-oriented models may still yield valid and meaningful results despite lower fit indices (Hair et al., 2019).

Hypothesis testing

Path analysis, as a component of Partial Least Squares Structural Equation Modeling (PLS-SEM), was used to test H1, assessing the relationship between coach-athlete interaction (LMX) and athlete burnout. PLS-

 © 2026 ARD Asociación Española

SEM was chosen as an appropriate analytical approach for this study, given its suitability for complex models and its robustness under conditions of non-normal data and moderate sample sizes (Hair et al., 2019).

Results indicate a significant negative association between LMX and athlete burnout (β = -.333, $p < .001$), supporting H1. This finding indicates that athletes reporting higher-quality relationships with their coach also tended to report lower levels of burnout. Results further indicated that coach–athlete interaction was positively associated with OCB, while OCB was negatively associated with athlete burnout. Consistent with the theoretical framework and hypotheses of the present study, the primary focus remains on the moderating role of OCB as a boundary condition influencing the association between coach–athlete interaction and athlete burnout.

Another notable finding, as illustrated in Figure 2, is the positive relationship between coach-athlete interaction and OCB in sports (β = 0.373, $p < .001$). This suggests that athletes reporting higher-quality relationships with their coaches were also more likely to report organizational citizenship behaviours. Additionally, a negative relationship between OCB in sports and athlete burnout was observed (β = -0.172, $p < .01$), indicating that athletes engaging in more OCB experience lower levels of burnout.

Overall, the findings indicate that higher-quality coach–athlete interaction is associated with lower burnout and that athletes' OCB operates as a boundary condition for this association. Specifically, the negative relationship between coach–athlete interaction and burnout was stronger when OCB was higher, consistent with a moderating (interaction) effect. In addition, coach–athlete interaction was positively related to OCB and OCB was negatively related to burnout, suggesting that constructive relational climates coincide with greater team-supportive behaviours and lower burnout.

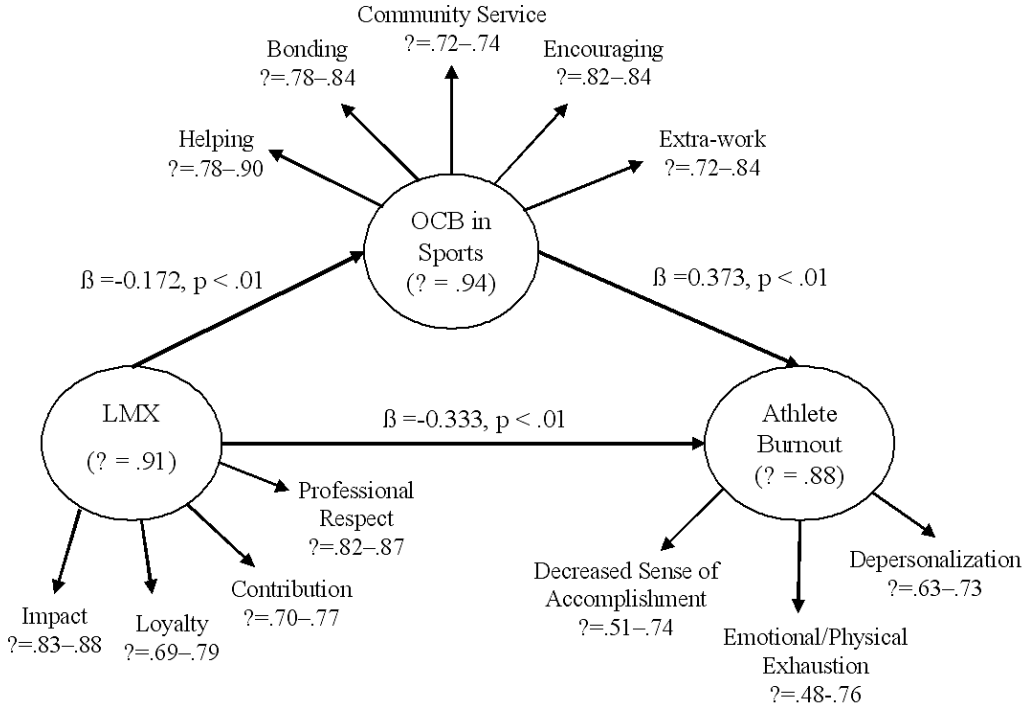


Figure 2. PLS-SEM results.

To further interpret the moderating effect of OCB, a simple slopes analysis was conducted (see Table 8):

Table 8. Simple slopes analysis of the relationship between coach–athlete interaction and athlete burnout at different levels of OCB.

	Original sample	Sample mean	Std. Dev.	t	*p*
LMX → Athlete Burnout OCB in Sports (at +1 SD)	-.505	-.518	.096	5.262	.000
LMX → Athlete Burnout OCB in Sports (at -1 SD)	-.161	-.172	.071	2.269	.023
LMX → Athlete Burnout OCB in Sports (at Mean)	-.333	-.345	.063	5.266	.000

To further interpret the moderating effect of OCB, a simple slopes analysis was conducted to examine the conditional effects of coach–athlete interaction on athlete burnout at low (−1 SD), mean, and high (+1 SD) levels of OCB (see Table 8 and Graph 1). The results indicate that the negative association between coach–athlete interaction and burnout was weakest at low levels of OCB and became progressively stronger at mean and high levels of OCB. Specifically, while coach–athlete interaction was negatively associated with burnout across all levels of OCB, the steepest negative slope was observed when athletes reported high levels of OCB. These findings suggest that athletes who more frequently engage in team-supportive, extra-role behaviours reported greater well-being benefits from high-quality coach–athlete interaction.

Figure 3 illustrates this moderating effect, showing how the slope of the relationship between coach-athlete interaction and athlete burnout steepens as OCB increases. This finding further supports the interpretation that higher levels of OCB were associated with a stronger negative association between coach–athlete interaction and burnout.

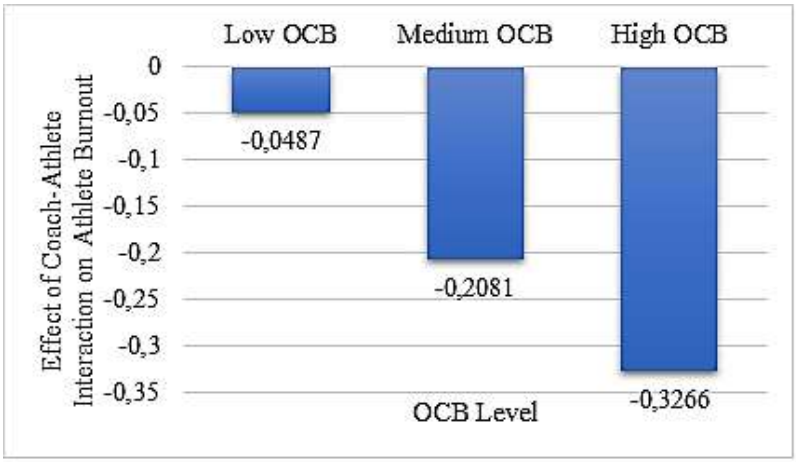


Figure 3. The moderating effect.

The interaction effect is illustrated conceptually, and the interpretation is supported by the simple slopes analysis presented in Table 8. The findings indicate that the negative association between coach–athlete interaction and burnout was stronger among athletes reporting higher levels of OCB than among those reporting lower levels of OCB. Accordingly, these findings may reflect that athletes reporting higher OCB also tend to report stronger connections with both their coach and teammates, alongside lower burnout levels. However, this interpretation should not be viewed as evidence of causality due to the cross-sectional design.

 © 2026 ARD Asociación Española

DISCUSSION

Theoretical contributions

This study contributes to coaching and sport science by showing that coach–athlete interaction quality is a robust relational correlate of athlete burnout in team sports. By applying an exchange-based lens to coaching relationships, the findings reinforce the practical value of relational coaching behaviours (e.g., trust building, individualized support, respectful communication) for sustaining athlete wellbeing. By situating coach–athlete interaction as a central relational mechanism within coaching practice, this study reinforces the relevance of exchange-based perspectives for understanding athlete burnout in real-world team sport environments.

A second contribution is the boundary-condition perspective on organizational citizenship behaviour in sport. Rather than treating OCB as uniformly beneficial, the study demonstrates that OCB shapes when coach–athlete interaction is most strongly associated with lower burnout. This aligns with contemporary discussions that 'going above and beyond' in sport can be both a resource and an expectation, highlighting the need to consider the normative context surrounding extra-role behaviour. In this respect, OCB appears to function as a boundary condition rather than a direct mechanism in the coach–athlete interaction–burnout relationship.

OCB as a conditional resource in coaching contexts

The moderation pattern suggests that athletes who frequently engage in team-supportive behaviours may benefit more from high-quality coach–athlete interaction when these behaviours are experienced as meaningful and self-endorsed. For coaches, this underscores a subtle but important distinction: encouraging constructive citizenship should not translate into moral pressure or assumed availability. Maintaining clarity about role expectations, recognizing effort without normalizing overcommitment, and monitoring signs of exhaustion may help ensure that extra-role contributions remain sustainable.

Taken together, these findings suggest that effective coaching is not only about fostering strong relationships and encouraging extra effort, but also about actively managing the boundaries of commitment within the team. Coaches who differentiate between required and discretionary contributions, and who explicitly legitimise recovery and personal limits alongside effort, may be better positioned to foster team environments associated with lower athlete burnout and sustained long-term engagement.

Managerial implications

From an applied coaching perspective, the results highlight two actionable levers. First, coaches should invest in relationship quality through consistent, autonomy-supportive communication, individualized feedback, and fair treatment, as relational quality is associated with lower burnout. Second, coaches and support staff should shape team norms so that helping and extra involvement remain genuinely voluntary. Practical steps include clarifying what is required versus optional, rotating informal responsibilities, publicly valuing recovery and boundaries, and checking in with athletes who regularly 'do more' to prevent accumulation of strain.

From a practical standpoint, these findings highlight that coaches should not only focus on building high-quality relationships with athletes but also remain attentive to how team norms shape the meaning of extra-role behaviours. Encouraging voluntary engagement while avoiding implicit pressure may be critical for preventing burnout in team sport environments.

Limitations and future research

This study has some limitations. First, the study employed a cross-sectional design based on convenience sampling and self-reported online questionnaires, which may limit the generalizability of the findings. Because

participation was voluntary and data were collected using self-report measures, the findings may be subject to selection bias, social desirability bias, and common method variance. Future studies are encouraged to adopt longitudinal and probability-based sampling designs to strengthen causal inference and external validity.

A further limitation concerns the interpretation of OCB in sport. Although the OCB-S scale captures team-supportive behaviours, it does not directly measure whether athletes perceive these behaviours as discretionary or as normative obligations. Future studies could incorporate perceived voluntariness, pressure, or role ambiguity to distinguish 'healthy' citizenship from compelled extra-role involvement.

Second, the study was conducted within a single country, which limits cross-cultural generalizability. In addition, the findings of this study are limited to Turkish team sports athletes over the age of 18. Future research should consider comparative designs that include multicultural and different age ranges to produce broader and more generalizable insights.

In addition, athletes were surveyed as individuals, yet team sports are inherently nested (athletes within teams and coaches). Future research could use multilevel designs to capture team- and coach-level effects (e.g., coaching climate, team norms) and to test whether the observed relationships vary across teams, sports branches, or competitive levels.

Thirdly, although Harman's single-factor test indicated potential common method variance (CMV), this test has been widely criticized for its limited sensitivity in detecting CMV. Therefore, the results should be interpreted with caution. Future studies are encouraged to adopt procedural and statistical remedies (e.g., marker variables, longitudinal designs) to better control for CMV. OCB achieved a score of 62.04%, LMX 60.59%, and Athlete Burnout 43.19%, and when all items were evaluated and tested as a single scale, a score of 35.62% was obtained. Therefore, these findings should be interpreted with caution, and the potential influence of common method variance is acknowledged as a limitation of the study.

Additionally, factors such as work-life balance (e.g., family support, work-family role conflicts) and coach support may also contribute to athlete burnout. Future studies are encouraged to incorporate these variables into research models. Furthermore, examining negative aspects of organizational behaviour—such as compulsory citizenship behaviour, presenteeism, and absenteeism—within sports contexts and across specific sports disciplines could provide a more comprehensive understanding of the dynamics between athletes and coaches.

CONCLUSION

The findings indicate that higher-quality coach–athlete interaction is associated with lower athlete burnout in team sports. Athletes who reported better interaction with their coach also reported higher levels of team-supportive (citizenship) behaviours, and those behaviours were linked to lower burnout.

Consistent with a boundary-condition view, athletes' OCB strengthened the negative association between coach–athlete interaction and burnout. The findings suggest that higher-quality coach–athlete interaction is associated with lower athlete burnout, particularly when extra-role contributions remain sustainable and are not driven by implicit obligation. Future research should continue to examine how team norms and perceived voluntariness shape the benefits and costs of citizenship behaviour in sport.

 © 2026 ARD Asociación Española

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Acelya Telli, Serdar Bozkurt. Methodology: Acelya Telli, Serdar Bozkurt. Formal analysis: Acelya Telli. Investigation: Acelya Telli. Data curation: Acelya Telli. Writing – original draft: Acelya Telli. Writing – review & editing: Acelya Telli, Serdar Bozkurt. Supervision: Serdar Bozkurt.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

ETHICAL CONSIDERATIONS

Ethical approval for this study was obtained on 18.02.2025 from the Istanbul Esenyurt University Ethics Committee (Approval No. 2025/01). All procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki.

CONSENT TO PARTICIPATE

Informed consent to participate was obtained from all participants prior to data collection.

DATA AVAILABILITY

The data that support the findings of this study are not publicly available due to ethical and confidentiality considerations but are available from the corresponding author upon reasonable request.

REFERENCES

Baş, T., Keskin, N., & Mert, İ. S. (20*10*). Leader-member exchange (LMX) model and validity and reliability of its instrument in Turkish. *Ege Academic Review*, *10*(3), *101*3–*103*9. https://doi.org/*10*.21121/eab.20*10*319626

Brown, L. A., & Roloff, M. E. (2015). Organizational citizenship behaviour, organizational communication, and burnout: The buffering role of perceived organizational support and psychological contracts. *Communication Quarterly*, *63*(4), 384–404. https://doi.org/10.1080/01463373.2015.1058287

Büyükbaşmacı, Y. E. (2024). Effect of coach-athlete relationship on athlete burnout. *International Journal of Turkish Sport and Exercise Psychology*, 4(2), 63–75. https://doi.org/10.55376/ijtsep.1590008

Cahyono, T., Hartono, F. V., Gani, R. A., Ahmedov, F., Sliz, M., Lobo, J., Kurtoğlu, A., Nasurudin, E., Tannoubi, A., Raman, A., & Setiawan, E. (2023). Coach leadership style, coach-athlete relationships and engagement in team sports: The mediating role of athlete burnout. *Revista Iberoamericana de Psicología del Ejercicio y el Deporte*, *18*(6), 687–692. https://www.riped-online.com/articles/coach-leadership-style-coachathlete-relationships-and-engagement-in-team-sports-the-mediating-role-of-athlete-burnout.pdf

Chelladurai, P. (2006). *Human resource management in sport and recreation (2nd ed.)*. Human Kinetics.

Chiu, S. F., & Tsai, M. C. (2006). Relationships among burnout, job involvement, and organizational citizenship behaviour. *The Journal of Psychology*, *140*(6), 517–530. https://doi.org/10.3200/JRLP.*140*.6.517-530

Choi, H., Jeong, Y., & Kim, S. (2020). *The relationship between coaching behaviour and athlete burnout: Mediating effects of communication and the coach-athlete relationship*. International Journal of Environmental Research and Public Health, 17, Article 8618. https://doi.org/10.3390/ijerph17228618

Davis, L., Appleby, R., Davis, P., Wetherell, M., & Gustafsson, H. (2018). The role of coach-athlete relationship quality in team sport athletes' psychophysiological exhaustion: Implications for physical and cognitive performance. *Journal of Sports Sciences*, *36*(17), 1985–1992. https://doi.org/10.1080/02640414.2018.1429176

Davis, L., Jowett, S., Sörman, D., & Ekelund, R. (2023). The role of quality relationships and communication strategies for the fulfillment of secure and insecure athletes' basic psychological needs. *Journal of Sports Sciences*, *40*(21), 1–13. https://doi.org/10.1080/026*40*414.2022.2162*240*

Deci, E. L., & Ryan, R. M. (2012). Motivation, personality, and development within embedded social contexts: An overview of self-determination theory. In R. M. Ryan (Ed.), *The Oxford handbook of human motivation* (pp. 84–108). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780195399820.013.0006

Dekas, K. H., Bauer, T. N., Welle, B., Kurkoski, J., & Sullivan, S. (2013). Organizational citizenship behaviour, version 2.0: A review and qualitative investigation of OCBs for knowledge workers at Google and beyond. *Academy of Management Perspectives*, *27*(3), 219–237. https://doi.org/10.5465/amp.2011.0097

Dienesch, R., & Liden, R. (1986). Leader-member exchange model of leadership: A critique and further development. *Academy of Management Review*, *11*(3), 618–634. https://doi.org/10.5465/amr.1986.4306242

Dixon, D. (2021). Examining burnout, leader member exchange quality, experience, and OCB in registered nurses [Doctoral dissertation, Northcentral University].

do Nascimento Junior, J. R. A., da Silva, E. C., Freire, G. L. M., Granja, C. T. L., da Silva, A. A., & de Oliveira, D. V. (2020). Athlete's motivation and the quality of his relationship with the coach. Apunts. *Educación Física y Deportes*, *142*, 21–28. https://doi.org/10.5672/apunts.2014-0983.es.(2020/4).*142*.03

Eby, L. T., Butts, M. M., Hoffman, B. J., & Sauer, J. B. (2015). Cross-lagged relations between mentoring received from supervisors and employee OCBs: Disentangling causal direction and identifying boundary conditions. *Journal of Applied Psychology*, *100*(4), 1275–1285. https://doi.org/10.1037/a0038628

Ellinger, A. D., & Cseh, M. (2007). Contextual factors influencing the facilitation of others' learning through everyday work experiences. *Journal of Workplace Learning*, *19*(7), 435–452. https://doi.org/10.1108/13665620710*19*384

Fan, F., Chen, J., Chen, Y., Li, B., Guo, L., Shi, Y., Yang, F., Yang, Q., Yang, L., Ding, C., & Shi, H. (2023). *How relationship-maintenance strategies influence athlete burnout: Mediating roles of coach-athlete relationship and basic psychological needs satisfaction*. Frontiers in Psychology, 13, Article 1104143. https://doi.org/10.3389/fpsyg.2022.1104143

Fletcher, D., & Wagstaff, C. R. D. (2009). Organizational psychology in elite sport: Its emergence, application and future. *Psychology of Sport and Exercise*, *10*, 427–434. https://doi.org/*10.10*16/j.psychsport.2009.03.009

 © 2026 ARD Asociación Española

Foulds, S. J., Hoffmann, S. M., Hinck, K., & Carson, F. (2019). *The coach-athlete relationship in strength and conditioning: High performance athletes' perceptions*. Sports, 7(12), Article 244. https://doi.org/10.3390/sports7120244

George, D., & Mallery, P. (2003). *SPSS for Windows step by step: A simple guide and reference (4th ed.)*. Allyn & Bacon.

Graen, G. B., & Uhl-Bien, M. (1995). Relationship-based approach to leadership: Development of leader-member exchange (LMX) theory of leadership over 25 years. *The Leadership Quarterly*, 6, 219–247. https://doi.org/10.1016/1048-9843(95)90036-5

Gu, S., Peng, W., Du, F., Fang, X., Guan, Z., He, X., & Jiang, X. (2023). *Association between coach-athlete relationship and athlete engagement in Chinese team sports: The mediating effect of thriving*. PLoS ONE, 18(8), e0289979. https://doi.org/10.1371/journal.pone.0289979

Güner, O., & Işık, U. (2023). Sporda örgütsel vatandaşlık davranışı ölçeğinin Türk kültürüne uyarlanması: Geçerlik ve güvenirlik çalışması. *Sportive*, 6(2), 111–125. https://doi.org/10.53025/sportive.1349799

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. *European Business Review*, *31*, 2–24. https://doi.org/10.1108/EBR-11-2018-0203

Hair, J. F., Hult, G. T. M., Ringle, C. M., Sarstedt, M., Danks, N. P., & Ray, S. (2021). *Evaluation of reflective measurement models. In Partial least squares structural equation modeling (PLS-SEM) using R*. Springer. https://doi.org/10.1007/978-3-030-80519-7_4

Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling*, 6, 1–55. https://doi.org/10.1080/10705519909540118

Jabeen, F., Farooq, Z. H., Al Nahyan, M. T., Stachowicz-Stanusch, A., & Tripathi, S. K. (*20*21). Athlete leadership and team performance: Moderating role of organizational citizenship behavior and mediating role of team cohesion and work passion. *Indian Journal of Economics and Business*, *20*(4), 189–214.

Jin, H., Kim, S., Love, A., & Jin, Y. (2022). *Effects of leadership style on coach-athlete relationship, athletes' motivations, and athlete satisfaction*. Frontiers in Psychology, 13, Article 1012953. https://doi.org/10.3389/fpsyg.2022.1012953

Jowett, S. (2007). Interdependence analysis and the 3+1Cs in the coach-athlete relationship. In S. Jowett & D. Lavallee (Eds.), *Social psychology in sport* (pp. 15–27). Human Kinetics. https://doi.org/10.5040/9781492595878.ch-002

Kelecek, S., Kara, F. M., Kazak Çetinkalp, Z., & Aşçı, H. (2016). Sporcu tükenmişliği ölçeğinin Türkçe uyarlaması. *Hacettepe Journal of Sport Sciences*, *27*(4), 149–161. https://doi.org/10.17644/sbd.311371

Kim, S., Liu, J., Love, A., & Park, S. (2022). Organizational citizenship behaviour in sport: Scale development and validation. *International Journal of Sports Science & Coaching*, *17*(5), 1018–1032. https://doi.org/10.1177/17479541211054246

Leduc, J. G., Boucher, F., Marques, D. L., & Brunelle, E. (2024). *Basic psychological need satisfaction of collegiate athletes: The unique and interactive effects of team identification and LMX quality*. Frontiers in Sports and Active Living, 6, Article 1342995. https://doi.org/10.3389/fspor.2024.1342995

Lee, S., Kwon, S., Jang, D., & Kwon, H. (2023). The effect of coach-athlete fit on the coach-athlete relationship in team sport: Role of trust in coach. *International Journal of Sports Science & Coaching*, *18*(4), 986–993. https://doi.org/10.1177/17479541231164771

Li, J., Chen, B., & Zhang, Y. (2021). *Adopting evaluative conditioning to improve coach-athlete relationships*. Frontiers in Psychology, 12, Article 751990. https://doi.org/10.3389/fpsyg.2021.751990

Li, Y., You, H., & Oh, S. (2024). *A study on the structural relationship between emotional labor, job burnout, and turnover intention among office workers in Korea: The moderated mediating effect of leader-member exchange*. BMC Psychology, 12, Article 54. https://doi.org/10.1186/s40359-024-01545-8

Love, A., & Kim, S. (2019). Organizational citizenship behaviours in sport: A perspective from athletes. *Journal of Sport Management*, *33*(1), 25–36. https://doi.org/10.1123/jsm.2018-0036

Nicholls, A. R., Madigan, D. J., & Earle, K. (2022). *Multi-wave analyses of coping, athlete burnout, and well-being among FA Premier League academy players*. Frontiers in Psychology, 13, Article 979486. https://doi.org/10.3389/fpsyg.2022.979486

Olsson, L. F., Madigan, D. J., Hill, A. P., & Grugan, M. C. (2022). *Do athlete and coach performance perfectionism predict athlete burnout? European Journal of Sport Science*, *22*(7), 1073–1084. https://doi.org/10.1080/17461391.2021.1916080

Podsakoff, P. M., MacKenzie, S. B., Paine, J. B., & Bachrach, D. G. (2000). Organizational citizenship behaviours: A critical review of the theoretical and empirical literature and suggestions for future research. *Journal of Management*, *26*(3), 513–563. https://doi.org/10.1177/014920630002600307

Raedeke, T. D., & Smith, A. L. (2001). Development and preliminary validation of an athlete burnout measure. *Journal of Sport & Exercise Psychology*, *23*, 281–306. https://doi.org/10.1123/jsep.23.4.281

Shang, Y., & Yang, S. Y. (2021). *The effect of social support on athlete burnout in weightlifters: The mediation effect of mental toughness and sports motivation*. Frontiers in Psychology, 12, Article 649677. https://doi.org/10.3389/fpsyg.2021.649677

Simons, E. E., & Bird, M. D. (2023). Coach-athlete relationship, social support, and sport-related psychological well-being in NCAA Division I student-athletes. *Journal for the Study of Sports and Athletes in Education*, *17*(3), 191–210. https://doi.org/10.1080/19357397.2022.2060703

Standage, M., & Ryan, R. M. (2020). *Self-determination theory in sport and exercise. In G*. Tenenbaum & R. C. Eklund (Eds.), Handbook of sport psychology (4th ed., pp. 37–56). Wiley. https://doi.org/10.1002/9781119568124.ch3

Stephen, S. A., Habeeb, C. M., & Arthur, C. A. (2022). *Congruence of efficacy beliefs on the coach-athlete relationship and athlete anxiety*. Psychology of Sport and Exercise, 58, Article 102062. https://doi.org/10.1016/j.psychsport.2021.102062

Stirling, A. E., & Kerr, G. A. (2009). Abused athletes' perceptions of the coach-athlete relationship. *Sport in Society*, *12*(2), 227–239. https://doi.org/10.1080/17430430802591019

Vapur, M., Yavuz, E., & Demirel, M. A. (2023). İşgörenlerde örgütsel vatandaşlık davranışı ile tükenmişlik ilişkisinde etkileşimci liderliğin aracı rolü. *Ucuncu Sektor Sosyal Ekonomi Dergisi*, *58*(1), 545–558. https://doi.org/10.15659/3.sektor-sosyal-ekonomi.23.03.1966

Wilczyńska, D., Qi, W., Jaenes, J. C., Alarcón, D., Arenilla, M. J., & Lipowski, M. (2022). *Burnout and mental interventions among youth athletes: A systematic review and meta-analysis*. International Journal of Environmental Research and Public Health, 19(17), Article 10662. https://doi.org/10.3390/ijerph191710662

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

ORIGINAL ARTICLE

Defensive behaviour against crosses in elite football: Spatial constraints, crossing characteristics, and tactical defensive adaptations (2022–2023)

Minas-Panagiotis Ispirlidis . *Department of Physical Education and Sport Science. Democritus University of Thrace. Komotini, Greece.*

Mert Isbilir. *Department of Physical Education and Sport Science. Democritus University of Thrace. Komotini, Greece.*

Theano Katsamperi. *Primary Education Directorate. Ministry of Education, Religious Affairs and Sports. Athens, Greece.*

Nikolaos E. Koundourakis. *Faculty of Sports Science and Physical Education. Metropolitan College, Campus Crete. Heraklion, Grecce.*
Department of Clinical Chemistry. School of Medicine. University of Crete. Heraklion, Greece.

Ioannis Ispirlidis. *Department of Physical Education and Sport Science. Democritus University of Thrace. Komotini, Greece.*

ABSTRACT

This study investigated the defensive behaviours adopted by the top five teams in the English, Spanish, and German leagues during the 2023–2024 season against crosses delivered into the penalty area. The analysis focused on three variables: (1) the crosser's dominant leg, (2) ball trajectory, and (3) defensive behaviour type. A total of 1,428 opposition crosses were examined using frequency and percentage analyses, while relationships between variables were assessed through Crosstabs and the chi-square (χ^2) test. The findings revealed that the crosser's leg significantly influenced defensive outcomes within the 11–5.5 m delivery zone ($p < .05$). Defensive failure rates were substantially higher for opposite-foot crosses (31.3%) than for same-side-foot crosses (13.9%). Ball trajectory also demonstrated a significant effect on defensive success in the LS: 5.5–0 m zone ($p < .05$). High-curved crosses generated the highest defensive failure rate (19.7%), whereas penetrating or cut-back passes resulted in the lowest failure rate (3.8%). Although the defensive behaviour type did not produce a statistically significant overall effect, frequency analysis indicated that the "*Opposite Diagonal*" defensive approach yielded the lowest failure rate (6.8%) compared with "*Zone Defence*" (15.2%).

Keywords: performance analysis; ball trajectory; types of defence; crosses.

Cite this article as:
Ispirlidis, M-P., Isbilir, M., Katsamperi, T., Koundourakis, N. E., & Ispirlidis, I. (2026). Defensive behaviour against crosses in elite football: Spatial constraints, crossing characteristics, and tactical defensive adaptations (2022–2023). *Journal of Human Sport and Exercise, 21*(4), 1395-1409. https://doi.org/10.55860/9v533m72

Corresponding author. *Department of Physical Education and Sport Science. Democritus University of Thrace. Komotini, Greece.*
E-mail: menasispyrlides@gmail.com

Submitted for publication May 23, 2026.
Accepted for publication July 21, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/9v533m72

INTRODUCTION

In modern football, performance optimisation is a central objective for coaches and performance staff, requiring a systematic understanding of tactical, technical, physical, and psychological components of performance (Weineck, 1992; Dost et al., 2015; Owen, 2022). Within this context, match performance analysis has become an essential tool for evaluating team behaviour, identifying opponent tendencies, and informing training design and match preparation processes (Salvo et al., 2015).

Contemporary performance analysis increasingly focuses on the structural organisation of match phases, commonly conceptualised through the cycle of play: defensive organisation, offensive organisation, and transitional phases. Within this framework, game models reflect context-dependent tactical interpretations shaped by competitive constraints and coaching decisions (Bordonau et al., 2019). These micro-interactions can be better understood through a constraints-led and ecological dynamics perspective, where behaviour emerges from task and environmental constraints.

Among these micro-interactions, attacking actions into the penalty area—particularly crosses—represent decisive events in goal-scoring sequences. Empirical evidence consistently demonstrates the importance of crossing situations in goal creation across elite competitions. For instance, Breen et al. (2006) reported that a substantial proportion of goals are preceded by passing and crossing actions, with approximately 70% of goals in the 2006 FIFA World Cup involving such sequences. Similarly, Pulling et al. (2018) identified 1,332 open-play crosses during the 2014 FIFA World Cup, resulting in 42 goals (3.2% conversion rate), highlighting both the frequency and limited efficiency of these actions.

Further research has examined cross typologies and their effectiveness. Mitrotasios et al. (2022) found that in-swinging, out-swinging, and straight crosses differ in their contribution to goal-scoring opportunities during the 2018 FIFA World Cup. In addition, spatial distribution analyses indicate that most goals following crosses are scored within the central penalty area, particularly between the penalty spot and the goal area (Jacquet et al., 2002; Kyranoudis et al., 2024). These findings suggest that both delivery characteristics and spatial context are key determinants of attacking success.

From a defensive perspective, existing research has primarily focused on pressure applied to the crosser rather than defensive organisation inside the penalty area. For example, Pulling et al. (2018) reported that medium (48.0%) and high pressure (42.9%) were the most frequently applied defensive pressures during crossing situations, while low pressure occurred less frequently (9.1%). Although these findings highlight the importance of the initial defensive action, they provide limited insight into how defensive line behaviour within the penalty area influences outcome effectiveness.

Despite the growing body of literature on crossing and goal-scoring dynamics, a notable gap remains in understanding collective defensive organisation inside the penalty area during crossing situations at the elite competitive level. Specifically, the interaction between cross characteristics, spatial delivery zones, and defensive structural responses remains underexplored as a coupled dynamic system in elite football.

Therefore, the aim of this study was to examine how spatial constraints, crossing characteristics, and defensive organisational structures interact to shape defensive effectiveness against crosses in elite football. The study specifically investigates how these interacting constraints influence defensive outcomes in relation to:

- Crosser foot dominance,

 © 2026 ARD Asociación Española

- Ball trajectory type,
- Defensive organisational structure inside the penalty area.

By integrating these variables, the study seeks to provide a more mechanistic understanding of defensive success against crosses in elite football.

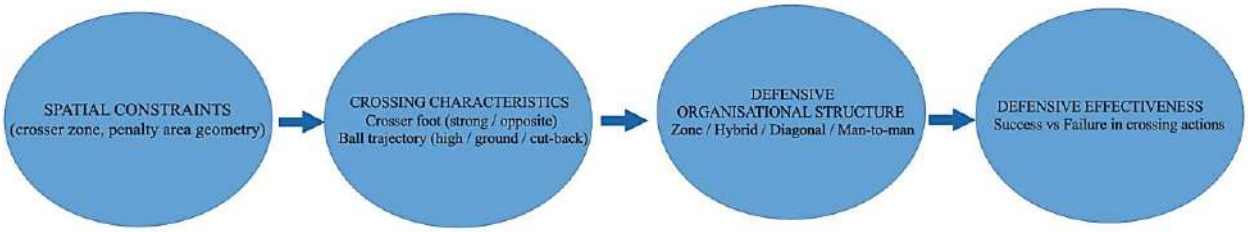


Figure 1. Conceptual framework of the study.

MATERIAL AND METHODS

Research sample

The sample consisted of the top five teams from the 2022/2023 season in three of Europe's elite leagues:

- Premier League: Manchester City, Arsenal FC, Manchester United, Newcastle United, Liverpool FC.
- La Liga: FC Barcelona, Real Madrid, Atletico de Madrid, Real Sociedad, Villarreal CF.
- Bundesliga: FC Bayern Munich, Borussia Dortmund, RB Leipzig, FC Union Berlin, SC Freiburg.

These teams were selected based on their status as the highest-performing clubs within their respective national leagues. Their consistent competitive success ensured a high standard of both attacking and defensive actions, with an expectation of advanced tactical organization, particularly in defensive phases.

The study employed a cross-sectional observational design and analysed 60 matches, comprising 1,428 defensive sequences, to assess the tactical behaviour of the defensive line during crosses into the penalty area. A defensive sequence was defined as the phase of play following loss of possession and lasting until possession was regained, the ball exited the penalty area, or play was interrupted.

Inclusion and exclusion criteria

Sequences were selected according to specific inclusion criteria:

- They occurred during full-time or extra-time periods of play.
- Only open-play defensive sequences were considered.
- Sequences were analysed using video recordings to ensure precise and reliable identification of all variables under examination.

Exclusion criteria included:

- Defensive actions resulting from set-piece situations or any subsequent developments.
- Sequences following penalty kicks, including actions after goalkeeper saves from penalties.
- Any defensive sequences that resulted in goal-scoring opportunities which were later deemed irregular according to the Laws of the Game (e.g., offsides or fouls).

This methodological approach ensured that the analysis was focused exclusively on defensive actions occurring during open play. By doing so, the study aimed to provide an accurate and objective measure of the tactical defensive effectiveness demonstrated by elite teams competing at the highest level of professional football.

Procedures

Data collection was conducted using the Wyscout® platform (Genoa, Italy) by selecting video footage that recorded all offensive actions performed by the teams under consideration during standard match conditions. All events were coded using predefined operational criteria, with each defensive sequence independently classified according to cross type, spatial zone, and defensive organisation at the moment of ball delivery. A filter was applied to focus exclusively on sequences involving opponent attacks from the flanks, followed by a detailed analysis of the defensive reactions exhibited by the teams in each instance. This analysis was carried out as many times as necessary, either at real-time speed or using the pause and frame-by-frame functions to ensure accuracy and clarity.

Definitions and tactical framework

The technical and tactical indicators recorded in this study were designed to evaluate the effectiveness of the defensive line's tactical behaviour in response to opponents' offensive actions. These indicators are defined as follows:

Leg of the crosser

- Side Leg: The ball was kicked with the leg on the same side as the ball's location (i.e., the player's strong-side foot), causing the ball to curve away from the goal.
- Opposite Leg: The ball was kicked with the opposite leg (the foot farthest from the ball's location), causing the ball to curve towards the goal.

Ball trajectory

- High curved cross: A cross delivered either at mid-height or high, with significant curve and power, into the opponent's penalty area (Bisanz & Gerisch, 2010, pp. 335-342).
- Ground crosses:
  - Penetrating ground cross: A fast, low cross typically executed with the strong-side foot from around or beyond the 16.5m mark. It follows a diagonal trajectory towards either the near post (first post) or the far post (second post) (Hamici et al., 2021; Marziali & Mora, 2011, p. 275).
  - Cut-back pass: A pass delivered by a player who reaches the end of the pitch and plays the ball back toward teammates positioned in the penalty area. This pass can be executed either along the ground or through the air (Hamici et al., 2021).

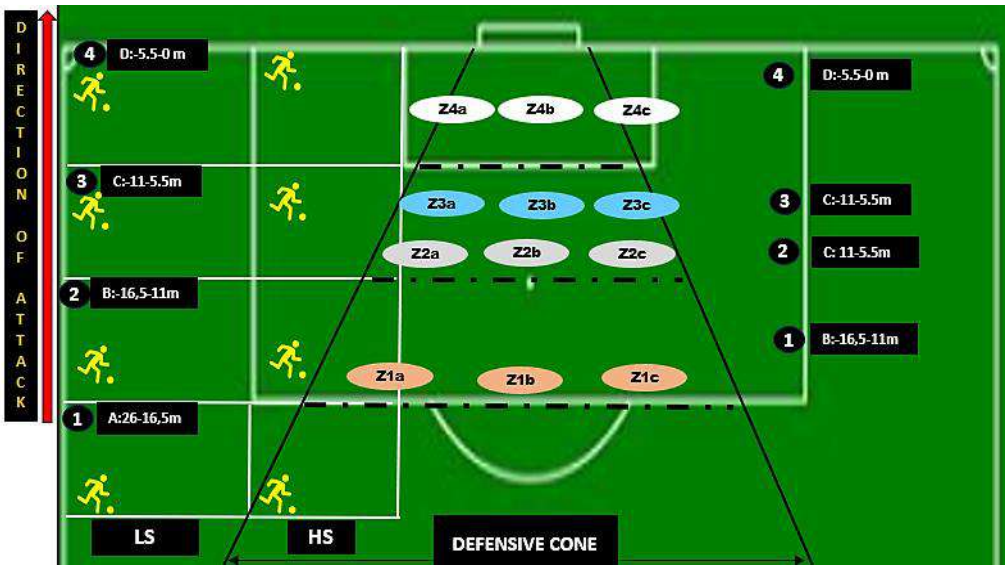
Type of defensive behaviour

The defensive line was analysed based on its formation and positioning when defending crosses inside the penalty area. The defensive structure typically consisted of three defenders (in a three-centre-back system) or four defenders (two centre backs and the far-side fullback). The near-side fullback either covered space or marked an opposing attacker positioned near the ball.

The defensive line adjusted its height and alignment depending on the ball's location and was organized within the defensive cone, adopting one of the following formations:

 © 2026 ARD Asociación Española

- Zone defence: The defenders are positioned in a flat line at varying depths from the goal line depending on the ball's location. Zones were classified as Z1a/b/c, Z2a/b/c, Z3a/b/c, and Z4a/b/c (see Figure 1) (Marziali & Mora, 2011, pp. 69-74; Longo & Aquino, 2012, pp. 148-149; Lucchessi, 2018, p. 115; Lucchessi, 2019, pp. 87-95).
- Zone with man-to-man defence: Initially arranged as in Zone Defence (see Figure 1), but defenders switch to marking attackers man-to-man as they enter their zone (Marziali & Mora, 2011, pp. 217-218, 225-226).
- Diagonal defence:
  - Normal diagonal: The first defender is positioned approximately in line with the near post (DZ1a, DZ2a, DZ3a) ; the second defender is diagonally placed relative to the first, functioning as a sweeper(DZ1b, DZ2b, DZ3b), while the third defender (usually the far-side defender) aligns with the second defender (DZ1c, DZ2c, DZ3c in Figure 2) (Longo & Aquino, 2012, p. 149).
  - Opposite diagonal: Defenders are positioned in a diagonal line opposite the direction of the incoming cross, typically when the cross originates from positions close to the goal line (DZ4a, DZ4b, DZ4c in Figure 2) (Marziali & Mora, 2011, pp. 75-76; Longo & Aquino, 2012, p. 150).
- Castle defence: A zone defence structure where the central defender positions closest to the goal (CAS1), while the other two defenders hold higher positions in front of him (CAS2, CAS3 (see Figure 2) (Longo & Aquino, 2012, p. 151).
- Mixed defence 1: The defender closest to the ball covers the space at the height of the near post, while the remaining defenders mark attackers man-to-man (Lucchessi, 2018, p. 114).
- Mixed defence 2: The first two defenders, in relation to the ball, cover the space in front of and behind the near post, while the other defenders engage in man-to-man marking (Lucchessi, 2018, p. 114).
- Man-to-Man defence: Each defender marks a specific opponent inside the penalty area within the defensive cone. When possible, defenders position themselves with their backs toward the goal and maintain physical contact with their assigned opponent (Marziali & Mora, 2011, p. 158).



Note. Explanation of Symbols: Ball in zone 1A., defence line in zone 1B (Z1a/b/c)., Ball in zone 2B, defence line in zone 2C (Z2a/b/c)., Ball in zone 3C, defence line in zone 3C (Z3a/b/c)., Ball in zone 4D, defence line in zone 4D (Z4a/b/c).

Figure 2. Zone of the crosser and defender in zone.

Note. Explanation of Symbols: Ball in zone 1A , defence line in zone 1B (DZ1a/b/c)., Ball in zone 2, defence line in zone 2C (DZ2a/b/c)., Ball in zone 3C, defence line in zone 3C(DZ3a/b/c)., Ball in zone 4D, defence line in zone 4D (DZ4a/b/c) or (CAS1/2/3).

Figure 3. Zone of the crosser and defenders in diagonal zone.

Reliability testing

Both intra-observer and inter-observer reliability were assessed using Cohen's kappa (κ) correlation coefficient. To evaluate intra-observer reliability, the primary observer analysed a sample of 150 randomly selected crosses on two separate occasions, with a one-week interval between observations. The calculated kappa values were greater than .80, indicating a strong level of agreement (McHugh, 2012).

For the inter-observer reliability assessment, a second independent football analyst examined the same sample of 150 crosses under similar conditions. The kappa values obtained were also greater than 0.80 across all performance indicators, demonstrating a strong level of agreement between observers (McHugh, 2012). The reliability results for each performance indicator are presented in Table 1.

Table 1. The Intra- and inter-rater reliability analysis (K) for crossing variables.

Variable	Intra-observer Kappa value	Inter-observer Kappa value
Zone of the Crosser and Leg of the crosser	1	1
Zone of the crosser and Ball trajectory	.95	.90
Zone of the crosser and type of the Defence Line	.84	.80

Data analysis

The statistical analysis of the data, which were recorded through digital video observation and coded using a computer, was performed using IBM SPSS Statistics version 29.0.0.0 (241). Descriptive statistics were applied, including frequency analysis (frequencies) and the calculation of percentage ratios. Additionally, Cross tabs and the non-parametric chi-square test (χ^2) were employed to examine the independence and possible relationships between the categorical variables.

Chi-square tests of independence were applied to examine associations between categorical variables ($p < .05$).

© 2026 ARD Asociación Española

RESULTS

Defence and leg of the crosser

In order to calculate the frequency and effectiveness of the defensive tactical behaviour during phases in which crosses were executed, a count was made of the total number of these phases in relation to the foot used by the crosser.

The analysis of the data revealed that the predominant type of cross execution was performed with the strong-side foot (Side Leg) across all zones of the crosser (Table 2).

Table 2. Percentages of crosses executed with the strong-side foot and opposite foot.

Zone of the crosser	Side leg	Opposite leg
LS: 26-16.5 m	67.5%	32.5%
LS: 16.5-11 m	76.6%	23.4%
LS: 11-5.5 m	86.7%	13.3%
LS: 5.5-0 m	93.6%	6.4%
HS: 26-16.5 m	64.3%	35.7%
HS: 16.5-11 m	75.7%	24.3%
HS: 11-5.5 m	72.7%	27.3%
HS: 5.5-0 m	91.5%	8.5%
All heights	79.1%	20.9%

Table 3. Defensive effectiveness in relation to the crosser's foot (side vs opposite foot).

Zone of the crosser	x^2, *p*	*p*-value
LS: 2616.5 m	$x^2(1) = 0.115$	.735
LS: 16.5-11 m	$x^2(1) = 0.039$	.843
LS: 11-5.5 m	$x^2(1) = 6.176$	.013*
LS: 5.5-0 m	$x^2(1) = 0.010$	.922
HS: 26-16.5 m	$x^2(1) = 1.800$	.189
HS: 16.5-11 m	$x^2(1) = 2.370$	.124
HS: 11-5.5 m	$x^2(1) = 0.204$	.651
HS: 5.5-0 m	$x^2(1) = 1.038$	.308

*Note. *p < .05.*

Table 4. Frequency percentages (%) of defensive success and failure in relation to the crosser's foot (side vs opposite leg).

Zone of the crosser	Side leg success	Side leg failure	Opposite leg success	Opposite leg failure
LS: 26-16.5 m	90.5%	9.5%	91.7%	8.3%
LS: 16.5-11 m	88.3%	11.7%	89.4%	10.6%
LS: 11-5.5 m	86.1%	13.9%	68.8%	31.3%
LS: 5.5-0 m	90%	10%	90.9%	9.1%
HS: 26-16.5 m	74.1%	25.9%	84.4%	15.6%
HS: 16.5-11 m	78.6%	21.4%	94.4%	5.6%
HS: 11-5.5 m	79.5%	20.5%	75.8%	24.2%
HS: 5.5-0 m	85.7%	14.3%	76.5%	23.5%

In order to determine the effectiveness of the defence across the different zones from which the cross was delivered, in relation to the foot used by the crosser, the non-parametric chi-square test (χ^2) was applied. The

results indicated a statistically significant difference ($p < .05$) in defensive effectiveness for the zone of the crosser LS: 11-5.5m (Table 3). The highest failure rates of the defence were observed when the cross was executed with the opposite foot, resulting in a 31.3% failure rate, compared to a 13.9% failure rate when the cross was executed with the strong-side foot (Table 4).

Overall, frequency analysis revealed higher defensive failure rates when the cross was executed with the side leg, with the exception of the zones LS: 11-5.5m, HS: 11-5.5m, and HS: 5.5-0m, where higher failure rates were observed when the cross was executed with the opposite leg (Table 4).

Defence and ball trajectory

In order to calculate the frequency and effectiveness of defensive tactical behaviour during phases in which crosses were delivered, a count was made of the total number of these phases in relation to the trajectory of the ball.

The analysis of the data revealed that the predominant ball trajectory was high curved across all zones of the crosser, except for the zones HS: 11-5.5m and HS: 5.5-0m, where the ground trajectory was the most frequently observed (Table 5).

Table 5. Percentages of ball trajectories from different crosser zones.

Zone of the crosser	Ground	Hight curved
LS: 26-16.5 m	25.8%	74.2%
LS: 16.5-11 m	42.5%	57.5%
LS: 11-5.5 m	46%	54%
LS: 5.5-0 m	40.6%	59.4%
HS: 26-16.5 m	14.4%	85.6%
HS: 16.5-11 m	43.1%	56.9%
HS: 11-5.5 m	65.9%	34.1%
HS: 5.5-0 m	66.2%	33.8%

Table 6. Defensive effectiveness in relation to the ball trajectory.

Zone of the crosser	x^2	*p*-value
LS: 26-16.5 m	$x^2(1) = 0.837$	.360
LS: 16.5-11 m	$x^2(1) = 1.593$	.207
LS: 11-5.5 m	$x^2(1) = 0.109$	.741
LS: 5.5-0 m	$x^2(1) = 6.769$	.009*
HS: 26-16.5 m	$x^2(1) = 0.416$	.519
HS: 16.5-11 m	$x^2(1) = 2.259$	.133
HS: 11-5.5 m	$x^2(1) = 2.368$	.124
HS; 5.5-0 m	$x^2(1) = 1.529$	.216

*Note. *p < .05.*

In order to determine the effectiveness of the defence across the different zones from which the cross was delivered, in relation to the trajectory of the ball, the non-parametric chi-square test (χ^2) was applied.

The results indicated a statistically significant difference for the LS: 5.5-0m zone (Table 6), where the defence was more effective against ground crosses, with a success rate of 96.2%, compared to a success rate of 80.3% against high curved crosses (Table 7).

 © 2026 ARD Asociación Española

In general, more defensive failures were recorded when the trajectory of the cross was high curved (except for the zone HS: 16.5-11m). On the other hand, fewer defensive failures were observed when the trajectory of the cross was ground (Table 7).

Table 7. Frequency percentages (%) of defensive success and failure in relation to ground and high curved crosses.

Zone of the crosser	Ground success defence	Ground failure defence	High curved success defence	High curved failure defence
LS: 26-16.5 m	92.9%	7.1%	89.1%	10.95%
LS: 16.5-11 m	90.1%	9.9%	83.35%	16.7%
LS: 11-5.5 m	82.5%	17.5%	80.7%	19.3%
LS: 5.5-0 m	96.2%	3.8%	80.3%	19.7%
HS: 26-16.5 m	81.3%	18.8%	73.7%	26.3%
HS: 16.5-11 m	71.4%	28.6%	85.5%	13.5%
HS: 11-5.5 m	76.7%	23.3%	61.3%	38.7%
HS: 5.5-0 m	83%	17%	74.5%	25.5%

Type of defence behaviour

In order to calculate the frequency and effectiveness of defensive tactical behaviour during phases in which crosses were delivered, a count was made of the total number of these phases in relation to the type of defence employed.

The analysis of the data revealed that the predominant defensive strategy was Zone Defence, except in the zones LS: 5.5-0m and HS: 5.5-0m, where Diagonal Defence was the most frequently used (Table 8).

Table 8. Percentages of defensive types used against crosses in the penalty area.

Zone of the crosser	Zone Defence (%)	Zone in man-to-man (%)	Diagonal Defence (%)	Castle Defence (%)	Mixed defence 1 (%)	Mixed defence 2 (%)	Man-to-man (%)	Else (%)
LS: 26-16.5 m	69.8	10.8	12.9		2.7			3.7
LS: 16.5-11 m	75.1	14.9	7		1.5			1.5
LS: 11-5.5 m	76.3	12.9	3.3		3.7			3.7
LS:5.5-0 m	27.5	12.6	52.7	3	1.2	1.2		1.8
HS: 26-16.5 m	59	11.5	26.2					3.3
HS: 16.5-11 m	56.2	19.2	24.7					
HS: 11-5.5 m	81.8	18.2						
HS: 5.5-0 m	27.9	13.7	49.2	2		1		6.1

In order to determine the effectiveness of the defence across the different zones from which the cross was delivered, in relation to the type of defence employed, the non-parametric chi-square test (χ^2) was applied.

The results indicated that there was no statistically significant difference in the effectiveness of the various types of defence at any cross delivery position (Table 9).

The frequency analysis of the different types of defence revealed generally higher success rates and lower failure rates when Zone Defence was employed.

An exception was noted in the zone HS: 5.5-0m, where Diagonal Defence demonstrated the highest success rates and the lowest failure rates (Table 10).

Table 9. Cross delivery zones and type of defence.

Zone of the crosser	x^2	*p*-value
LS: 26-16.5 m	$x^2(4) = 3.655$	.455
LS: 16.5-11 m	$x^2(4) = 5.515$	.238
LS: 11-5.5 m	$x^2(4) = 4.303$	.367
LS: 5.5-0 m	$x^2(6) = 7.953$	.242
HS: 26-16.5 m	$x^2(3) = 6.072$	.108
HS: 16.5-11 m	$x^2(2) = 0.647$	.724
HS: 11-5.5 m	$x^2(1) = 0.982$	.322
HS: 5.5-0 m	$x^2(5) = 9.726$	.083

*Note. *p < .05.*

Table 10. Frequency percentages (%) of defensive success and failure by type of defence.

Ball position	Zone Defence (%)		Zone in man-to-man (%)		Diagonal Defence (%)		Castle Defence (%)		Mixed defence 1 (%)		Mixed defence 2 (%)		man-to-man (%)		Else (%)	
	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F
LS: 26-16.5 m	91.3	8.7	84.4	15.6	89.5	10.5			100	0					100	0
LS: 16.5-11 m	87.4	12.6	93.3	6.7	100	0			66.7	33.3					66.7	33.3
LS: 11-5.5 m	84.8	15.2	74.2	25.8	87.5	12.5			100	0					77.8	22.2
LS: 5.5-0 m	84.8	15.2	95.2	4.8	93.2	6.8	80	20	50	50	100	0			100	0
HS: 26-16.5 m	70.8	29.2	100	0	81.3	18.8									75	25
HS: 16.5-11 m	85.4	14.6	78.6	21.4	77.8	22.2										
HS: 11-5.5 m	76.8	23.2	86.4	13.6												
HS: 5.5-0 m	85.5	14.5	85.2	14.8	87.6	12.4	100	0			50	50			58.3	41.7

Note. S = Success, F = Failure.

DISCUSSIONS

Defence and leg of the crosser

The frequency analysis revealed that, across all zones of the crosser, 79.1% of crosses were executed using the strong-side foot, while 20.9% were executed with the opposite foot. Notably, there was an increased frequency of crosses performed with the strong-side foot when the delivery took place close to the goal line, specifically in zones LS: 5.5-0m and HS: 5.5-0m, with percentages of 93.6% and 91.5%, respectively. This pattern may reflect increased spatial and temporal pressure near the goal line, which constrains decision-making options for attackers.

In their studies, Pulling et al. (2018) and Mitrotasios et al. (2022) classified types of crosses not by the foot used but according to the trajectory of the ball—specifically distinguishing between Out-swinging crosses (curving away from goal), In-swinging crosses (curving towards goal), and Straight crosses (with no curve). They reported similar frequencies of Out-swinging crosses (77.8%, 69.1%), In-swinging crosses (13.4%, 16.9%), and Straight crosses (8.9%, 14%) in their respective studies.

As Mitrotasios et al. (2022) pointed out, when a cross is performed with the strong-side foot, it usually follows an Out-swinging trajectory, curving away from the goalkeeper. Conversely, crosses executed with the opposite foot tend to have an In-swinging trajectory, converging towards the goalkeeper. Therefore, the findings of this study are largely consistent with those of previous research (see Table 2).

 © 2026 ARD Asociación Española

Moreover, Sainz de Baranda, López-Riquelme, and Ortega (2011), Casal et al. (2015), Pulling et al. (2018), and Mitrotasios et al. (2022) all highlighted that Out-swinging crosses performed with the strong-side foot generally result in fewer goalkeeper interventions compared to In-swinging crosses, increasing the success rate of goal-scoring opportunities and posing greater challenges to defensive lines. However, this was not fully confirmed by the current study.

In the present analysis, higher defensive failure rates were recorded in zones LS: 11-5.5m, HS: 11-5.5m, and HS: 5.5-0m when crosses were executed with the opposite foot (In-swinging), corroborating the findings of Carling et al. (2005), who concluded that corner kicks taken with the opposite foot to the side of the pitch lead to more goals (Table 4).

Additionally, statistically significant differences ($p < .05$) were found in the defensive effectiveness related to the crosser's foot in the LS: 11-5.5m zone (Table 3).

Defensive failure rates reached 31.3% when crosses were executed with the opposite foot, compared to 13.9% when crosses were performed with the strong-side foot.

In conclusion, crosses delivered with the opposite foot from the LS: 11-5.5m zone present significant challenges for the defence, particularly when the cross is aimed: Between the second central defender and the wide defender (defensive failure rate: 31.6%), In the space between the penalty area line and the penalty spot (defensive failure rate: 29.4%), And in the area between the penalty spot and the goal area (defensive failure rate: 22.4%), based on the findings of this study. These results underline the necessity of training the defensive line to handle such specific match situations effectively.

Defence and trajectory of the ball

The analysis of the percentages related to the trajectory of the ball showed that, in the zones of the crosser HS: 11-5.5m and HS: 5.5-0m, teams predominantly opted for ground crosses. In contrast, in all other zones, high curved crosses were the preferred choice (Table 5). However, it is noteworthy that in zones farther from the goal line—specifically LS: 26-16.5m and HS: 26-16.5m—the percentage of ground passes was unexpectedly low. This finding suggests that, despite the availability of space behind the defensive line, teams preferentially targeted aerial deliveries rather than low-penetrating passes from these zones.

It seems that, from these areas, teams preferred to deliver high curved crosses instead, aiming for the space between the penalty spot and the goal area, as well as behind the second central defender. These results indicate that crossing effectiveness is influenced by both spatial exploitation and delivery type.

Regarding the effectiveness of the defence based on the trajectory of the ball, a statistically significant difference was found only in the LS: 5.5-0m zone (Table 6). From this position, the defence recorded its highest failure rates when dealing with high curved crosses, with a failure rate of 19.7%, compared to just 3.8% failure against penetrating or cut-back passes (Table 7).

This finding highlights the importance of focusing on defensive training to improve the ability to handle such scenarios, especially when defending against high curved crosses delivered from close-range positions near the goal line.

Type of defence

According to the literature, the types of defensive tactical behaviour adopted by the defensive line were categorized as: Zone Defence, Zone Defence in Man-to-Man, Diagonal Defence, Man-to-Man Defence,

Castle Defence, and two variations of Mixed Defence (Ferrari, 2001; Marziali & Mora, 2011; Longo & Aquino, 2012; Lucchessi, 2018; Lucchessi, 2019). The data analysis revealed that, depending on the position of the ball, the defensive line adapted its formation. However, there was a clear tendency for certain elite-level teams to predominantly adopt Zone Defence in a majority of situations—ranging from 56.2% to 81.8%—when defending crosses from all delivery zones, with the exception of crosses delivered from zones LS: 5.5-0m and HS: 5.5-0m, where Diagonal Defence, and more specifically the Opposite Diagonal, was preferred in 49.2% to 52.7% of cases (Table 8).

With regard to the effectiveness of the defence in relation to the type of defensive formation, no statistically significant differences were found at any cross delivery zone (Table 9). However, frequency analysis indicated that Opposite Diagonal Defence, when used to defend crosses delivered from positions close to the goal line, recorded the lowest failure rates of the defensive line (6.8%) compared to Zone Defence, which showed a failure rate of 15.2% (Table 10). Other types of defence were not considered in this comparison due to their very low selection rates in these match situations.

CONCLUSIONS

Overall, defensive success against crosses is shaped by the interaction between spatial constraints, crossing characteristics, and defensive organisation, rather than by defensive structure alone. A total of 1,428 crosses were recorded and analysed. The main findings of the study are as follows:

1. Higher defensive failure rates were observed when crosses were executed with the side leg, except in zones LS: 11-5.5m, HS: 11-5.5m, and HS: 5.5-0m, where higher failure rates occurred when the cross was executed with the opposite leg.

The foot used to deliver the cross (strong-side or opposite foot) significantly influenced the effectiveness of the defence in the LS: 11-5.5m delivery zone. Defensive failure rates were 31.3% when the cross was delivered with the opposite foot, compared to 13.9% when the strong-side foot was used.

2. The predominant ball trajectory was high and curved across all crosser zones, except for HS: 11-5.5m and HS: 5.5-0m, where ground-level trajectories were most frequently observed.

The ball trajectory (ground or high curved) had a significant impact on defensive effectiveness in the LS: 5.5-0m delivery zone. From this position, defences recorded a higher failure rate when dealing with high curved crosses (19.7%) compared to ground cut-back passes (3.8%).

3. There was a clear tendency to predominantly adopt Zone Defence in most situations, except for crosses delivered from zones near the goal line, where the Opposite Diagonal was preferred.

The type of defensive behaviour did not show a statistically significant impact on defensive effectiveness. However, frequency analysis indicated that Opposite Diagonal Defence, when applied against crosses from positions close to the goal line, achieved the lowest failure rates (6.8%) compared to Zone Defence (15.2%). Other defensive types were excluded from this comparison due to their limited use in such situations.

Despite the methodological robustness and the large dataset analysed, several limitations should be acknowledged. First, the study adopts a univariate analytical approach using chi-square tests, which does not fully capture the potential interaction effects between spatial constraints, crossing characteristics, and

 © 2026 ARD Asociación Española

defensive organisational structures. Future research should employ multivariate statistical models (e.g., logistic regression or machine learning approaches) to better explain the combined influence of these interacting variables on defensive outcomes.

Limitations

Despite the methodological robustness and the large dataset analysed, several limitations should be acknowledged.

First, the study adopts a univariate analytical approach using chi-square tests, which does not fully capture the potential interaction effects between spatial constraints, crossing characteristics, and defensive organisational structures. Future research should employ multivariate statistical models (e.g., logistic regression or machine learning approaches) to better explain the combined influence of these interacting variables on defensive outcomes.

Second, contextual match-related variables such as scoreline status (winning, drawing, losing), opponent quality, match importance, and temporal phase of the game were not included in the analysis. These factors may significantly influence both defensive organisation and risk-taking behaviour, potentially affecting defensive effectiveness against crosses.

Third, the study focuses exclusively on elite teams from top European leagues (Premier League, La Liga, Bundesliga), which enhances internal validity but limits the generalisability of the findings to lower competitive levels or different tactical contexts.

Fourth, while inter- and intra-observer reliability were high ($\kappa > .80$), the observational nature of the study still carries inherent limitations related to subjective event coding, despite the use of clear operational definitions and repeated video analysis.

Finally, only open-play crossing situations were included, excluding set-piece contexts such as corners and free kicks, which represent a significant proportion of crossing-related defensive scenarios in elite football.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Minas-Panagiotis Ispirlidis, Mert Isbilir, Theano Katsamperi, Nikolaos E. Koundourakis, and Ioannis Ispirlidis. Methodology: Minas-Panagiotis Ispirlidis, Mert Isbilir, Theano Katsamperi, Nikolaos E. Koundourakis, and Ioannis Ispirlidis. Formal analysis: Minas-Panagiotis Ispirlidis and Mert Isbilir. Investigation: Minas-Panagiotis Ispirlidis. Data curation: Minas-Panagiotis Ispirlidis. Writing – original draft: Minas-Panagiotis Ispirlidis. Writing – review & editing: Minas-Panagiotis Ispirlidis, Mert Isbilir, Theano Katsamperi, Nikolaos E. Koundourakis, and Ioannis Ispirlidis. Supervision: Ioannis Ispirlidis, Mert Isbilir.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Armatas, V., & Mitrotasios, M. (2014). Analysis of goal-scoring patterns in the 2012 European Football Championship. *The Sport Journal, 1*, 1-11.

Bisanz, G., & Gerisch, G. (2010). Fußball: Kondition, Technik, Taktik & Coaching. Meyer & Meyer Verlag.

Breen, A., Iga, J., Ford, P. R., & Williams, A. M. (2006). World Cup 2006 - Germany: A quantitative analysis of goals scored. Insight - The F.A. *Coaches Association Journal, 6*, 45-53.

Carling, C., Williams, A. M., & Reilly, T. (2005). Handbook of Soccer Match Analysis: A Systematic Approach to Improving Performance. *Routledge*.

Casal, C. A., Maneiro, R., Ardá, T., Losada, J. L., & Rial, A. (2015). Analysis of corner kick success in elite football. International *Journal of Performance Analysis in Sport, 15*(2), 430-451. https://doi.org/10.1080/24748668.2015.11868805

Dost, H., te Poel, D., & Hyballa, P. (2015). Fußballfitness: Athletik-Training. Meyer & Meyer Verlag.

Efstratios, K., Papadimitriou, K., Kyranoudis, A., Giannakopoulos, A., & Konstantinidou, X. (2024). Final pass and its relationship with final actions to create goal-scoring opportunities at EURO 2020. *Journal of Human Sport and Exercise, 19*(2), 1-14. https://doi.org/10.55860/hf7g0141

Ferrari, F. (2001). Elementi di Tattica Calcistica (Vol. 1). *Editoriale Sport Italia*.

Hyballa, P., Dost, H., & te Poel, D. (2015). Soccer Fitness: Athletic Training for Football. *Meyer & Meyer Sport*.

Ispirlidis, M.- panagiotis, Ispirlidis, I., Pafis, G., Kyranoudis, A., & Isbilir, M. (2025). Defensive Actions in Crossing: Analysis of Top Spanish, English and German Elite Teams in 2022-2023 Season. *Pamukkale Journal of Sport Sciences, 16*(2), 449-467. https://doi.org/10.54141/psbd.1650552

Jacquet, A., Morlans, J. P., Blaquart, F., Domenech, R., Doyen, J., Dusseau, C., Mankowski, P., Martini, B., & Rabat, L. (2002). Analyses et Enseignements de la Coupe du Monde 2002. Direction Technique Nationale, *Fédération Française de Football*.

Kyranoudis, E., Papadimitriou, K., Kyranoudis, A., Giannakopoulos, A., & Konstantinidou, X. (2024). Final pass and its relationship with final action for the creation of goal-scoring opportunities at EURO 2020. *Journal of Human Sport and Exercise, 19*(2), 499-509. https://doi.org/10.55860/hf7g0141

Longo, E., & Aquino, M. (2012). Solidità Difensiva: Principi e Sviluppo della Fase Difensiva. *Allenatore.net SAS*.

Lucchesi, M. (2018). Organizzazione Liquida: Modelli Evolutivi di Gioco nel Calcio Moderno. *Allenatore.net SAS*.

Lucchesi, M. (2019). Allenare le Letture della Linea a Quattro. *Allenatore.net SAS*.

 © 2026 ARD Asociación Española

Mitrotasios, M., Kubayi, A., Armatas, V., & Larkin, P. (2022). Analysis of crossing opportunities at the 2018 FIFA World Cup. *Montenegrin Journal of Sports Science and Medicine, 11*(1), Ahead of Print. https://doi.org/10.26773/mjssm.220305

Pulling, C., Eldridge, D., Ringshall, E., & Robins, M. T. (2018). Analysis of crossing at the 2014 FIFA World Cup. *International Journal of Performance Analysis in Sport, 18*(4), 657-677. https://doi.org/10.1080/24748668.2018.1509255

Reilly, T. (Ed.). (2005). Handbook of Soccer Match Analysis. Routledge.

Sainz de Baranda, P., López-Riquelme, D., & Ortega, E. (2011). Offensive efficiency criteria for corner kicks in the 2006 World Cup: Application to training. *Revista Española de Educación Física y Deportes, 395*, 47-59. https://doi.org/10.55166/reefd.v0i395.212

Salvo, M. (2015). La Match Analysis nel Calcio: Metodologia, Strumenti e Applicazioni. Allenatore.net.

Weineck, J. (1992). Optimales Fußballtraining: Konditionstraining im Fußball (Teil 1). *Medizinische Verlagsgesellschaft mbH*.

Wright, C., Atkins, S., Jones, B., & Polman, R. (2011). Key performance factors related to goal creation in elite professional soccer. *International Journal of Performance Analysis in Sport, 11*(3), 438-449. https://doi.org/10.1080/24748668.2011.11868563

Yamada, H., & Hayashi, Y. (2015). Characteristics of goal-scoring crosses in international soccer tournaments. *Football Science, 12*, 24-32.

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Notational analysis of the Croatian first football league: Technical, tactical and performance indicators during the 2025/2026 season

Ahmet Naci Dilek. *Faculty of Sport Science. Bartın University. Türkiye.*
Adem Preljević. *Faculty of Sport and Physical Education. University of Novi Pazar. Serbia.*
Boriss Bazanov. *School of Natural Sciences and Health. Tallinn University. Estonia.*
Ivana Grle. *Department of Physical Medicine and Rehabilitation. University Clinical Hospital Mostar. Bosnia and Herzegovina.*
Maki Grle. *Department of Orthopaedics. University Clinical Hospital Mostar. Bosnia and Herzegovina.*
Ernest Šabić. *Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Naim Ćeleš. *Deparment of Physical Education and Sport. Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Nijaz Skender. *Deparment of Physical Education and Sport. Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Goran Sporiš ✉ **.** *Department of General and Applied Kinesiology. Faculty of Kinesiology. University of Zagreb. Croatia.*
Jerko Prlić. *Department of Orthopaedics. University Clinical Hospital Mostar. Bosnia and Herzegovina.*
Dejan Tiric. *Department of Obstetrics and Gynecology. University Clinical Hospital Mostar. Bosnia and Herzegovina.*
Bozenka Galic Tiric. *Chair of Occupational Medicine. Faculty of Medicine. University of Mostar. Bosnia and Herzegovina.*
Natalija Kurtović. *Deparment of Physical Education and Sport. Faculty of Pedagogy. University of Bihać. Bosnia and Herzegovina.*
Davorin Antonić. *Larus Sport d.o.o. Croatia.*
Dražen Čular. *Faculty of Kinesiology. University of Split. Croatia.*
Ivica Franjko. *Faculty of Kinesiology. Josip Juraj Srossmayer University in Osijek. Croatia.*
Ivan Duroci. *Faculty of Kinesiology. University of Zagreb. Croatia.*
Davor Ljesević. *Faculty of Kinesiology. University of Zagreb. Croatia.*
Hrvoje Ajman. *Faculty of Kinesiology. Josip Juraj Srossmayer University in Osijek. Croatia.*
Željko Širić. *Faculty of Kinesiology. Josip Juraj Srossmayer University in Osijek. Croatia.*
Fredi Fiorentini. *Faculty of Kinesiology. University of Split. Croatia.*
Zeljko Kovacevic. *Faculty of Health Sciences. University of Split. Croatia.*
Besnik Morina. *Faculty of Physical Education and Sport. University of Pristina "Hasan Pristina". Kosovo.*
Milan Milošević. *Ribnjak Polyclinic. Croatia.*
Veljko Vukicevic. *Faculty of Sport and Physical Education. University of Novi Sad. Serbia.*

ABSTRACT

The aim of this study was to analyse technical and tactical performance indicators in the Croatian First Football League (SuperSport HNL) during the 2025/2026 competitive season. Match analysis has become an essential tool in modern football, allowing coaches, analysts, and researchers to identify performance patterns associated with successful outcomes. This study evaluated offensive and defensive parameters, possession-based indicators, passing efficiency, shots on target, expected goals (xG), pressing intensity, and situational variables related to match outcome. Data were collected from official league statistics and video analysis platforms across all league matches during the observed season. Variables included total passes, successful passes, possession percentage, shots, shots on target, expected goals, duels won, high-intensity pressing actions, recoveries in the final third, and set-piece efficiency. Descriptive statistics and inferential analyses were applied to determine differences between winning, drawing, and losing teams. The results demonstrated that winning teams achieved significantly greater passing accuracy, higher xG values, more successful high pressing sequences, and increased efficiency in transition phases. Teams positioned in the upper part of the league table also showed greater tactical compactness and offensive organization compared to lower-ranked teams. Furthermore, home teams demonstrated statistically significant advantages in ball possession and attacking efficiency. The findings contribute to the growing body of literature regarding notational analysis in elite football and provide practical implications for coaches, analysts, and performance specialists working within Croatian and European football environments.

Keywords: performance analysis; football; notational analysis; Croatian football league; tactical analysis; match statistics; elite football.

Cite this article as:
Dilek, A. N., Preljević, A., Bazanov, B., Grle, I., Grle, M., Šabić, E., Ćeleš, N., Skender, N., Sporiš, G., Prlić, J., Tiric, D., Galić Tiric, B., Kurtović, N., Antonić, D., Čular, D., Franjko, I., Duroci, I., Ljesević, D., Ajman, H., Širić, Ž., Fiorentini, F., Kovacevic, Z., Morina, B., Milošević, M., & Vukicevic, V. (2026). Notational analysis of the Croatian first football league: Technical, tactical and performance indicators during the 2025/2026 season. *Journal of Human Sport and Exercise, 21*(4), 1410-1427. https://doi.org/10.55860/0p88sm64

✉ **Corresponding author.** *Department of General and Applied Kinesiology. Faculty of Kinesiology. University of Zagreb. Croatia.*
E-mail: goran.sporis@kif.unizg.hr

Submitted for publication May 25, 2026.
Accepted for publication July 21, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/0p88sm64

© 2026 ARD Asociación Española

INTRODUCTION

Modern football has evolved into a highly complex and analytically driven sport in which scientific performance evaluation plays a central role in competitive success. The rapid development of sports analytics, positional tracking systems, machine learning models, and tactical data platforms has fundamentally transformed how coaches, analysts, and researchers interpret football performance. In elite football environments, notational analysis has become one of the most important scientific methods for objectively quantifying technical, tactical, and situational aspects of match play (Almeida et al., 2024).

Notational analysis allows systematic observation, recording, and classification of match events in order to identify behavioural and tactical patterns associated with successful performance outcomes. Through modern analytical approaches, football performance can now be evaluated using advanced indicators such as expected goals (xG), expected assists (xA), pressing intensity, progressive passing, transition efficiency, possession sequences, spatial occupation, and defensive compactness (Castellano et al., 2024).

The scientific foundations of football performance analysis were established through early investigations focused on technical efficiency, passing sequences, and tactical organization in elite football (Hughes & Bartlett, 2002; Hughes & Franks, 2005). These pioneering studies demonstrated the importance of systematic observation in understanding successful football performance and represented the basis for modern notational analysis methodologies currently used in professional football environments.

Within Croatian sports science, significant contributions to football analysis and kinesiology research were provided by Goran Sporiš and collaborators. Early research conducted by Sporiš emphasized the importance of football match analysis in the planning and programming of physical preparation processes in elite football environments (Sporiš, 2003). Furthermore, Sporiš and colleagues investigated conditioning preparation, injury prevention, and applied kinesiology models relevant to football performance optimization (Mihačić et al., 2003; Sporiš & Tomić, 2004).

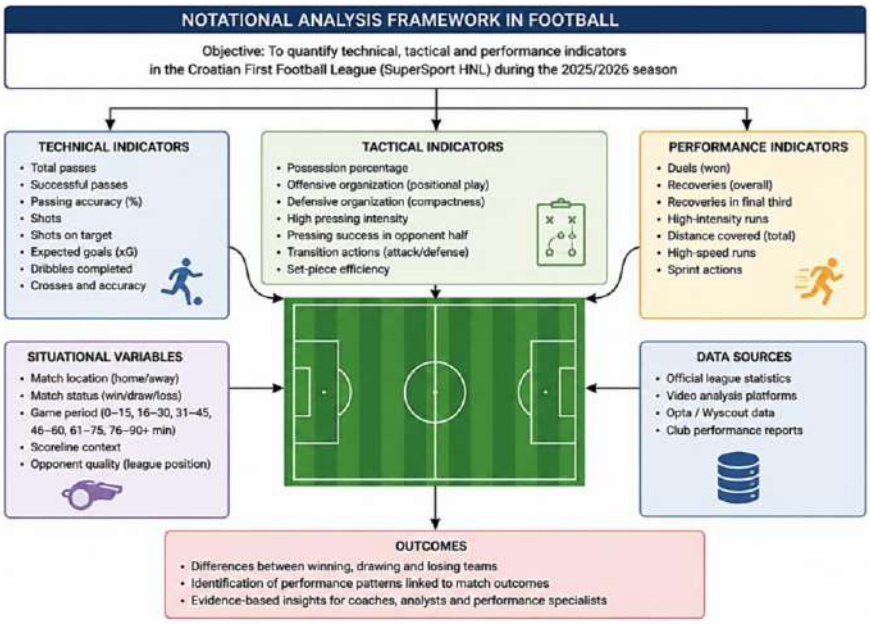


Figure 1. Framework of the notational analysis in the Croatian First Football League (SuperSport HNL) 2025/2026 season.

Recent scientific literature increasingly emphasizes the importance of probabilistic and contextual models in football analytics. Contemporary studies demonstrated that expected goals metrics possess significantly stronger predictive validity for match outcomes than traditional variables such as total shots or possession percentage alone (Liu et al., 2025). Furthermore, modern football analysis increasingly integrates tactical and positional data with physical performance indicators, enabling multidimensional interpretation of team behaviour during offensive and defensive phases of play (Fernandez-Navarro et al., 2024).

The tactical evolution of football during recent seasons has been strongly characterized by high-intensity pressing systems, compact defensive organization, vertical attacking transitions, and rapid ball recoveries in advanced field zones. Elite teams competing in UEFA competitions increasingly rely on coordinated pressing structures designed to disrupt opposition build-up phases and create transitional attacking opportunities (Bradley & Ade, 2024). Tactical analyses from recent European competitions further demonstrated that successful teams perform greater numbers of high-intensity defensive actions while simultaneously maintaining superior positional organization during possession phases (Clemente et al., 2025).

Another increasingly important area within football analytics involves possession-sequence analysis and transition efficiency. Recent investigations reported that successful teams demonstrate significantly greater efficiency during offensive transition phases and create higher-quality scoring opportunities through progressive passing and positional superiority (Sarmento et al., 2024). Similarly, studies focusing on elite football demonstrated that tactical efficiency in transition phases may represent one of the strongest determinants of successful match outcomes in contemporary football (Goes et al., 2025).

In addition to offensive tactical indicators, current literature highlights the growing importance of defensive compactness and coordinated pressing behaviour. Teams capable of reducing effective playing space and applying synchronized pressure on opponents demonstrate significantly greater defensive efficiency and lower expected goals conceded (Memmert & Rein, 2024). Moreover, recent studies suggest that modern football success is increasingly determined by collective tactical synchronization rather than isolated technical performance variables (Dellal et al., 2024).

The influence of contextual variables such as match location, opposition quality, scoreline, and competition phase has also become an important research focus in football performance analysis. Previous investigations demonstrated that home teams generally achieve greater offensive efficiency, possession dominance, and tactical initiative compared to away teams (Lago-Peñas et al., 2024). Furthermore, elite teams competing in domestic and European competitions frequently adapt tactical structures according to situational and contextual demands during matches.

Although extensive research has examined the English Premier League, UEFA Champions League, Bundesliga, La Liga, and Serie A, relatively few studies have focused on the Croatian First Football League (SuperSport HNL). Given the growing international visibility of Croatian football, including regular participation in UEFA competitions and the continued development of elite international players, comprehensive scientific analysis of its tactical and technical characteristics is increasingly needed.

The Croatian football environment represents an especially interesting research context due to its tactical diversity, developmental structures, and increasing tactical modernization influenced by contemporary European football trends. Despite these developments, scientific literature addressing notational analysis in SuperSport HNL remains scarce, particularly regarding modern analytical indicators such as expected goals, pressing efficiency, transition organization, and tactical compactness.

 © 2026 ARD Asociación Española

Therefore, the primary aim of this study was to conduct a comprehensive notational analysis of the Croatian First Football League during the 2025/2026 season and identify the key technical and tactical indicators associated with successful competitive performance. Additionally, the study aimed to examine the relationships between expected goals metrics, possession-based indicators, pressing structures, offensive transitions, and match outcomes in Croatian elite football.

Conceptual framework

Contextual variables (home advantage, match status, opposition quality) influence tactical organization (pressing, compactness, transitions), which affects offensive production quality (xG, shots, final-third entries) and ultimately match success.

This investigation represents one of the first comprehensive analytical mappings of Croatian elite football integrating sports analytics, machine learning, performance modelling, and applied artificial intelligence approaches.

This investigation additionally contributes to the emerging fields of sports analytics, data science, predictive modelling, machine learning, and applied artificial intelligence in sport.

To our knowledge, this study represents one of the first comprehensive analytical mappings of Croatian elite football integrating traditional performance indicators, expected goals metrics, tactical variables, contextual factors, and predictive modelling approaches.

METHODS

Study design

This study employed a retrospective observational research design based on systematic notational analysis of matches played during the 2025/2026 SuperSport HNL season. The investigation was conducted using quantitative performance analysis methods commonly applied in elite football research. Technical, tactical, and situational variables were collected and analysed to determine their relationship with successful competitive performance.

The study followed methodological principles previously applied in elite football analytics research involving performance indicators, expected goals models, tactical transitions, and contextual match variables (Castellano et al., 2024; Clemente et al., 2025).

Sample and match selection

The sample consisted of all official matches played during the 2025/2026 SuperSport HNL competitive season. A total of 180 matches involving all participating teams were included in the analysis.

Inclusion criteria:

- Official league matches only.
- Full match statistical availability.
- Availability of video recordings and event data.
- Matches completed without interruption.

Exclusion criteria:

- Abandoned matches.

- Matches with incomplete tracking data.
- Matches with corrupted event statistics.

The observational units included both team-level and match-level performance indicators.

Data sources and data collection

Match data were obtained from:

- Official SuperSport HNL statistical databases.
- Wyscout performance platform.
- Opta event data.
- Video recordings of all analysed matches.
- Tactical coding performed by licensed performance analysts.

All matches were independently coded by two experienced analysts trained in football notational analysis procedures. Inter-observer reliability was assessed using Cohen's Kappa coefficient.

The reliability analysis demonstrated excellent agreement:

- Technical variables: $\kappa = 0.91$.
- Tactical variables: $\kappa = 0.88$.
- Transition coding: $\kappa = 0.86$.
- Pressing sequences: $\kappa = 0.84$.

Values above $\kappa = 0.80$ were considered highly reliable according to contemporary sports performance analysis standards.

Variables

Technical variables

The following technical indicators were analysed:

- Total passes.
- Successful passes.
- Passing accuracy (%).
- Progressive passes.
- Crosses.
- Successful dribbles.
- Total shots.
- Shots on target.
- Goals scored.
- Expected goals (xG).
- Expected assists (xA).
- Set-piece efficiency.

Tactical variables

The following tactical indicators were observed:

- Ball possession (%).
- Possession sequences.

 © 2026 ARD Asociación Española

- Final-third entries.
- Counter-attacks.
- Offensive transitions.
- Defensive transitions.
- Pressing intensity.
- PPDA (Passes Allowed Per Defensive Action).
- High pressing recoveries.
- Defensive compactness.
- Width and depth occupation.
- Build-up organization.

Defensive variables

- Duels won.
- Interceptions.
- Tackles.
- Defensive recoveries.
- Clearances.
- Blocks.
- xG conceded.
- Pressing success rate.

Contextual variables

- Match location (home/away).
- Match outcome (win/draw/loss).
- Opposition ranking.
- Match status.
- Score differential.
- Competition phase.

Operational definitions

Expected goals (xG) represented the probability of a shot resulting in a goal based on shot location, shot angle, body part used, defensive pressure, and assist type.

Pressing intensity was measured using PPDA methodology, representing the number of opposition passes allowed before a defensive action occurred.

Offensive transition was operationally defined as a rapid attacking sequence initiated within eight seconds following ball recovery.

Defensive compactness referred to the average horizontal and vertical team dispersion during out-of-possession phases.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics 29.0 and R statistical software.

Descriptive statistics
Descriptive statistical parameters included:

- Arithmetic mean (M).
- Standard deviation (SD).
- Minimum values.
- Maximum values.
- Coefficient of variation (CV).
- 95% confidence intervals (CI).

Normality testing
The normality of data distribution was evaluated using:

- Shapiro–Wilk test.
- Kolmogorov–Smirnov test.
- Q-Q plots.
- Skewness and kurtosis coefficients.

Variables demonstrating non-normal distribution were transformed using logarithmic normalization procedures when necessary.

Inferential statistics
Independent samples t-tests were used to determine differences between:

- Winning vs. losing teams.
- Home vs. away teams.
- Top-ranked vs. bottom-ranked teams.

One-way ANOVA analyses with Bonferroni post hoc correction were applied to compare:

- Match outcomes.
- Tactical efficiency groups.
- Possession categories.

Repeated measures ANOVA was used to evaluate tactical changes across different match periods.

Effect size analysis
Effect sizes were calculated using:

- Cohen's d.
- Partial eta squared (η^2).
- Odds ratios (OR).

Effect sizes were interpreted according to established guidelines:

- Small effect: $d = 0.20$.
- Moderate effect: $d = 0.50$.
- Large effect: $d \geq 0.80$.

Correlation analysis
Pearson and Spearman correlation coefficients were used to evaluate relationships between:

- xG and match outcome.

 © 2026 ARD Asociación Española

- Possession and offensive efficiency.
- Pressing intensity and ball recoveries.
- Passing accuracy and league ranking.

Correlation strength interpretation:

- Weak: r < .30.
- Moderate: r = .30 – .49.
- Strong: r ≥ .50.

Regression models

Multiple linear regression analysis was conducted to identify predictors of:

- Match success.
- League ranking.
- Offensive efficiency.
- Defensive stability.

Logistic regression models were additionally constructed to estimate probabilities of match victory based on tactical and technical variables.

Multicollinearity diagnostics included (multicollinearity diagnostics revealed acceptable values for all predictors (VIF < 5), indicating no problematic multicollinearity):

- Variance Inflation Factor (VIF).
- Tolerance values.
- Durbin-Watson statistics.

Machine learning analysis

Machine learning workflow: models were trained using an 80:20 train-test split, validated using stratified five-fold cross-validation, and optimized using hyperparameter tuning procedures. Feature selection and out-of-sample validation were applied.

Advanced predictive analysis was conducted using:

- Random Forest models.
- Decision Tree analysis.
- Gradient Boosting models.

Predictive accuracy was evaluated through:

- ROC curves.
- Area Under the Curve (AUC).
- Precision-recall metrics.
- Cross-validation procedures.

Significance threshold

Statistical significance was established at: $p < .05$. Highly significant findings were reported at: $p < .01$ and $p < .001$.

Table 1. Multicollinearity diagnostics (Variance Inflation Factor, VIF) for predictor variables included in the regression models.

Variable	VIF
xG	2.11
Passing accuracy	1.89
PPDA	2.34
High pressing recoveries	1.97
Final-third entries	2.28

Ethical considerations

The study utilized publicly available match data and observational performance analysis without involving direct athlete intervention. Therefore, formal ethical approval was not required according to institutional guidelines for observational sports analytics research. All procedures were conducted in accordance with the ethical standards of sports science research and the Declaration of Helsinki.

RESULTS

Descriptive analysis of match performance indicators

A total of 180 matches from the 2025/2026 SuperSport HNL season were included finally. The dataset consisted of 360 team-match observations, representing both home and away team performances. Across all analysed matches, the average number of goals per match was 2.61 ± 1.34, while the mean expected goals value per team was 1.32 ± 0.64.

The average ball possession per team was 50.0 ± 8.7%, with substantial differences observed between higher-ranked and lower-ranked teams. Teams positioned in the upper part of the league table demonstrated greater possession control, higher passing accuracy, more final-third entries, and superior expected goals production compared with lower-ranked teams.

Winning teams achieved higher values in nearly all offensive and tactical indicators compared with drawing and losing teams. The largest differences were observed in expected goals, shots on target, final-third entries, progressive passes, and pressing recoveries.

Match outcome differences

When performance indicators were analysed according to match outcome, winning teams demonstrated significantly greater offensive efficiency compared with losing teams.

Winning teams recorded higher ball possession (57.8 ± 6.9%) than drawing teams (50.6 ± 7.4%) and losing teams (44.3 ± 7.1%). One-way ANOVA showed a statistically significant difference between groups, $F(2,357) = 28.41$, $p < .001$, $\eta^2 = 0.14$. Bonferroni post hoc analysis confirmed significant differences between winning and losing teams, as well as between winning and drawing teams.

Passing accuracy also differed significantly between match outcome groups. Winning teams achieved an average passing accuracy of 84.9 ± 4.1%, drawing teams 80.7 ± 4.8%, and losing teams 76.8 ± 5.2%. The difference was statistically significant, $F(2,357) = 31.76$, $p < .001$, $\eta^2 = 0.15$.

Expected goals represented one of the strongest differentiating variables. Winning teams produced significantly higher xG values (2.04 ± 0.58) compared with drawing teams (1.21 ± 0.43) and losing teams

 © 2026 ARD Asociación Española

(0.86 ± 0.37), F(2,357) = 46.92, $p < .001$, $\eta^2 = 0.21$. This indicates that successful teams were not only more frequent in shot production but also created higher-quality goal-scoring opportunities.

Offensive performance indicators

Winning teams produced an average of 15.4 ± 3.6 total shots per match, compared with 11.2 ± 3.1 among drawing teams and 8.7 ± 2.9 among losing teams. Shots on target followed a similar pattern, with winning teams recording 6.8 ± 1.9 shots on target, drawing teams 4.2 ± 1.5, and losing teams 2.9 ± 1.3.

Final-third entries were significantly higher among successful teams. Winning teams entered the final third 52.6 ± 9.8 times per match, while losing teams recorded 34.9 ± 8.2 final-third entries. Progressive passes were also more frequent among winning teams, suggesting superior vertical ball progression and more effective positional play.

Set-piece efficiency represented an additional important offensive indicator. Approximately 26.8% of all goals were scored following set-piece situations, including corners, indirect free kicks, direct free kicks, and second-ball situations after dead-ball phases. Top-ranked teams demonstrated greater set-piece conversion efficiency compared with lower-ranked teams.

Defensive and pressing indicators

Defensive performance indicators revealed that successful teams were more effective in regaining possession in advanced zones. Winning teams recorded significantly more high pressing recoveries (9.7 ± 2.8) than drawing teams (6.4 ± 2.2) and losing teams (4.8 ± 1.9), F(2,357) = 24.13, $p < .001$, $\eta^2 = 0.12$.

PPDA values were lower among successful teams, indicating higher pressing intensity. Winning teams demonstrated an average PPDA of 8.9 ± 2.1, compared with 11.7 ± 2.6 for drawing teams and 14.2 ± 3.1 for losing teams. Lower PPDA values were moderately associated with higher final-third recoveries and improved attacking transition efficiency.

Defensive compactness also differed between groups. Teams finishing in the top four league positions maintained lower average vertical and horizontal dispersion during defensive phases, suggesting more coordinated collective defensive behaviour. These teams also conceded lower xG values, indicating superior defensive structure and shot prevention.

Home and away performance

Home teams demonstrated a measurable performance advantage across several variables. Home teams won 52.2% of analysed matches, away teams won 28.9%, while 18.9% of matches ended in a draw.

Home teams recorded higher average possession (53.4 ± 7.8%) compared with away teams (46.6 ± 8.1%), t(358) = 6.42, $p < .001$. Home teams also produced more total shots, shots on target, and final-third entries.

Expected goals were higher for home teams (1.51 ± 0.61) compared with away teams (1.13 ± 0.54), t(358) = 5.87, $p < .001$. This finding indicates that home advantage was not only reflected in match outcome but also in chance quality and attacking production.

Correlation analysis

Correlation analysis revealed several meaningful relationships between tactical and technical indicators.

Expected goals showed the strongest association with match outcome, r = .61, $p < .001$. Shots on target were also strongly correlated with match success, r = .58, $p < .001$. Passing accuracy demonstrated a moderate-to-strong correlation with league ranking, r =0.52, $p < .001$.

High pressing recoveries were positively correlated with xG production, r = .47, $p < .001$, suggesting that successful pressing frequently created high-quality attacking opportunities. PPDA was negatively correlated with match success, r = -.49, $p < .001$, confirming that lower PPDA values were associated with better competitive outcomes.

Ball possession showed a moderate correlation with match success, r = .38, $p < .01$, indicating that possession alone was not sufficient to explain performance success unless combined with progression, chance creation, and pressing efficiency.

Regression analysis

Multiple linear regression analysis was conducted to identify predictors of match success. The final model explained 48.6% of variance in match success, $R^2 = .486$, adjusted $R^2 = .472$, $F(6,353) = 34.21$, $p < .001$.

The strongest predictors of match success were:

- Expected goals: $\beta = 0.42$, $p < .001$.
- Shots on target: $\beta = 0.31$, $p < .001$.
- High pressing recoveries: $\beta = 0.24$, $p = .004$.
- Passing accuracy: $\beta = 0.21$, $p = .009$.
- Final-third entries: $\beta = 0.19$, $p = .013$.

Ball possession was not a significant independent predictor when xG, pressing, and shot quality variables were included in the model, $\beta = 0.08$, $p = .117$. This suggests that the effectiveness of possession was more important than possession volume itself.

Logistic regression model

Binary logistic regression was used to estimate the probability of winning a match. The model correctly classified 76.4% of match outcomes.

The odds of winning increased significantly when a team achieved:

- xG above 1.75: OR = 3.84, 95% CI = 2.21–6.67, $p < .001$.
- At least 5 shots on target: OR = 3.12, 95% CI = 1.88–5.19, $p < .001$.
- More than 8 high pressing recoveries: OR = 2.46, 95% CI = 1.41–4.29, $p = .002$.
- Passing accuracy above 83%: OR = 2.18, 95% CI = 1.29–3.68, $p = .004$.

These findings suggest that match victory in the SuperSport HNL was most strongly associated with high-quality chance creation, offensive precision, pressing success, and technical consistency.

Machine learning prediction

Random Forest analysis was used to identify the most important performance variables for predicting match outcome. The model achieved an overall prediction accuracy of 79.1%, with an AUC value of 0.82. Although predictive performance was promising, external validation on independent datasets is recommended to minimize potential overfitting and improve model generalizability.

 © 2026 ARD Asociación Española

The most important predictors were:

- Expected goals.
- Shots on target.
- Final-third entries.
- High pressing recoveries.
- PPDA.
- Passing accuracy.
- Progressive passes.
- xG conceded.
- Set-piece efficiency.
- Ball possession.

The model confirmed that chance quality and pressing-related variables were more influential than simple possession measures.

Summary of key findings

The results demonstrated that successful teams in the Croatian First Football League were characterized by superior chance creation, higher expected goals values, greater passing accuracy, more effective pressing, and increased final-third presence.

The most important performance predictors were expected goals, shots on target, high pressing recoveries, and passing accuracy. Possession was relevant but not independently decisive unless accompanied by progressive passing and attacking efficiency.

Overall, the findings suggest that competitive success in the SuperSport HNL is increasingly determined by multidimensional tactical efficiency, including high-quality attacking production, coordinated pressing, defensive compactness, and effective transition play.

DISCUSSION

The primary aim of this study was to conduct a comprehensive notational analysis of the Croatian First Football League (SuperSport HNL) during the 2025/2026 season and identify the technical and tactical performance indicators most strongly associated with successful competitive outcomes. The findings demonstrated that successful teams consistently achieved superior values across multiple offensive, defensive, and tactical dimensions, particularly regarding expected goals production, passing efficiency, high pressing recoveries, and offensive transition organization.

Unlike several major European leagues characterized by prolonged possession phases, Croatian elite football appears to rely more strongly on:

- Vertical progression,
- Transition efficiency,
- Coordinated pressing,
- Tactical compactness,
- Rapid attacking organization.

One of the most important findings of the present investigation was the strong relationship between expected goals (xG) and match success. Teams generating higher xG values achieved significantly greater competitive success, indicating that the quality of scoring opportunities was substantially more important than the simple quantity of shots performed during matches. This finding strongly supports recent football analytics literature emphasizing the predictive superiority of xG-based models compared with traditional statistical indicators (Liu et al., 2025). Contemporary probabilistic models increasingly demonstrate that xG represents one of the most reliable indicators of attacking efficiency and long-term team performance stability in elite football competitions.

Furthermore, the present study demonstrated that shots on target and final-third entries were strongly associated with successful outcomes. Winning teams produced significantly greater offensive penetration and attacking continuity, indicating superior positional organization and more efficient progression through offensive phases of play. Similar findings were reported by Sarmento et al. (2024), who emphasized the importance of offensive transition quality and vertical progression in elite football environments. The results additionally support the observations of Castellano et al. (2024), who identified offensive territorial dominance and advanced field occupation as key characteristics of successful professional football teams.

Passing accuracy also emerged as a highly significant performance indicator. Teams achieving higher passing efficiency demonstrated greater tactical control, superior positional structure, and increased competitive stability throughout matches. These findings align with previous investigations conducted within elite European competitions, where successful teams consistently demonstrate superior technical precision and possession stability (Almeida et al., 2024). However, the present findings additionally suggest that possession effectiveness was more important than possession volume itself. Although winning teams generally demonstrated higher possession percentages, possession alone was not an independent predictor of success within regression models once xG, pressing intensity, and attacking efficiency variables were included.

This observation reflects the broader tactical evolution of contemporary football. Modern elite football increasingly prioritizes vertical progression, positional superiority, and transition effectiveness rather than passive possession accumulation. Similar tactical trends were described by Fernandez-Navarro et al. (2024), who reported that modern successful teams utilize possession primarily as a mechanism for spatial manipulation and progression rather than simple territorial control.

The present study also demonstrated that pressing-related variables represented some of the strongest determinants of successful match outcomes. Winning teams performed significantly more high pressing recoveries and maintained substantially lower PPDA values compared with unsuccessful teams. These findings indicate that aggressive pressing organization and coordinated defensive pressure played an essential role within contemporary Croatian elite football.

Recent football literature increasingly emphasizes the strategic importance of pressing systems in elite competitions (Clemente et al., 2025). Coordinated pressing structures enable teams to disrupt opposition build-up phases, reduce opponent progression time, and create advantageous offensive transitions immediately following ball recovery. The current findings support the conclusions of Bradley and Ade (2024), who demonstrated that elite football increasingly depends on high-intensity coordinated tactical behaviours during defensive and transition phases.

 © 2026 ARD Asociación Española

Additionally, the relationship observed between high pressing recoveries and expected goals production further highlights the growing integration between defensive organization and offensive efficiency in modern football. Teams capable of regaining possession in advanced zones generated significantly higher-quality scoring opportunities, suggesting that defensive pressing structures now directly contribute to attacking production rather than functioning solely as defensive mechanisms.

The findings regarding defensive compactness additionally support recent theoretical frameworks emphasizing collective tactical synchronization. Teams positioned in the upper part of the league table demonstrated significantly lower horizontal and vertical dispersion during defensive phases, indicating superior collective organization and spatial control. Similar observations were reported by Memmert and Rein (2024), who identified defensive compactness as one of the central determinants of shot prevention and defensive efficiency in elite football environments.

The concept of collective synchronization was further supported by the findings of Dellal et al. (2024), who argued that modern football success increasingly depends on coordinated collective tactical behaviours rather than isolated individual technical quality. The present results strongly support this perspective, as successful teams consistently demonstrated greater organizational coherence during offensive progression, defensive transitions, and pressing phases.

Another important finding involved the influence of home advantage. Home teams demonstrated significantly higher offensive production, greater xG values, and increased tactical initiative compared with away teams. These results align with extensive previous literature demonstrating the influence of contextual variables on football performance (Lago-Peñas et al., 2024). Home environments may provide psychological, motivational, environmental, and tactical advantages that facilitate greater attacking confidence and territorial dominance.

Contextual dynamics analysis suggests that home advantage interacts with tactical initiative, pressing intensity, and offensive production, highlighting the importance of situational tactical adaptation.

Within the context of Croatian football specifically, the findings suggest that tactical modernization within SuperSport HNL increasingly reflects broader European tactical trends. Croatian elite football appears progressively characterized by (compared with major European leagues, Croatian football appears to rely more heavily on vertical progression, transition efficiency, tactical compactness, and coordinated pressing structures):

- Organized pressing systems,
- Structured positional play,
- Vertical attacking transitions,
- Tactical compactness,
- Increased analytical optimization.

These developments may partially explain the growing international competitiveness of Croatian clubs and players within UEFA competitions and European football markets.

An especially important theoretical contribution of the present study relates to the integration of traditional notational analysis with modern performance analytics frameworks. Historically, football match analysis primarily focused on descriptive variables such as shots, possession, and passes (Hughes & Bartlett, 2002; Hughes & Franks, 2005). However, contemporary football increasingly requires multidimensional

interpretation integrating tactical, positional, probabilistic, and contextual indicators simultaneously. The present investigation contributes to this growing analytical paradigm by combining expected goals metrics, pressing variables, transition indicators, and contextual tactical behaviours within a unified performance model.

Within Croatian sports science, the present findings also extend the applied football research tradition established by Goran Sporiš and collaborators. Early investigations by Sporiš emphasized the importance of integrating match analysis with conditioning preparation and tactical planning processes in football environments (Sporiš, 2003). Furthermore, Sporiš and colleagues highlighted the necessity of applying scientific methodology to football performance optimization and injury prevention (Mihačić et al., 2003; Sporiš & Tomić, 2004). The current investigation expands these foundational approaches through the integration of contemporary analytical indicators such as xG, PPDA, pressing recoveries, and predictive statistical modelling.

The practical implications of the study are substantial for coaches, analysts, conditioning specialists, and football organizations operating within Croatian elite football. The findings suggest that training methodologies should increasingly emphasize:

- Coordinated pressing organization,
- Transition efficiency,
- Progressive passing structures,
- Attacking spatial occupation,
- Defensive compactness,
- High-quality chance creation.

Moreover, football clubs may benefit from integrating advanced analytical systems and performance modelling into tactical preparation, opposition scouting, recruitment strategies, and player development processes.

Several limitations should nevertheless be acknowledged. First, the study analysed only a single competitive season, limiting long-term trend interpretation. Second, although advanced event and tactical indicators were included, full spatiotemporal positional tracking data were not available for all matches. Third, physiological variables such as sprint load, acceleration profiles, and fatigue indicators were not incorporated into the current analytical framework.

Additional limitations include the absence of player-level analysis, positional tracking data, tactical network analysis, and tactical micro-structure evaluation.

Future investigations should therefore examine longitudinal tactical evolution across multiple seasons while integrating positional tracking systems, machine learning approaches, biomechanical variables, and contextual tactical models. Additionally, future studies should investigate individual player networks, tactical adaptability, and opponent-specific strategic behaviours within Croatian elite football environments.

Future studies should integrate tracking systems, player interaction networks, biomechanical variables, artificial intelligence models, and longitudinal multi-season analyses.

Overall, the present investigation contributes to the growing scientific literature regarding football notational analysis and represents one of the more comprehensive analytical examinations of the Croatian First Football

 © 2026 ARD Asociación Española

League currently available. The findings demonstrate that competitive success within SuperSport HNL is increasingly determined by multidimensional tactical efficiency involving offensive precision, coordinated pressing systems, transition effectiveness, and collective tactical synchronization.

The findings have broader global applicability and support the ongoing tactical evolution of elite football toward multidimensional performance optimization.

The findings of the present study extend beyond Croatian football and support broader tactical trends observed in elite football worldwide. The increasing importance of expected goals, coordinated pressing, and transition efficiency appears to represent a universal characteristic of contemporary football performance.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Boriss Bazanov, Ivica Franjko, Veljko Vukicevic. Methodology: Maki Grle, Goran Sporiš, Besnik Morina, Milna Milošević. Formal analysis: Davorin Antonić. Investigation: Ernest Šabić, Davor Lješević, Fredi Fiorentini, Zeljko Kovačević. Data curation: Naim Ćeleš, Davorin Antonić, Ivan Duroci, Hrvoje Ajman, Zeljko Širič. Writing – original draft: Ivana Grle, Goran Sporiš, Bozenka Galic Tiric. Writing – review & editing: Nijaz Skender, Jerko Prlić, Ahmet Naci Dilek, Adem Preljević. Supervision: Goran Sporiš, Dejan Tiric, Natalija Kurtović.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

Individuals who contributed to the research through support, acknowledgements, funding, and donations: Vjekoslav Radovčić, Željko Kovačević, Adnan Mustedanagić, Štefan Modrić, Ivan Stevura, Josip Lepeš, Igor Sabo, Ivan Đuroci, Miloš Maravić, Marko Žigman, Miloš Stojković, Željko Širić, Agim Hasani, Darko Dumančić, Stjepan Babić, Robert Citozi, Jakov Gogić, Veljko Vukičević, Marin Nikolić, Mario Anić Kremić, Krešimir Maronić, Tomislav Brlečić, Dino Kluk, Davor Lješević, Dominik Pick, Mladen Muškovac, Deni Hajdarović, Josip Zornjak, Štefan Modrić, Karlo Zornjak, Željko Ostrman, Baltazar Bogulin, Marijan Spehnjak, Baltazar Bogulin, Nijaz Skender, Perica Vidak, Marko Žigman, Krševan Santini, Željko Širić, Goran Špaleta, Darko Dumančić, Damir Benedeković, Robert Citozi, Dominik Mohorocić, Veljko Vukičević, Goran Vučković, Mario Anić Kremić, Nic Jamec, Tomislav Brlečić, Besim Morina, Davor Lješević, Bojan Šestan, Mladen Muškovac, Mladen Muškovac, Josip Zornjak, Hrvoje Ajman, Karlo Zornjak, Ivana Grle, Baltazar Bogulin, Maki Grle, Zoran Bogulin, Jerko Prlić, Perica Vidak, Dejan Tiric, Krševan Santini, Bozenka Galic Tiric, Goran Špaleta, Vedran Režić, Lazar Zaknić, Jose Antonio Perez Turpin, Damir Benedeković, Boriss Bazanov, Dominik Mohorocić, Davor Bučević, Bojan Šestan, Sandra Kerim, Jakov Gogić, Marko Čurković, Deni Hajdarović, Haris Čoćić, Marin Nikolić, Ivan Žižić, Hrvoje Ajman, Zlatko Triplat, Mate Vukoja, Robet Čović, Zvezdan Stefanović, Josip Zekić, Faisal Osama Mohamed Hasan Mohamed, Tomas Marczinka, Ahmed Kamal Ahmed Hasan Ali, Juraj Govorčin, Ivan Pavić, Vatroslav Horvat, Andrej Radić, Anto Aračić, Dino Bartoluci, Jasmin Ičanović, Milan Milošević, Vlatka Tomić, Dalija Kuvačić, Petra Špaleta, Vid Kučko, Miroslav Hrženjak, Goran Jelaska, Srđan Prodanović, Peruško Manuel, Šutić Danijel, Vlašić Jan, Petra Mandić, Damir Jurko, Ante Vukoja, Mauro Carvalho, Tomislav Lopac, Haris Alić, Ahmed Kamal, Marijan Jozić, Marko Erceg, Ahmet Naci Dilek, Gaetano Raiola, Deniss Dunik, Fjodor Dunik, Ilja Jazev, Mindaugas Balčiūnas, Arūnas

Emeljanovas, Brigita Miežiene, Balčiuniene Vaiva, Tolga Tek, Perez Aleixandre Pablo, Sport Sapiens OU, Milan Milošević, Andrej Radić, Poliklinika Ribnjak.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

ETHICAL APPROVAL

Ethical approval for this study was obtained within the framework of the Croatian Science Foundation project (IP-2020-02-3366), which was approved by the relevant Ethics Committee and conducted in accordance with the Croatian Science Foundation's Code of Ethics. The study was carried out in accordance with the ethical principles of the Declaration of Helsinki.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Almeida, C. H., Ferreira, A. P., & Volossovitch, A. (2024). Technical and tactical determinants of football performance in elite competitions. *International Journal of Performance Analysis in Sport, 24*(2), 115–129.

Bradley, P. S., & Ade, J. D. (2024). High-intensity tactical behaviour in elite football competitions. *Journal of Sports Sciences, 42*(4), 411–425.

Castellano, J., Alvarez-Pastor, D., & Bradley, P. S. (2024). Contextual variables and tactical performance in professional football. *International Journal of Sports Science & Coaching, 19*(1), 66–81.

Clemente, F. M., Sarmento, H., & Rabbani, A. (2025). Pressing structures and tactical efficiency in elite football. *Sports Medicine, 55*(1), 73–91.

Dellal, A., Lago-Peñas, C., & Rey, E. (2024). Collective tactical synchronization in professional football. *Biology of Sport, 41*(2), 215–228.

Fernandez-Navarro, J., Fradua, L., & Zubillaga, A. (2024). Positional data and tactical dynamics in elite football. *Frontiers in Sports and Active Living, 6*, 1–14.

Goes, F. R., Kempe, M., & Meerhoff, L. A. (2025). Transition efficiency and match success in elite football. *European Journal of Sport Science, 25*(3), 341–355.

Hughes, M. D., & Bartlett, R. M. (2002). The use of performance indicators in performance analysis. *Journal of Sports Sciences, 20*(10), 739–754. https://doi.org/10.1080/026404102320675602

Hughes, M., & Franks, I. M. (2005). Analysis of passing sequences, shots, and goals in soccer. *Journal of Sports Sciences, 23*(5), 509–514. https://doi.org/10.1080/02640410410001716779

Jovanović, M., Sporiš, G., Omrčen, D., & Fiorentini, F. (2011). Effects of speed, agility, quickness training method on power performance in elite soccer players. *Journal of Strength and Conditioning Research, 25*(5), 1285–1292. https://doi.org/10.1519/JSC.0b013e3181d67c65

 © 2026 ARD Asociación Española

Lago-Peñas, C., Gómez-Ruano, M., & Yang, G. (2024). Home advantage and contextual effects in elite football performance. *Journal of Human Kinetics, 91*, 55–69.

Liu, H., Gómez, M. A., & Gonçalves, B. (2025). Expected goals and predictive analytics in elite football. *PLOS ONE, 20*(1), Article e0312245.

Memmert, D., & Rein, R. (2024). Spatial control and defensive compactness in football. *Frontiers in Psychology, 15*, 1–13.

Mihačić, V., Sporiš, G., Jukić, I., Milanović, D., Ivanković, B., & Komes, Z. (2003). Strength and conditioning training in football [Unpublished manuscript].

Milanović, Z., Pantelić, S., Čović, N., Sporiš, G., & Krustrup, P. (2015). Is recreational soccer effective for improving physical fitness? A systematic review and meta-analysis. *Sports Medicine, 45*(9), 1339–1353. https://doi.org/10.1007/s40279-015-0361-4

Milanović, Z., Sporiš, G., Trajković, N., James, N., & Šamija, K. (2013). Effects of a 12-week SAQ training programme on agility with and without the ball among young soccer players. *Journal of Sports Science and Medicine, 12*(1), 97–103.

Sarmento, H., Clemente, F. M., & Afonso, J. (2024). Offensive transition patterns in elite football. International *Journal of Environmental Research and Public Health, 21*(4), 1882–1897.

Sporiš, G. (2003). The analysis of the football game in the function of planning and programming physical preparedness [Unpublished manuscript]. Faculty of Kinesiology, University of Zagreb.

Sporiš, G. (2026). Notational analysis in football: A review paper [Conference presentation]. HAIPER Conference, Split, Croatia.

Sporiš, G., & Tomić, V. (2004). Applying some of the content of kinesiology in the prevention of back muscle injury in football [Unpublished manuscript].

Sporiš, G., Čanaki, M., & Barišić, V. (2007). Morphological differences of elite Croatian female soccer players according to the team position. *Hrvatski Športskomedicinski Vjesnik, 22*(2), 91–96.

Sporiš, G., Jukić, I., Milanović, L., & Vučetić, V. (2010). Reliability and factorial validity of agility tests for soccer players. *Journal of Strength and Conditioning Research, 24*(3), 679–686. https://doi.org/10.1519/JSC.0b013e3181c4d324

Sporiš, G., Jukić, I., Ostojić, S. M., & Milanović, D. (2009). Fitness profiling in soccer: Physical and physiologic characteristics of elite players. *Journal of Strength and Conditioning Research, 23*(7), 1947–1953. https://doi.org/10.1519/JSC.0b013e3181b3e141

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Influence of age category and playing position on match physical demands in football players

Nicola Trotta . *Department of Neurosciences, Biomedicine and Movement Sciences. University of Verona. Verona, Italy.*
Department of Clinical and Experimental Medicine. University of Foggia. Foggia, Italy.
Luigi Armiento. *Department of Neurosciences, Biomedicine and Movement Sciences. University of Verona. Verona, Italy.*
Department of Clinical and Experimental Medicine. University of Foggia. Foggia, Italy.
Italo Sannicandro. *Department of Clinical and Experimental Medicine. University of Foggia. Foggia, Italy.*

ABSTRACT

This study aimed to compare the physical match demands between first-team and U19 players during the football season and to evaluate the differences across playing positions. A total of 41 matches and 395 individual player game observations (U19 = 188 and first-team = 207) were included in this study. The following playing positions were examined: Centre Backs (CB), Wide Midfielders (WM), Defensive Midfielders (DM), Attacking Midfielders (AM) and Forwards (FW). Total distance covered (TD), high-speed running distance (HSR), sprint running distance (SR), high metabolic load distance (HMLD), number of sprints (NS) and maximal sprinting speed (MSS) were measured using an 18.18 Hz global positioning system (GPEXE® SYSTEM, EXELIO srl, Udine, Italy). First-team players demonstrated greater physical match demands and higher exposure to high-intensity activities than U19 players, although no significant difference was observed for MSS. Regarding positional differences, WM, AM, and FW exhibited greater physical requirements, while CB and DM generally experienced lower locomotor and sprint-related demands during competitive matches. These findings may help practitioners facilitate the progression of young players into senior environments and optimize training prescriptions according to playing position.

Keywords: performance analysis; youth soccer; motor activity; global positioning system; team sport.

Cite this article as:
Trotta, N., Armiento, L., & Sannicandro, I. (2026). Influence of age category and playing position on match physical demands in football players. *Journal of Human Sport and Exercise, 21*(4), 1428-1442. https://doi.org/10.55860/hta61465

Corresponding author. *Department of Neurosciences, Biomedicine and Movement Sciences. University of Verona. Verona, Italy.*
E-mail: nicola.trotta@univr.it
Submitted for publication June 07, 2026.
Accepted for publication July 21, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/hta61465

© 2026 ARD Asociación Española

INTRODUCTION

Football is one of the most widely played sports in the world and requires players to possess well-developed aerobic and anaerobic capacities to cope with the substantial physical demands of competitive matches (Bangsbo et al., 2006; D'Elia et al., 2023). In recent years, the analysis of football performance models has gained considerable attention in the scientific literature following the development of advanced tracking technologies such as global positioning systems (GPS) (D'Isanto et al., 2019; Altavilla et al., 2017). These tools enable practitioners and sports scientists to quantify players' external load demands, design sport-specific training exercises that replicate the intensities required by the performance model (Dios-Álvarez et al., 2024), and support coaches in planning recovery strategies based on the load imposed during a game (Buckthorpe et al., 2019; Vanrenterghem et al., 2017). An earlier study has reported that professional football players cover approximately 10–13 km during competitive matches (Taylor et al., 2023), and the total distance covered has been associated with the aerobic component (Impellizzeri et al., 2006). However, this parameter may have some limitations, as it does not account for the different movement intensities of football players (Kavanagh et al., 2024). Currently, high-speed running (distance covered at speeds between 19.8 $km \cdot h^{-1}$ and 25.2 $km \cdot h^{-1}$) and sprinting (>25.2 $km \cdot h^{-1}$) are of huge importance in training load monitoring, as they may contribute to hamstring injury prevention and represent key physical characteristics required to compete in official matches (Gualtieri et al., 2023; Edouard et al., 2023). Based on these considerations, although the total distance covered showed only minor changes (3%) between the FIFA World Cup Russia 2018 and Qatar 2022, the high-speed running distance substantially increased by 16–19% (Bradley, 2024). Additionally, the high metabolic load distance has become increasingly integrated into external load analysis by sports scientists (Gaudino et al., 2014). As suggested by Osgnach et al. (2010), this parameter quantifies the energetic expenditure derived from football-specific actions and is significantly related to the aerobic component of football players (Manzi et al., 2022).

Professional football is a well-established organization that encompasses youth teams up to the first-team. This aspect is particularly relevant, as physical performance may vary significantly based on players' age (Palucci Vieira et al., 2019; Giardullo et al., 2026). Although a substantial body of literature has investigated external load in professional football, limited evidence is currently available regarding differences across age categories within Italian youth football (Izzo and Vardè, 2017). Indeed, the advanced technologies mentioned above entail substantial financial costs, which may constrain youth academies from assessing external load metrics (Reynolds et al., 2021). Moreover, the transition from academy to first-team represents a complex process in the development of elite youth players (Tomás et al., 2025). During this phase, players are required to adapt to the greater physical demands of senior professional football to successfully progress to the highest competitive level. Therefore, understanding the differences in match-running demands between U19 and first-team players may help practitioners better prepare academy players for this developmental transition.

Furthermore, as observed in a prior study involving an Italian professional football team, physical performance can be affected by playing position (Perrotta et al., 2025). Although this topic has been extensively investigated, inconsistent findings and a lack of consensus regarding positional classification persist (Sarmento et al., 2024). This may lead to misleading interpretations of the findings and limit the development of practical applications tailored to the specific demands of each playing position. Therefore, the aims of the present study were: i) to compare external load demands imposed during competitive matches between a professional first-team and U19, and ii) to investigate the differences in external load metrics according to playing position. We hypothesized that first-team players would demonstrate greater physical demands than U19. Furthermore, wide midfielders and attacking players are expected to exhibit superior high-intensity performance compared to players positioned in the central areas of the pitch.

MATERIAL AND METHODS

Participants

A total of 51 male football players from the same Italian club were included in this study. The sample consisted of first-team players (n = 23; age = 25.78 ± 0.87 years; height = 183.3 ± 2.9 cm; weight = 79.9 ± 3.23 kg) competing in the Italian third professional division and U19 players (n = 28; age = 17.32 ± 0.49 years; height = 175.32 ± 2.15cm; weight = 75.9 ± 1.87 kg) from the Primavera 2 championship during the 2024–2025 competitive season. The use of the same playing formation (1-3-5-2) in both squads improved the comparability between age categories and reduced the potential bias associated with positional match demands (Savoia et al., 2024). The following playing positions were examined: Centre Backs (CB), Wide Midfielders (WM), Defensive Midfielders (DM), Attacking Midfielders (AM) and Forwards (FW). The Ethics Committee of University of Foggia approved this study (approval number 0069/2024; date of approval: 06-09-2024). Informed consent to take part in this research was signed by the club. All procedures were conducted in accordance with the Declaration of Helsinki for human studies.

Measures

External load was collected using 18.18 Hz GPS units (GPEXE® SYSTEM, EXELIO srl, Udine, Italy) previously validated (Hoppe et al., 2018). All devices were activated 30-min before data collection to allow the acquisition of satellite signals and to synchronize the GPS clock with the satellite's atomic clock (Maddison and Ni Mhurchu, 2009). Total distance (TD), maximum sprinting speed (MSS), number of sprints (NS), high-speed running distance (HSR; 19.8 $km \cdot h^{-1}$ and 25.2 $km \cdot h^{-1}$), sprint running distance (SR; >25.2 $km \cdot h^{-1}$), and high metabolic load distance (HMLD), defined as the distance covered with a power consumption >20 $W \cdot kg^{-1}$, were analysed in the present study. To standardize the data according to effective match exposure and facilitate comparisons between players, distance-based variables ($m \cdot min^{-1}$) and sprint events ($n \cdot min^{-1}$) were expressed relative to the playing time.

Procedures

A total of 41 matches and 395 individual player game observations (U19 = 188 and first-team = 207) from an Italian club were included in the analysis. Table 1 presents the number of players according to their positional role in each age category. The inclusion criteria were as follows: i) absence of disease and musculoskeletal injuries among outfield players, as certified by the club's medical staff; and ii) players who completed at least 60 min of match play. In contrast, matches played under numerical inferiority following a red card were excluded, as this condition may have altered the physical demands of remaining players. Similarly, games involving playing formation modifications or positional changes imposed by the coach during the match were excluded, since players were required to perform different tactical roles.

Table 1. Number of players according to playing position in first-team and U19.

Category	Playing position				
	CB (n = 11)	WM (n = 15)	DM (n = 4)	AM (n = 8)	FW (n = 12)
First team	4	6	2	4	6
U19	7	9	2	4	6

Note. CB: centre backs; WM: wide midfielders; DM: defensive midfielders; AM: attacking midfielders; FW: forward.

Analysis

Mean ± standard deviation (SD) were reported for all external load metrics. The data were tested for normality using Q-Q plots and the Shapiro-Wilk test. Linearity and homoscedasticity were evaluated using scatterplots of independent versus dependent variables and residuals versus predicted values. Linear Mixed Models (LMM) was used to assess the differences in external load variables in relation to age category (first-team vs

 © 2026 ARD Asociación Española

U19 team; fixed effects), playing position (CB vs DM vs WM vs AM vs FW; fixed effects), and their interaction on physical performance. The players' identity was modelled as a random effect to account for repeated measurements. When there was a significant effect of playing position, marginal mean values (contrasts) were estimated using post-hoc Tukey corrections for multiple comparisons. The estimated marginal means, 95% CIs for positions (CB, WM, DM, AM, and FW), and contrasts analysis are reported in the Supplementary Materials. Effect sizes (ES) were calculated from the t and df of the contrast, as suggested by Beato et al. (2024), and interpreted using Cohen's d principle as follows: trivial = < 0.2, small = 0.2–0.6, moderate = 0.6–1.2, large = 1.2–2.0, and very large = >2.0 (Hopkins et al., 2009). The statistical analyses were carried out using JASP software (version 0.19.2, Amsterdam, The Netherlands), with a significance level of $p < .05$.

RESULTS

Table 2. External load metrics according to playing positions and age category.

Parameters	First-team	U19
Centre-backs		
TD (m·min⁻¹)	106.78 ± 5.49	97.03 ± 7.12
MSS (km·h⁻¹)	29.89 ± 1.84	29.14 ± 1.43
NS (n·min⁻¹)	0.06 ± 0.03	0.04 ± 0.03
HSR (m·min⁻¹)	4.53 ± 1.46	3.22 ± 1.13
SR (m·min⁻¹)	1.30 ± 0.71	0.81 ± 0.63
HMLD (m·min⁻¹)	15.09 ± 2.99	13.02 ± 3.47
Defensive midfielders		
TD (m·min⁻¹)	116.42 ± 5.03	107.70 ± 4.65
MSS (km·h⁻¹)	28.10 ± 1.84	28.28 ± 2.13
NS (n·min⁻¹)	0.03 ± 0.02	0.02 ± 0.01
HSR (m·min⁻¹)	5.02 ± 1.43	3.00 ± 1.27
SR (m·min⁻¹)	0.61 ± 0.40	0.40 ± 0.30
HMLD (m·min⁻¹)	18.85 ± 2.92	13.07 ± 3.71
Wide midfielders		
TD (m·min⁻¹)	114.22 ± 6.17	110.73 ± 8.89
MSS (km·h⁻¹)	30.26 ± 1.51	30.06 ± 1.46
NS (n·min⁻¹)	0.08 ± 0.04	0.09 ± 0.05
HSR (m·min⁻¹)	7.47 ± 1.31	6.55 ± 1.85
SR (m·min⁻¹)	1.86 ± 0.95	2.03 ± 1.17
HMLD (m·min⁻¹)	20.75 ± 3.13	17.78 ± 3.62
Attacking midfielders		
TD (m·min⁻¹)	120.65 ± 7.39	109.54 ± 10.75
MSS (km·h⁻¹)	29.99 ± 1.56	30.42 ± 1.67
NS (n·min⁻¹)	0.09 ± 0.03	0.06 ± 0.03
HSR (m·min⁻¹)	8.35 ± 1.83	5.20 ± 1.68
SR (m·min⁻¹)	2.03 ± 0.91	1.48 ± 0.72
HMLD (m·min⁻¹)	22.17 ± 4.04	16.69 ± 3.29
Forward		
TD (m·min⁻¹)	114.61 ± 6.46	105.56 ± 10.08
MSS (km·h⁻¹)	29.83 ± 1.69	29.09 ± 1.42
NS (n·min⁻¹)	0.07 ± 0.03	0.06 ± 0.03
HSR (m·min⁻¹)	6.50 ± 1.04	4.72 ± 1.59
SR (m·min⁻¹)	1.42 ± 0.86	1.21 ± 0.69
HMLD (m·min⁻¹)	19.35 ± 3.38	15.20 ± 3.63

Table 2 reports the mean ± SD of the examined external load variables collected during the official season.

Significant differences between the first-team and U19 were found for the following external variables: TD ($F = 16.864$, $p < .001$; ES = 1.37), NS ($F = 4.880$, $p = .034$; ES = 0.74), HSR ($F = 19.481$, $p < .001$; ES = 1.50), SR ($F = 4.988$, $p = .032$; ES = 0.73), and HMLD ($F = 23.389$, $p < .001$; ES = 1.48). Conversely, no significant age-related differences were observed for MSS ($F = 2.884$, $p = .098$; ES = 0.56). Significant differences between playing positions were reported for the following external load metrics: TD ($F = 8.682$, $p < .001$), MSS ($F = 4.263$, $p = .006$), NS ($F = 5.199$, $p = .002$), HSR ($F = 10.203$, $p < .001$), SR ($F = 4.802$, $p = .003$), and HMLD ($F = 8.835$, $p < .001$). The LMM analysis revealed no significant team x position interaction effects ($p > .05$) for all examined dependent variables.

The estimated marginal means, 95% CIs for playing positions (CB, WM, DM, AM, and FW), and contrasts analyses are provided in Supplementary materials (Appendix 1).

DISCUSSION

The present study aimed to compare physical match demands between first-team and U19 players, and to analyse position-related differences within an Italian football club. The main findings significantly revealed greater TD, NS, HSR, SR, and HMLD values in first-team players compared with the U19 group. In contrast, no significant differences were observed between the groups for MSS. Regarding playing position, WM, AM, and FW exhibited greater physical demands than players positioned in central roles. Overall, the results of the present study support our initial hypothesis.

The greater exposure to high-intensity activities observed in first-team players may be associated with their superior repeated sprint ability (RSA) performance compared to youth players (Kessouri et al., 2026). The RSA test reflects the capacity to perform multiple short-duration sprints interspersed with brief recovery periods and is considered a key physical quality during crucial phases of match play (Asimakidis et al., 2025). In support of this interpretation, Wong et al. (2012) reported that first-team players showed a lower percentage decrement than U19 players (1.75 ± 0.98% vs 2.51 ± 1.17%, respectively). Consequently, players experiencing lower fatigue during repeated sprint tasks may be better able to sustain high-intensity efforts and maintain greater locomotor outputs throughout competitive matches. This advantage may also be related to the greater aerobic fitness typically observed in first-team players, which may improve recovery during repeated high-intensity efforts (Tomlin and Wenger, 2001). Consistent with this interpretation, first-team players have shown greater Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) performance than youth players (Mujika et al., 2009; Rodríguez-Fernández et al., 2018), a test strongly associated with repeated high-intensity match actions (Castagna et al., 2010; Aquino et al., 2018). Overall, these age-related differences provide further insight into the physical performance gap between academy and senior professional football. This information may contribute to a better understanding of the physical demands associated with the transition to first-team competition. Nonetheless, previous studies examining differences in external match load across age groups have yielded inconsistent results. More precisely, Vigh-Larsen et al. (2018) reported greater acceleration and deceleration values in U19 players compared with both U17 and first-team players, whereas comparable results were observed in high-intensity running and sprint distance. Likewise, Morgans et al. (2022) reported similar physical performance between U18 and senior players competing in the Scottish Championship. Additionally, Kessouri et al. (2026) reported comparable high-intensity metrics between senior and U20 teams, except for greater walking distance in senior professionals. Conversely, Reynolds et al. (2021) reported that first-team and U23 players demonstrated greater match demands than U18 in terms of sprint distance, high-intensity burst distance, and dynamic stress load. These heterogeneous findings

 © 2026 ARD Asociación Española

reported in the scientific literature may be attributed to differences in playing style, competitive standards, and cultural contexts across countries, which are known to influence locomotor demands in football (Morgans et al., 2022).

No statistically significant difference was identified for MSS across the various age categories. These findings suggest that U19 players may have already completed most of the physical adaptations associated with maximal sprint speed. To further reinforce this interpretation, Rey et al. (2023) reported similar results in the maximum running speed between Spanish professional players aged 18–20 and 20–25 years. However, this finding is not in line with those reported by Kessouri et al. (2026), who observed superior MSS values in first-team players compared with those in youth categories.

Playing position is widely recognized as one of the main factors influencing the physical demands of football matches (Perrotta et al., 2025; Sarmento et al., 2024). Notably, wide and offensive playing positions are generally associated with greater locomotor demands. These findings are consistent with the normative benchmarks proposed by Savoia et al. (2024), who reported greater high-intensity demands in wide and offensive positions than in central defenders within the 1-3-5-2 playing system.

Regarding TD, DM demonstrated the greatest locomotor demands and a large difference compared with CB, which exhibited the lowest values for this parameter among all playing positions. This may be explained by the tactical demands associated with the DM role, as players are required to cover multiple areas of the pitch to support build-up play and contribute to the defensive phase. In contrast, CB tended to adopt a more positional behaviour aimed at maintaining defensive compactness and facilitating ball possession. These findings are consistent with those of previous studies that reported lower physical requirements in CB and greater TD values in DM during competitive matches (Sarmento et al., 2024; Chaize et al., 2024).

The analysis of HSR reported that AM and WM significantly demonstrated higher demands than CB and DM. This may be associated with the tactical responsibilities performed in different areas of the pitch.

More specifically, during the offensive phase, these playing positions require players to perform high-speed actions to attack the opponent's penalty area, create numerical superiority, and generate goal-scoring opportunities. Conversely, during the defensive phase, they must track opponents' off-ball movements to regain possession and limit attacking opportunities.

Similar results have been reported previously, indicating greater high-intensity running demands in WM and AM (Beato et al., 2024; Sarmento et al., 2024), whereas CB were exposed to lower physical load requirements (Chaize et al., 2024).

Sprint-related activities and MSS are crucial physical qualities for both football performance and hamstring injury risk prevention (Gualtieri et al., 2023; Tedeschi et al., 2025).

Regarding MSS, DM exhibited significantly lower values than all other playing positions, with *moderate* differences compared with FW and a *large* ES relative to AM and WM. These findings align with previous evidence reporting higher maximal running speed in wide midfielders, full-backs, and forwards throughout an entire competitive season (Nakamura et al., 2025). A possible explanation for this finding may be that players positioned in central areas of the pitch have less available space to reach higher running speeds, whereas WM and offensive players are more frequently exposed to 1vs1 situations.

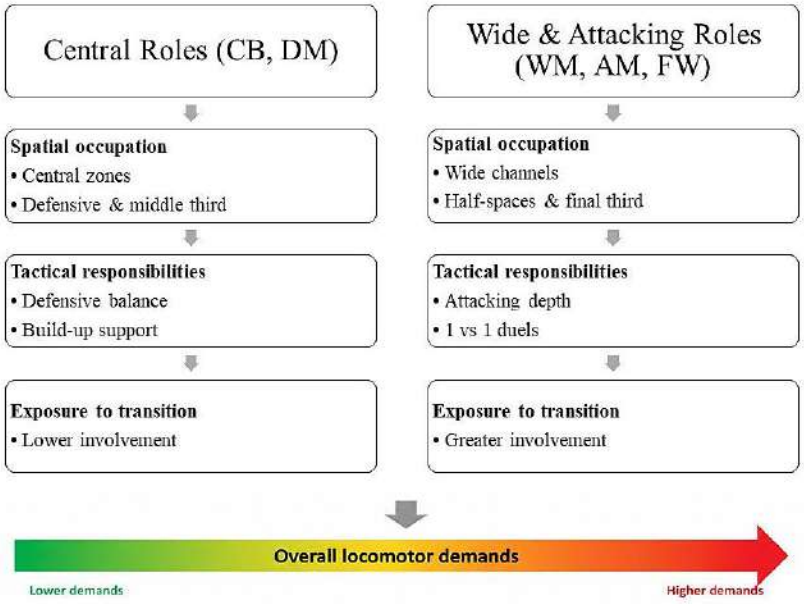
Similarly, WM demonstrated increased exposure to sprint demands, as highlighted by elevated NS and SR values, with *moderate* and *large* differences than CB and DM, respectively. Furthermore, AM and FW significantly displayed elevated values and *moderate* differences than DM.

One plausible rationale is that these positional roles are predominantly engaged in counterattacking situations, during which players attempt to attack space rapidly for generating goal-scoring opportunities.

Interestingly, the sprint distances covered by DM from first-team in the present study were substantially lower compared to those previously reported in players from the English Premier League and UEFA Champions League (Morgans et al., 2025). This comparison may help contextualize the gap in sprint-related performance between DM from the Italian third professional division and players competing at the international level.

The analysis of HMLD highlighted that AM, WM and FW were subjected to greater metabolic demands than CB. These findings are consistent with those reported for high-intensity parameters, indicating that greater exposure to high-intensity activities may have contributed to the increased HMLD demands observed in these playing positions. Consistent with our findings, Beato et al. (2024) reported similar HMLD values in AM and CB, whereas Chaize et al. (2024) found the highest HMLD values in CM and AM and the lowest in WM and CB. Interestingly, in the present study WM were among the playing positions exposed to substantial metabolic demands during competitive matches, partially contrasting with previous findings. This discrepancy may be explained by differences in the thresholds adopted for HMLD quantification and/or tactical characteristics associated with the playing formation, which was not explicitly reported in the previous investigation.

Overall, the positional differences observed in the present study may reflect the interaction between spatial occupation, tactical responsibilities, and transition involvement associated with each playing role. The conceptual framework provides a practical interpretation of how positional characteristics may contribute to the distinct locomotor demands observed during competitive match play (Figure 1).



Note: AM: attacking midfielders; CB: centre backs; DM: defensive midfielders; FW: forwards; WM: wide midfielders.

Figure 1. Conceptual framework of positional characteristics influencing locomotor demands in football.

 © 2026 ARD Asociación Española

Practical implications

The present findings have several practical implications for coaches and sports scientists involved in the development of academy players and their transition to senior professional football. The greater match-running demands observed in first-team players suggest that academy players may benefit from progressive training interventions designed to reproduce the neuromuscular and metabolic demands of senior professional match play. For example, large-sided games and running drills involving distances of 40-60 m could be useful in achieving these objectives. Additionally, practitioners should promote high volumes of football-specific practice throughout the developmental pathway, as this has been associated with a greater likelihood of successfully progressing from academy to senior professional football (Ford and Williams, 2012; Hendry and Hodges, 2018). However, physical preparation alone is unlikely to ensure a successful transition. Progression to senior professional football also requires well-developed tactical competencies, particularly positioning and decision-making, together with psychological attributes such as resilience, self-regulation, and intrinsic motivation (Tomás et al., 2025). Therefore, an integrated multidisciplinary approach combining physical, tactical, and psychological development may better support the progression of talented academy players toward first-team. Furthermore, the position-specific differences identified in the present study highlight the importance of implementing training and conditioning interventions that reflect the distinct locomotor demands of each playing position. For example, central players may benefit from greater exposure to small-sided games, complemented by aerobic conditioning, to better reflect the locomotor profile observed during competitive matches. Conversely, wide and attacking players may require a greater emphasis on transition-based games and speed-endurance maintenance training given the greater high-intensity demands identified in these positions.

Limitations

Despite the practical relevance of the present findings, several limitations should be acknowledged. First, given that this study included a single Italian football club, caution is required when generalizing the findings to other competitive contexts. Indeed, the observed physical demands may partly reflect the club's playing philosophy, coaching methodology, and competitive environment rather than universal developmental patterns. Therefore, future studies should include a greater number of professional clubs and elite academies to confirm these findings. Second, the sample of matches was not balanced in terms of home and away fixtures, and this contextual factor should be considered when analysing players' physical data. Moreover, other contextual match factors (e.g., opponent quality, match outcome, ball possession and playing style) were not included in the present analysis and may have contributed to the observed results in external load metrics. Future research should also examine the effects of age category and playing position using the worst-case scenario approach, which is increasingly adopted by sports scientists to quantify peak external load demands during match play (Mandorino and Lacome, 2024). Furthermore, a further step may involve the use of individualized speed thresholds, as suggested by Kavanagh et al. (2024), and internal load measures (e.g., heart rate responses). This may provide a more comprehensive understanding of the physical and physiological demands experienced by first-team and U19 players.

CONCLUSIONS

The present study aimed to compare external load demands between age categories (first-team vs U19) and examine positional differences in match physical performance. The main findings showed that U19 were subjected to lower physical requirements than first-team players, particularly in variables associated with high-speed and sprinting activities. Regarding positional differences, WM, AM, and FW demonstrated greater physical demands among all playing positions during competitive matches. In addition, CB generally exhibited lower external load demands, whereas DM demonstrated reduced sprint-related performance

compared with other playing positions. These findings may support sports scientists and coaches in the prescription of tailored interventions according to age groups and playing position in professional football players.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Nicola Trotta, Italo Sannicandro. Methodology: Nicola Trotta, Italo Sannicandro. Formal analysis: Nicola Trotta, Luigi Armiento. Investigation: Nicola Trotta, Luigi Armiento. Data curation: Nicola Trotta, Luigi Armiento. Writing – original draft: Nicola Trotta, Italo Sannicandro. Writing – review & editing: Nicola Trotta, Italo Sannicandro. Supervision: Italo Sannicandro.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Altavilla, G., Riela, L., Di Tore, A. P., & Raiola, G. (2017). The physical effort required from professional football players in different playing positions. *Journal of Physical Education and Sport*, 17(3), 2007-2012. https://doi.org/10.7752/jpes.2017.03200

Aquino, R., Palucci Vieira, L. H., De Paula Oliveira, L., Cruz Gonçalves, L. G., & Pereira Santiago, P. R. (2018). Relationship between field tests and match running performance in high-level young Brazilian soccer players. *The Journal of Sports Medicine and Physical Fitness*, *58*(3), 256-262. https://doi.org/10.23736/S0022-4707.17.06651-8

Asimakidis, N. D., Bishop, C., Beato, M., & Turner, A. N. (2025). Assessment of aerobic fitness and repeated sprint ability in elite male soccer: A systematic review of test protocols used in practice and research. *Sports Medicine*, *55*(5), 1233-1264. https://doi.org/10.1007/s40279-025-02188-4

 © 2026 ARD Asociación Española

Bangsbo, J., Mohr, M., & Krustrup, P. (2006). Physical and metabolic demands of training and match-play in the elite football player. *Journal of Sports Sciences*, *24*, 665-674. https://doi.org/10.1080/02640410500482529

Beato, M., Youngs, A., & Costin, A. J. (2024). The analysis of physical performance during official competitions in professional English football: Do positions, game locations, and results influence players' game demands? Journal of Strength and Conditioning Research, 38(5), e226-e234. https://doi.org/10.1519/JSC.0000000000004717

Bradley, P. S. (2024). Setting the benchmark part 2: Contextualising the physical demands of teams in the FIFA World Cup Qatar 2022. *Biology of Sport*, *41*(1), 271-278. https://doi.org/10.5114/biolsport.2024.131091

Buckthorpe, M., Wright, S., Bruce-Low, S., Nanni, G., Sturdy, T., Gross, A. S., Bowen, L., Styles, B., Della Villa, S., Davison, M., & Gimpel, M. (2019). Recommendations for hamstring injury prevention in elite football: Translating research into practice. *British Journal of Sports Medicine*, *53*(7), 449-456. https://doi.org/10.1136/bjsports-2018-099616

Castagna, C., Manzi, V., Impellizzeri, F., Weston, M., & Barbero Alvarez, J. C. (2010). Relationship between endurance field tests and match performance in young soccer players. *Journal of Strength and Conditioning Research*, *24*(12), 3227-3233. https://doi.org/10.1519/JSC.0b013e3181e72709

Chaize, C., Allen, M., & Beato, M. (2024). Physical performance is affected by players' position, game location, and substitutions during official competitions in professional Championship English football. *Journal of Strength and Conditioning Research*, *38*(12), e744-e753. https://doi.org/10.1519/JSC.0000000000004926

D'Elia, F., D'Isanto, T., Altavilla, G., Esposito, G., & Raiola, G. (2023). Does training with visual occlusion improve technical skills in Under-14 football players? *Acta Gymnica, 53*. https://doi.org/10.5507/ag.2023.004

D'Isanto, T., D'Elia, F., Raiola, G., & Altavilla, G. (2019). Assessment of sport performance: Theoretical aspects and practical indications. *Sport Mont*, *17*(1), 79-82. https://doi.org/10.26773/smj.190214

Dios-Álvarez, V. D., Castellano, J., Padrón-Cabo, A., & Rey, E. (2024). Do small-sided games prepare players for the worst-case scenarios of match play in elite young soccer players? Biology of Sport, 41(1), 95-106. https://doi.org/10.5114/biolsport.2024.127389

Edouard, P., Mendiguchia, J., Guex, K., Lahti, J., Prince, C., Samozino, P., & Morin, J. B. (2023). Sprinting: A key piece of the hamstring injury risk management puzzle. *British Journal of Sports Medicine*, *57*(1), 4-6. https://doi.org/10.1136/bjsports-2022-105532

Ford, P. R., & Williams, A. M. (2012). The developmental activities engaged in by elite youth soccer players who progressed to professional status compared to those who did not. *Psychology of Sport and Exercise*, *13*(3), 349-352. https://doi.org/10.1016/j.psychsport.2011.09.004

Gaudino, P., Alberti, G., & Iaia, F. M. (2014). Estimated metabolic and mechanical demands during different small-sided games in elite soccer players. *Human Movement Science*, *36*, 123-133. https://doi.org/10.1016/j.humov.2014.05.006

Giardullo, G., Taleb, M., Raiola, G., Ruggieri, R. A., Lascio, G. D., & Ceruso, R. (2026). Influence of age category and anthropometric characteristics on aerobic and explosive performance in youth soccer players. *Sci*, *8*(6), 139. https://doi.org/10.3390/sci8060139

Gualtieri, A., Rampinini, E., Dello Iacono, A., & Beato, M. (2023). High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. *Frontiers in Sports and Active Living*, *5*, 1116293. https://doi.org/10.3389/fspor.2023.1116293

Hendry, D. T., & Hodges, N. J. (2018). Early majority engagement pathway best defines transitions from youth to adult elite men's soccer in the UK: A three time-point retrospective and prospective study. *Psychology of Sport and Exercise*, *36*, 81-89. https://doi.org/10.1016/j.psychsport.2018.01.009

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3-12. https://doi.org/10.1249/MSS.0b013e31818cb278

Hoppe, M. W., Baumgart, C., Polglaze, T., & Freiwald, J. (2018). Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. *PLOS ONE*, *13*(2), e0192708. https://doi.org/10.1371/journal.pone.0192708

Impellizzeri, F., Marcora, S., Castagna, C., Reilly, T., Sassi, A., Iaia, F., & Rampinini, E. (2006). Physiological and performance effects of generic versus specific aerobic training in soccer players. *International Journal of Sports Medicine*, *27*(6), 483-492. https://doi.org/10.1055/s-2005-865839

Izzo, R., & Vardè, I. C. H. (2017). Differences by field positions between young and senior amateur soccer players using GPS technologies. *Ovidius University Annals: Series Physical Education and Sport/Science, Movement and Health*, 17, 344-352.

Kavanagh, R., Carling, C., Malone, S., Di Michele, R., Morgans, R., & Rhodes, D. (2024). Bridging the gap: Differences in training and match physical load in first-team and U23 players from the English Premier League. *International Journal of Sports Science & Coaching*, *19*(3), 1011-1018. https://doi.org/10.1177/17479541231186227

Kessouri, O., Grine, W., & Belfritas, Y. (2026). Match running performance in elite soccer: A comparison of team and individual performance across age categories. *The Journal of Sports Medicine and Physical Fitness*, *66*(1), 120-129. https://doi.org/10.23736/S0022-4707.25.17085-0

Maddison, R., & Ni Mhurchu, C. (2009). Global positioning system: A new opportunity in physical activity measurement. *International Journal of Behavioral Nutrition and Physical Activity*, *6*(1), 73. https://doi.org/10.1186/1479-5868-6-73

Mandorino, M., & Lacome, M. (2024). Defining worst-case-scenario thresholds in soccer: Intensity versus volume. *International Journal of Sports Physiology and Performance*, *19*(8), 836-840. https://doi.org/10.1123/ijspp.2024-0038

Manzi, V., Annino, G., Savoia, C., Caminiti, G., Padua, E., Masucci, M., D'Onofrio, R., & Iellamo, F. (2022). Relationship between aerobic fitness and metabolic power metrics in elite male soccer players. *Biology of Sport*, *39*(3), 599-606. https://doi.org/10.5114/biolsport.2022.106389

Morgans, R., Bezuglov, E., Orme, P., Burns, K., Rhodes, D., Babraj, J., Di Michele, R., & Oliveira, R. F. S. (2022). The physical demands of match-play in academy and senior soccer players from the Scottish Premiership. *Sports*, *10*(10), 150. https://doi.org/10.3390/sports10100150

Morgans, R., Di Michele, R., Ceylan, I. H., Ryan, B., Haslam, C., King, M., Zmijewski, P., & Oliveira, R. (2025). Physical match performance of elite soccer players from the English Championship League and the English Premier League: The effects of opponent ranking and positional differences. *Biology of Sport*, *42*(1), 29-38. https://doi.org/10.5114/biolsport.2025.139079

Mujika, I., Santisteban, J., Impellizzeri, F. M., & Castagna, C. (2009). Fitness determinants of success in men's and women's football. *Journal of Sports Sciences*, *27*(2), 107-114. https://doi.org/10.1080/02640410802428071

Nakamura, F. Y., Gómez-Diaz, A., Menezes, P., Marcelino, R., & Silva, H. (2025). Match peak speed of elite male soccer players across a full season: The influence of playing position, competition, match outcome, and match location. *Kinesiology*, *57*(1), 83-91. https://doi.org/10.26582/k.57.1.7

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & Di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: A new match analysis approach. *Medicine & Science in Sports & Exercise*, *42*(1), 170-178. https://doi.org/10.1249/MSS.0b013e3181ae5cfd

Palucci Vieira, L. H., Carling, C., Barbieri, F. A., Aquino, R., & Santiago, P. R. P. (2019). Match running performance in young soccer players: A systematic review. *Sports Medicine*, *49*(2), 289-318. https://doi.org/10.1007/s40279-018-01048-8

Perrotta, R., Ungureanu, A. N., Cherubini, D., Brustio, P. R., & Lupo, C. (2025). Technical, tactical, and time-motion match profiles of the forwards, midfielders, and defenders of a men's football Serie A team. *Sports*, *13*(2), 28. https://doi.org/10.3390/sports13020028

 © 2026 ARD Asociación Española

Rampinini, E., Impellizzeri, F. M., Castagna, C., Azzalin, A., Bravo, D. F., & Wisløff, U. (2008). Effect of match-related fatigue on short-passing ability in young soccer players. *Medicine & Science in Sports & Exercise*, *40*(5), 934-942. https://doi.org/10.1249/MSS.0b013e3181666eb8

Rey, E., Costa, P. B., Corredoira, F. J., & Sal de Rellán Guerra, A. (2023). Effects of age on physical match performance in professional soccer players. *Journal of Strength and Conditioning Research*, *37*(6), 1244-1249. https://doi.org/10.1519/JSC.0000000000003244

Reynolds, J., Connor, M., Jamil, M., & Beato, M. (2021). Quantifying and comparing the match demands of U18, U23, and first-team English professional soccer players. *Frontiers in Physiology*, *12*, 706451. https://doi.org/10.3389/fphys.2021.706451

Rodríguez-Fernández, A., Sánchez-Sánchez, J., Ramirez-Campillo, R., Rodríguez-Marroyo, J. A., Villa Vicente, J. G., & Nakamura, F. Y. (2018). Effects of short-term in-season break detraining on repeated-sprint ability and intermittent endurance according to initial performance of soccer player. *PLOS ONE*, *13*(8), e0201111. https://doi.org/10.1371/journal.pone.0201111

Sarmento, H., Martinho, D. V., Gouveia, É. R., Afonso, J., Chmura, P., Field, A., Savedra, N. O., Oliveira, R., Praça, G., Silva, R., Barrera-Díaz, J., & Clemente, F. M. (2024). The influence of playing position on physical, physiological, and technical demands in adult male soccer matches: A systematic scoping review with evidence gap map. *Sports Medicine*, *54*(11), 2841-2864. https://doi.org/10.1007/s40279-024-02088-z

Savoia, C., Laterza, F., Lucadamo, A., Manzi, V., Azzone, V., Pullinger, S. A., Beattie, C. E., Bertollo, M., & Pompa, D. (2024). The relationship between playing formations, team ranking, and physical performance in the Serie A soccer league. *Sports*, *12*(11), 286. https://doi.org/10.3390/sports12110286

Taylor, J. M., Madden, J. L., Hunter, F., Thorne, B. J., & McLaren, S. J. (2023). Mind the gap: A comparison of the weekly training loads of English Premier League academy soccer players in under-23, under-18, and under-16 age groups. *Journal of Science in Sport and Exercise*, *5*(1), 34-43. https://doi.org/10.1007/s42978-022-00162-4

Tedeschi, R., Giorgi, F., & Donati, D. (2025). Sprint training for hamstring injury prevention: A scoping review. *Applied Sciences*, *15*(16), 9003. https://doi.org/10.3390/app15169003

Tomás, J., Araújo, D., Martinho, D., Ribeiro, J., Sousa, H., Field, A., & Sarmento, H. (2025). Barriers and facilitators in the junior-to-senior transition in male football: A scoping review. *Sports*, *13*(12), 440. https://doi.org/10.3390/sports13120440

Tomlin, D. L., & Wenger, H. A. (2001). The relationship between aerobic fitness and recovery from high-intensity intermittent exercise. *Sports Medicine*, *31*(1), 1-11. https://doi.org/10.2165/00007256-200131010-00001

Vanrenterghem, J., Nedergaard, N. J., Robinson, M. A., & Drust, B. (2017). Training load monitoring in team sports: A novel framework separating physiological and biomechanical load-adaptation pathways. *Sports Medicine*, *47*, 2135-2142. https://doi.org/10.1007/s40279-017-0714-2

Vigh-Larsen, J. F., Dalgas, U., & Andersen, T. B. (2018). Position-specific acceleration and deceleration profiles in elite youth and senior soccer players. *Journal of Strength and Conditioning Research*, *32*(4), 1114-1122. https://doi.org/10.1519/JSC.0000000000001918

Wong, D. P., Chan, G. S., & Smith, A. W. (2012). Repeated-sprint and change-of-direction abilities in physically active individuals and soccer players: Training and testing implications. *Journal of Strength and Conditioning Research*, *26*(9), 2324-2330. https://doi.org/10.1519/JSC.0b013e31823daeab

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

APPENDIX 1. SUPPLEMENTARY MATERIALS

Table 3 (a-o). Estimated marginal means and contrasts analyses for external load variables according to playing position.

Table 3a. Estimated marginal means - total distance.

Row	Position	Estimate	SE	df	Lower (95% CI)	Upper (95% CI)
1	FW	111.722	1.756	44.868	108.186	115.258
2	DM	112.870	2.614	31.554	107.541	118.198
3	CB	102.851	1.550	45.700	99.730	105.973
4	AM	115.385	1.934	35.514	111.461	119.309
5	WM	112.159	1.659	56.427	108.837	115.481

Table 3b. Contrasts.

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-8.871	2.342	45.230	-3.787	.002
Contrast 2	-10.018	3.040	34.562	-3.296	.009
Contrast 3	-12.534	2.479	39.077	-5.056	<.001
Contrast 4	-10.067	2.117	76.343	-4.396	<.001

Note. † P-values are adjusted using Tukey adjustment; Contrast estimates were calculated using CB as the reference playing position.

Table 3c. Estimated marginal Means – Maximum sprinting speed.

Row	Position	Estimate	SE	df	Lower (95% CI)	Upper (95% CI)
1	FW	29.582	0.365	46.815	28.848	30.316
2	DM	27.759	0.528	30.064	26.681	28.838
3	CB	29.369	0.322	43.368	28.720	30.017
4	AM	30.117	0.394	34.532	29.315	30.918
5	WM	30.150	0.349	54.934	6.384	30.849

Table 3d. Contrasts.

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-1.823	0.642	34.388	-2.841	.030
Contrast 2	-1.609	0.618	33.017	-2.603	.054
Contrast 3	-2.357	0.659	31.564	-3.577	.005
Contrast 4	-2.390	0.633	35.566	-3.777	.002

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using DM as the reference playing position.

Table 3e. Estimated marginal Means – High-speed running distance.

Row	Position	Estimate	SE	df	Lower (95% CI)	Upper (95% CI)
1	FW	5.916	0.372	41.444	5.165	6.666
2	DM	4.377	0.563	30.689	3.228	5.525
3	CB	4.101	0.328	44.928	3.441	4.761
4	AM	6.340	0.414	34.204	5.499	7.181
5	WM	6.504	0.347	54.709	5.808	7.200

Table 3f. Contrasts (DM reference).

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-1.539	0.674	33.489	-2.282	.111
Contrast 2	0.276	0.651	33.608	0.424	.989
Contrast 3	-1.963	0.699	31.861	-2.810	.033
Contrast 4	-2.128	0.661	35.522	-3.217	.011

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using DM as the reference playing position.

 © 2026 ARD Asociación Española

Table 3g. Contrasts (CB reference).

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-1.815	0.495	42.918	-3.664	.003
Contrast 2	-0.276	0.651	33.608	-0.424	.989
Contrast 3	-2.239	0.528	37.856	-4.242	<.001
Contrast 4	-2.403	0.437	81.678	-5.501	<.001

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using CB as the reference playing position.

Table 3h. Estimated marginal Means – Sprint running distance.

Row	Position	Estimate	SE	df	Lower (95% CI)	Upper (95% CI)
1	FW	1.510	0.194	45.314	1.119	1.901
2	DM	0.431	0.293	33.405	-0.166	1.027
3	CB	1.142	0.171	48.545	0.797	1.486
4	AM	1.608	0.216	37.241	1.170	2.045
5	WM	1.751	0.182	59.039	1.388	2.115

Table 3i. Contrasts (DM reference).

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-1.079	0.352	36.513	-3.067	.016
Contrast 2	-0.711	0.340	36.542	-2.092	.163
Contrast 3	-1.177	0.364	34.686	-3.231	.011
Contrast 4	-1.321	0.345	38.640	-3.826	.002

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using DM as the reference playing position.

Table 3j. Contrasts (CB reference).

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-0.368	0.259	46.689	-1.423	.506
Contrast 2	0.711	0.340	36.542	2.092	.163
Contrast 3	-0.466	0.276	41.119	-1.692	.339
Contrast 4	-0.610	0.229	85.714	-2.658	.037

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using CB as the reference playing position.

Table 3k. Estimated marginal Means – Number of sprints.

Row	Position	Estimate	SE	df	Lower (95% CI)	Upper (95% CI)
1	FW	0.073	0.008	44.467	0.056	0.090
2	DM	0.024	0.012	30.749	-0.002	0.049
3	CB	0.056	0.007	44.520	0.041	0.071
4	AM	0.075	0.009	34.730	0.056	0.094
5	WM	0.083	0.008	55.266	0.067	0.099

Table 3l. Contrasts (DM reference).

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-0.050	0.015	34.305	-3.317	.009
Contrast 2	-0.033	0.014	33.699	-2.256	.117
Contrast 3	-0.051	0.015	32.082	-3.336	.009
Contrast 4	-0.060	0.015	35.946	-4.059	.001

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using DM as the reference playing position.

Table 3m. Contrasts (CB reference).

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-0.017	0.011	44.490	-1.528	.436
Contrast 2	0.033	0.014	33.699	2.256	.117
Contrast 3	-0.019	0.012	38.174	-1.604	.392
Contrast 4	-0.027	0.010	73.219	-2.677	.036

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using CB as the reference playing position.

Table 3n. Estimated marginal Means – High metabolic load distance.

Row	Position	Estimate	SE	df	Lower (95% CI)	Upper (95% CI)
1	FW	17.915	0.742	48.376	16.422	19.407
2	DM	16.666	1.126	34.204	14.377	18.954
3	CB	14.460	0.654	44.386	13.142	15.777
4	AM	19.505	0.801	35.493	17.880	21.130
5	WM	19.030	0.711	56.261	17.606	20.454

Table 3o. Contrasts (CB reference).

Contrast	Estimate	SE	df	t	*p*†
Contrast 1	-3.455	0.989	46.574	-3.492	.004
Contrast 2	-2.206	1.302	36.433	-1.694	.341
Contrast 3	-5.045	1.034	38.721	-4.879	<.001
Contrast 4	-4.570	0.922	67.330	-4.957	<.001

Note. † P-values are adjusted using Tukey adjustment. Contrast estimates were calculated using CB as the reference playing position.

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

ORIGINAL ARTICLE

Optimal serve distance for greater ball flight deviation in volleyball float serves

Alexandros Laios . *School of Physical Education and Sport Science. Department of Physical Education and Sport Science. National and Kapodistrian University of Athens. Athens, Greece.*

Irene Karanasiou. *Department of Military Sciences. Division of Mathematics and Engineering Sciences. Hellenic Military Academy. Athens, Greece.*

Konstantinos Sotiropoulos. *School of Physical Education and Sport Science. Department of Physical Education and Sport Science. National and Kapodistrian University of Athens. Athens, Greece.*

Miltiades Kyprianou. *Independent Biostatistician. Hellenic Institute for the Study of Sepsis (HISS). Athens, Greece.*

Karolina Barzouka. *School of Physical Education and Sport Science. Department of Physical Education and Sport Science. National and Kapodistrian University of Athens. Athens, Greece.*

ABSTRACT

In volleyball, the float serve is used to create aerodynamic instabilities that will cause deviations from the normal parabolic trajectory. Previous studies have examined serve speed and ball aerodynamics, but the relationship between serve flight distance and trajectory deviation remains unknown. Using a dual camera system, standing float serves were recorded in real conditions. Serves were executed from 9-13m before the net aiming at 3-9 m beyond the net, generating 1224 different serve trajectories. Early frame prediction of landing coordinates for each serve was compared with the real landing coordinates to quantify deviations from the expected parabolic trajectory. Prediction errors were analysed for their dependence on the serve distances with the ANOVA procedure, and the found optimal distances were associated with the increased expectation of achieving high deviations (≥27.1cm) with the Fisher's exact test. Results showed that 16-17 m is associated with increased trajectory deviation when compared to shorter ($p < .001$) and longer ($p < .001$) distances. Optimal distance serves were 28% more likely to achieve high deviations. This study shows that the serve distance can be used as a simple, equipment-free coaching tool to achieve trajectory deviation of a float serve in training and in a match.

Keywords: performance analysis, coaching, aerodynamics, sports performance, trajectory analysis.

Cite this article as:
Laios, A., Karanasiou, I., Sotiropoulos, K., Kyprianou, M., & Barzouka, K. (2026). Optimal serve distance for greater ball flight deviation in volleyball float serves. *Journal of Human Sport and Exercise, 21*(4), 1443-1458. https://doi.org/10.55860/cr051k36

Corresponding author. *School of Physical Education and Sport Science. Department of Physical Education and Sport Science. National and Kapodistrian University of Athens. 41Ethnikis Antistasis Str., 17237, Dafni Athens, Greece.*
E-mail: alxlaios@gmail.com

Submitted for publication June 14, 2026.
Accepted for publication July 27, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/cr051k36

INTRODUCTION

In the modern indoor volleyball, the serve is a unique action. Serve is defined as the first offensive action of each rally (Masumura et al., 2007; Palao et al., 2004), while it is the only one that has autonomy. According to FIVB (2025) rule 12.4.4, the server has eight seconds to hit the ball which means that the player can hold the ball and he is not reacting or affected by a previous action (Marcelino et al., 2012). Within that eight second window the server can decide on the type, trajectory, and power of the hit (Garcia-Tormo & Vaquera, 2015; Stamm et al., 2016). Serving is the starting point of every rally, and subsequently it is used as the primary tactical tool to disrupt the opponent's reception-set-attack complex and is recognized as a critical performance factor, as it can directly lead to a point (Ascic et al., 2024; Silva et al., 2014). Due to the rotation regulation (FIVB, 2025, Rule 7.6), every player on the court (excluding the Libero) must execute this skill, making the ability to manipulate the serve's trajectory a requirement for every player, since the serve effectiveness has an impact on game outcome (Drikos, Ntzoufras & Apostolidis, 2019).

Serves can primarily be categorized by their rotational characteristics and the resulting aerodynamic forces. Players may use the spin serve that has high angular velocity. Then due to Magnus Effect a downward pressure is generated (Goff, 2013) that allows high-velocity trajectories to land within the 18m court boundaries. Alternatively, players may use the float serve. That relies on executing the hit with little or no rotation of the ball (Ascic et al., 2024), so as to cause an unpredictable change in its trajectory in flight (Logan, 2023).

In contrast to the float serve, the spin serve creates a predictable trajectory. Its flight path behaviour is described by the relationship between velocity and the Reynolds Number (Re). Mikasa V200W, which is used in our analysis, has been FIVB's official indoor ball since 2018 and differs substantially from previous models in terms of panel configuration and aerodynamic characteristics (Tamaru et al., 2021). As it travels through the air, its 18-panel 'double-dimple' surface influences the boundary layer transition, a phenomenon observed in earlier studies on honeycomb-panel balls (Asai et al., 2010). As air resistance reduces the ball's speed, it goes through a critical velocity threshold where airflow becomes unstable, resulting in sudden lateral and vertical forces that cause the ball to wobble or deviate from a standard parabolic path (Depra et al., 1998; Dumek et al., 2018; Hong et al., 2019; Hong et al., 2020).

Research has extensively examined the speed of the serve and its relationship with both athletic performance and industrial design factors, including surface patterning and panel configuration (Hong et al., 2019). It has been found that the speed of the serve varies significantly depending on the player's position, the current score of the match and the level of the competition. Additionally, higher competition levels are associated with faster execution speeds (Altundag et al., 2024). Similarly, the physical ability to generate force and force-velocity profiles are significantly related to spike and serve speed in high-level players (Baena-Raya et al., 2021). However, these studies mainly focus on speed as a final indicator of performance rather than the shape of the ball's trajectory in flight.

Likewise, other more applied analyses have shown that 'floating' the ball is an important element of serve success, as it is associated with poor reception and (Logan, 2023; Reiser et al., 2020), consequently, lower setting quality (Gonzalez-Silva et al., 2020). However, the majority of the work available focuses on two things. The effectiveness of the serve as an in-game result and the accuracy/speed of execution. Therefore, missing out the mechanism through which the ball begins to deviate from the ideal parabolic trajectory in real-world flight conditions.

 © 2026 ARD Asociación Española

In addition, modern techniques of video analysis and three-dimensional trajectory reconstruction have made it possible to study the movement of the volleyball in more detail (Alptekin, 2016; Chen & Chu, 2021; Cheng et al., 2022; Depra et al., 1998; Horiuchi et al., 2019; Kawakami et al., 2017; Reiser et al., 2020). Chen & Chu (2021) showed that 3D reconstruction of trajectories by two cameras can support advanced forms of analysis in the sport, highlighting the importance of three-dimensional information in interpreting ball flight. However, these applications have been used primarily for action recognition and tactical analysis rather than for studying the deviation from the parabolic orbit of the float serve.

Therefore, despite significant progress in the study of efficiency, speed and aerodynamics of the serve, there remains a research gap as to the relationship between the total flight distance of the ball and the occurrence of deviations from the ideal parabolic trajectory in real float serves. Exploring this gap is of value because it can bridge the theoretical understanding of the ball's aerodynamic behaviour with a directly applicable training direction. That was highlighted by Altundag et al. (2024) who concluded that targeted training interventions are necessary to optimize serving speed.

The distance between the expected and the actual ball position is related to float serve efficiency (Reiser et al., 2020). In this context, the purpose of the present study was to investigate the relationship between the execution distance of a float serve's starting point to the landing point and the occurrence of deviations from the ideal parabolic trajectory of the ball during its flight. The study was based on the analysis of real three-dimensional ball trajectories, and to determine whether flight distance can be used as a practical, externally observable coaching variable through which the aerodynamic conditions associated with float behaviour can be achieved. Based on the results of the analysis, it is hypothesized that the execution of float serve with a target total distance of about 17 m creates the right conditions for the occurrence of deviations from the parabolic orbit.

This finding can be used as a practical tool in the coaching process, offering coaches a clear direction for learning and practicing float serve with the goal of maximizing the instability of ball flight. Identifying a distance range with increased float behaviour could be used as a simple and equipment-free method of training float serves. Beyond identifying an optimal flight distance, the present study proposes a practical framework for float serve training which can easily be transferred to match conditions. Instead of attempting to estimate ball velocity or Reynolds number during practice, coaches and players may use serve flight distance. Therefore the study aims not to explain float serve aerodynamics per se but to translate this knowledge into an easily applicable coaching method.

MATERIAL AND METHODS

Experimental design

The study analysed the flight trajectories of volleyball non jump float serves, performed by a highly experienced competitive player. The purpose of the study was not to compare athletes or serving techniques, but to investigate the relationship between serve flight distance and trajectory deviation under real conditions. Therefore, data were collected by a single highly experienced player who was capable of repeatedly producing float serves with minimal or no ball spin across a wide range of flight distances. The independent variable was the ball trajectory distance and not any player-related characteristic. So the player served primarily as a mean of generating a large number of realistic launch conditions. The study aimed to sample as many combinations of serve flight distances as possible, rather than to evaluate individual serving performance. The force required to produce the investigated trajectories lies well within the physical capabilities of male, female, and junior volleyball players. Consequently, the objective was not to determine

the maximum force a player could generate, but to examine how different realistic serve flight distances can influence the aerodynamic behaviour of the ball, once appropriate launch conditions have been achieved.

The float serves were executed from five serving positions located 9, 10, 11, 12 and 13 m from the net, targeting seven landing zones positioned 3-9 m beyond the net (Figure 1). For each serving position and target combination, 40 serves were recorded. All serves were performed using a Mikasa V200W volleyball, the official ball used in international competitions that is approved by the International Federation of Volleyball (FIVB). The net height was set at 2.24 m. A women's net height was used to ensure that the findings would be applicable to both male and female players. Also, the server's height (1.90 m) was representative of adult players regardless of gender so the net height does not affect the relationship between serve distance and trajectory deviation. Only serves that met the following criteria were included in the analysis: no visible ball spin, ensuring that the trajectory corresponded to a true float serve; no contact with the net; a trajectory below antenna height; unobstructed visibility in both camera views. A total of 1224 serves were recorded. After applying the inclusion criteria and excluding the serves that did not meet those criteria, 823 serves were kept for analysis. The procedures received University Ethics Committee approval (no: 1490/15-02-2023, SPESS-NKUA).

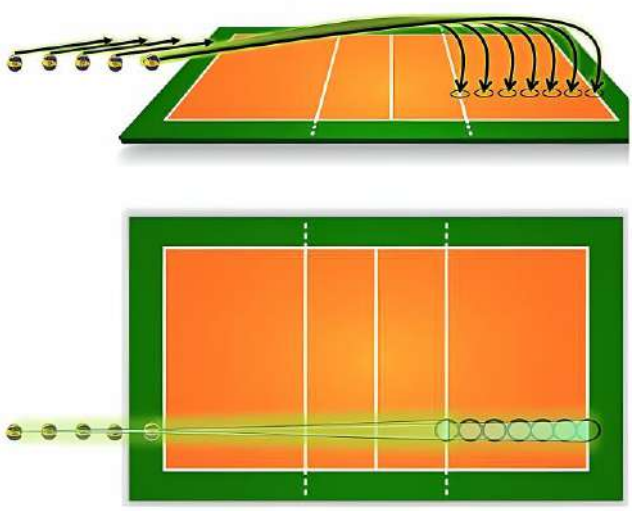


Figure 1. Experimental setup showing five serving positions and seven target landing zones.

Video recording

The ball trajectories were recorded using two DJI Osmo Action 3 cameras positioned orthogonally around the court. The cameras were placed at ground level with these specifications: lens height at 25.2 mm; focal length of 2.28 mm; resolution at 3840p x 2160p (4K); frame rate at 60 fps; field of view of 155°. One camera was positioned along the net's extension, while the second camera was placed perpendicular to the net. This orthogonal configuration enabled reconstruction of the three-dimensional trajectory of the ball from two synchronized two-dimensional image sequences.

Court calibration

To convert image coordinates to real-world coordinates, a calibration procedure was performed using known reference points on the court. A calibration pole with markers placed at heights of 0, 1, 2, and 3 m was positioned at 18 locations across the court. That produced 72 reference points distributed throughout the court volume, enabling accurate spatial reconstruction of ball trajectories across the entire flight region.

 © 2026 ARD Asociación Española

For each calibration point were recorded: (i) the real-world coordinates (X, Y, Z) and (ii) the corresponding pixel coordinates in both camera images. These calibration data were used to establish the mathematical relationship between pixel coordinates and real-world spatial coordinates.

3D Reconstruction of the ball trajectory

The theoretical relationship between image coordinates and spatial coordinates can be described using the Direct Linear Transformation (DLT) framework, which relates the position of a point in three-dimensional space to its projections in two camera views.

However, the wide field-of-view of the action cameras introduced noticeable lens distortion, which reduces the accuracy of classical DLT reconstruction.

Therefore, a regression-based calibration approach was implemented. Using the calibration dataset, regression models were constructed to estimate the three-dimensional position of the ball from the pixel coordinates observed in both cameras.

The resulting mapping can be expressed as:

$$(X, Y, Z) = F(x_s, z_s, y_b, z_b)$$

where

- x_s, z_s are pixel coordinates from the side camera
- y_b, z_b are pixel coordinates from the back camera.

To further improve accuracy across the large spatial volume of the court, the court space was subdivided into smaller spatial regions, and separate regression models were fitted for each region using nearby calibration points.

Ball tracking

For each recorded serve, the centre of the volleyball was manually identified in each frame of both camera videos. The centre corresponded to the centre of the circular outline of the ball.

The recording frame rate (60 fps) with the typical flight duration of a float serve (~1 - 1.5 sec), resulted in approximately 60-90 tracked positions per trajectory. Those provided sufficient information regarding the ball flight.

Dataset size

The experimental protocol produced a total of 823 float serves, corresponding to combinations of five serving positions and seven target areas in the opponent's court.

Each serve was recorded at 60 frames per second, resulting in approximately 60-90 frames per trajectory depending on the flight duration of the ball.

For each frame, the centre of the ball was identified in both camera views, yielding four pixel coordinates:

- x_s, z_s from the side camera
- y_b, z_b from the back camera.

Consequently, the dataset contained approximately 300,000 raw coordinate observations, which were used for three-dimensional reconstruction of the ball trajectories. This high temporal resolution allowed detailed reconstruction of ball trajectories and enabled reliable estimation of early-flight dynamics.

Trajectory modelling

After reconstruction, the ball trajectory was described using projectile motion models. The vertical component of the trajectory was approximated by a quadratic function:

$$z(t) = at^2 + bt + c$$

while the horizontal motion was approximated using linear functions:

$$x(t) = v_x t + x_0$$
$$y(t) = v_y t + y_0$$

These equations were estimated using the early portion of the recorded trajectory data. The parabolic model represents the theoretical trajectory as expected under ideal projectile motion. Therefore it is a reference framework against which deviations in the observed float-serve trajectories can be quantified. This approach allows the comparison between the theoretical projectile trajectory (the predicted one) and the experimentally observed ball flight (the real one). That enables the identification of distance-dependent deviations from the ideal parabolic motion.

Landing prediction

The predicted landing time t_{land} was determined by solving the vertical trajectory equation for the condition

$$z(t_{land}) = 0$$

The corresponding landing coordinates were then calculated using the horizontal motion equations. The predicted landing position (x_p, y_p) was compared with the actual landing position (x_a, y_a), determined from the frame corresponding to the first visible contact between the ball and the court surface.

Prediction error was calculated as

$$error = \sqrt{(x_p - x_a)^2 + (y_p - y_a)^2}$$

which represents the 2D distance between predicted and actual landing points. This error quantifies the accuracy of the trajectory-based landing prediction.

Calculations and statistical analysis

The real travelling distances were rounded to the nearest integer. Thus, a distance of 11 m denotes all serves with a real travelling distance ≥10.5 m and <11.5 m and so on. The primary outcome variable, which is the prediction error in meters was subjected to one-way analysis of variance (ANOVA) with the distance groups as calculated above.

 © 2026 ARD Asociación Española

Based on the above results, the distance groups were further categorized into three groups (Group 1: 11-15 m, Group 2: 16-17 m, Group 3: 18-22 m). These three groups were once more subjected to the ANOVA procedure with prediction error as the dependent variable.

To the purpose of providing more useful practical information, once the distance range that provides the optimal (maximum) prediction error has been determined, a binomial (dichotomous) variable with optimal versus non-optimal distances was created. Against this variable a Receiver Operating Characteristics (ROC) analysis with prediction error as the discrimination variable was performed. The purpose was, after the proof of significant discrimination ability with area under the curve (AUC) significantly greater than 0.5, to find the Youden's index, i.e. the cutoff value of prediction error that provides the best trade-off between sensitivity and specificity. The practical value of this cutoff is to provide through the odds ratio (OR) direct information on the increased expectation of maximal prediction error when the serve is directed at optimal distances.

RESULTS

The ANOVA procedure showed that the prediction error is significantly associated with the distance travelled by the volleyball (F = 17.3, df = 11,811, $p < .001$). As Figure 2 shows this association is rather complex. Starting from the minimum distance of 11 m and up to 15 m the prediction error was quite low and remained consistently below 0.21 m. However, at the distance of 16 m there was a very sharp increase of the prediction error, rising above 0.25 m. There was a further increase of the prediction error for the 17 m distance that reached almost 0.3 m. Further on, for the longer distances 18-20 m there was once again a reduction in the prediction error that remained within the 0.21-0.25 bounds.

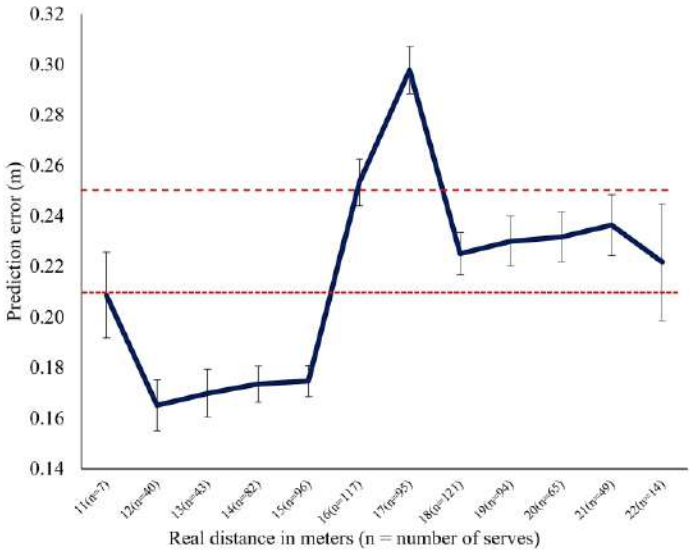


Figure 2. Mean prediction error (±SE) as a function of real serve distance. Red dashed lines indicate the thresholds used to classify low, medium, and high prediction error serves.

The ANOVA procedure was repeated using as the independent variable the three calculated distance groups (F = 85.6, df = 2,850, $p < .001$). As Figure 3 shows the optimal distance group, where the maximal prediction error can be observed is for the 16-17 m. The mean value of the prediction error for this group is significantly greater than for the shorter distances of 11-15 m ($p < .001$), but also than from the longer distances 18-20 m ($p < .001$). On their own turn, these longer distances provide significantly greater prediction errors than the

shorter distances (p < .001). Serves performed over longer distances are characterized by higher initial velocities but are subject to greater aerodynamic deceleration, enabling the ball to enter the critical velocity range during flight, whereas shorter-distance serves are executed below this threshold and therefore cannot reach the conditions required for aerodynamic instability.

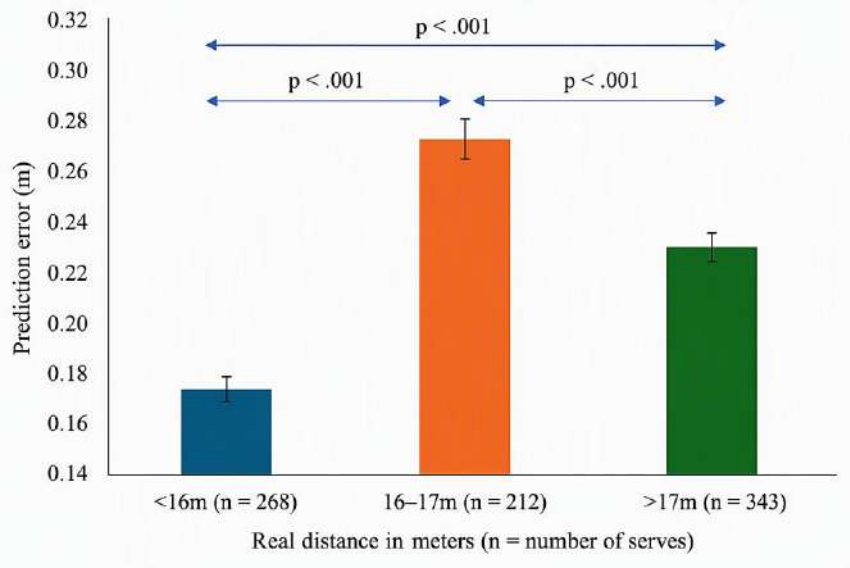


Figure 3. Mean prediction error (±SE) for the three serve distance groups and p-values for the between-group differences.

According to the above results the group distances were categorized into the binomial variable of optimal (16-17 m) versus non-optimal distances (all the other distances). Figure 4 shows the significant discrimination ability of prediction error on the optimal distance.

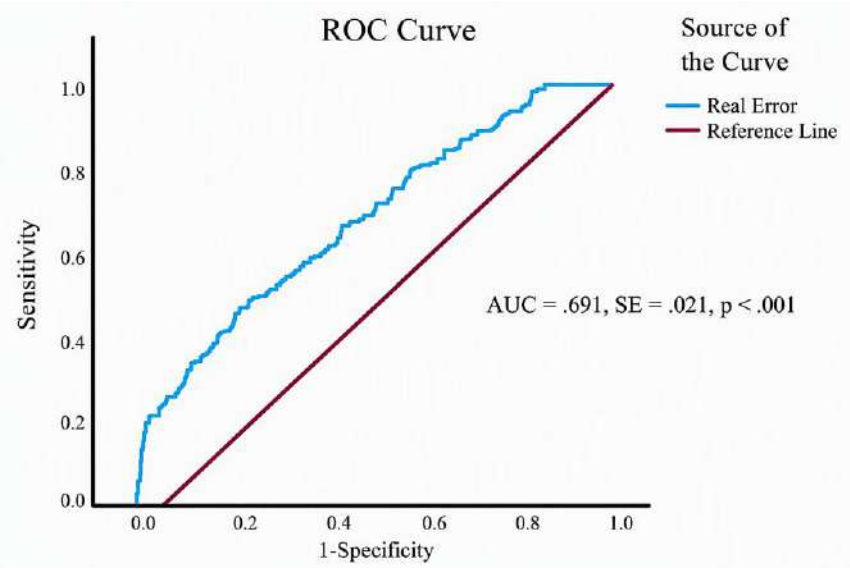


Figure 4. ROC curve showing the ability of prediction error to discriminate optimal serve distances.

 © 2026 ARD Asociación Española

Figure 5 provides the Youden's index for the prediction error on the optimal distance. This was found to be at 0.271 m, which is slightly greater than the diameter of the Mikasa V200W ball.

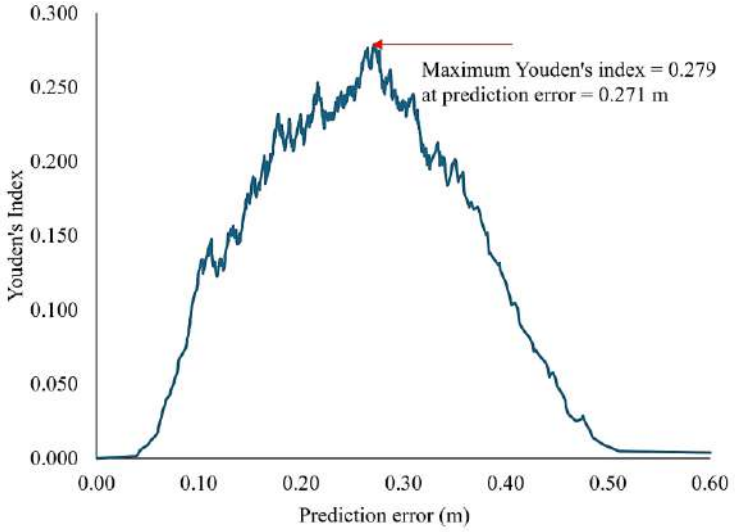


Figure 5. Youden's index as a function of prediction error.

According to the found Youden's index prediction, errors were dichotomized into low prediction errors (<0.271 m) and high prediction errors (≥0.271 m), The 2X2 contingency table of the association between optimal vs non-optimal serve distance with low versus high prediction errors provide the results shown in Figure 6.

Figure 6 shows that serving an optimal serve dramatically increases the chance of achieving high prediction error by almost 28%. The OR = 3.53, which is the effect size, is interpreted as how many times the odds of high to low prediction error is increased when performing an optimal serve against a non-optimal serve.

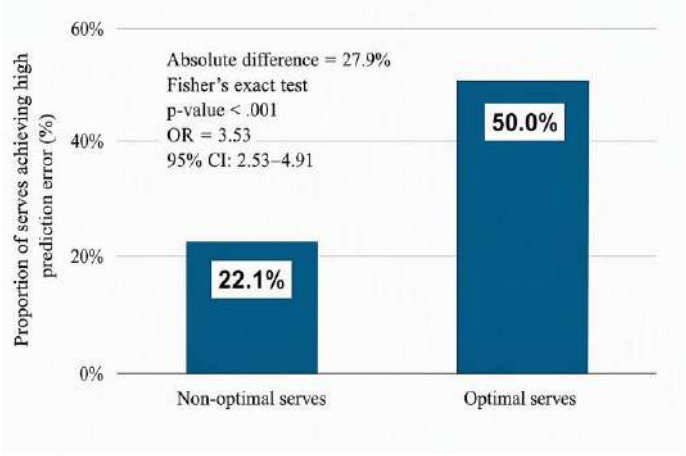


Figure 6. Proportions of high prediction error for non-optimal and optimal serves.

DISCUSSION

Although prediction error does not constitute a direct measurement of aerodynamic instability, it provides a practical proxy for deviations from the theoretical projectile trajectory. Several methodological precautions

were implemented to minimize alternative sources of error. This includes rigorous camera calibration, synchronized image acquisition, standardized data processing, and strict inclusion criteria requiring minimal or no ball spin. Under these controlled conditions, systematic differences in prediction error across flight distance groups are more plausibly attributed to changes in ball flight behaviour than to measurement variability. Nevertheless, future studies employing direct measurements of in-flight aerodynamic forces or higher resolution motion capture systems could further validate prediction error as an indicator of float behaviour.

This study showed that the trajectory prediction error was used as an operational measure of trajectory deviation, consistent with previous approaches linking deviation from expected parabolic motion to float behaviour. This relation is nonlinear since there was a peak at the 16-17 m distance. That supports the idea of using the serving distance as a tool to achieve the ideal speed that will result in trajectory deviation. Although maximum values were found at that distance, there is a wider range distance (16-18 m), within which aerodynamic forces will push the ball away from the predicted landing point. In that sense a volleyball player can focus on serving at the last three meters of the opponents' court, provided that he is behind the serve line. That secures his accuracy of giving the ball the appropriate initial speed without using any equipment. This finding is consistent with the theoretical expectation (MacKenzie et al., 2012) that float behaviour emerges when the ball velocity decreases into a specific critical speed during flight.

On the same note previous wind tunnel experiments on Mikasa V200W, showed that sudden lateral and lift forces were generated only within a specific Reynolds number range. The result of that was unpredictable trajectory deviations (Hong et al., 2020). Similarly, Tamaru et al. (2021) demonstrated that float serve trajectories are strongly influenced by the initial ball velocity. The Reynolds number is directly proportional to ball velocity and velocity decreases as a function of distance. This relationship supports the present findings of a specific serve distance range within which float behaviour is most likely to occur. In support of that, Kawakami et al. (2017) concluded that changes in the ball's trajectory occur within a critical velocity range.

The present study extends previous findings by demonstrating that these aerodynamic effects can be identified through flight distance, providing a practical bridge between controlled laboratory findings and real-world performance. Float serve behaviour depends on two essential conditions. (a) Minimal or zero ball rotation and (b) Ball velocity within a critical range. The first condition, minimal rotation, is determined by the mechanics of ball contact. Spin is introduced when the point of force application does not align with the ball's centre of mass. For example, a contact above the centre produces topspin. This point can be easily addressed during training, as rotation is visually observable during flight. Players can therefore receive immediate visual and audio feedback and adjust their contact point accordingly to minimize spin.

The second condition, achieving the critical velocity range, is considerably more complex. Aerodynamic studies have shown that float behaviour occurs within a narrow velocity window corresponding to a critical Reynolds number regime (Hong et al., 2020). However, this speed is reached during flight as the ball decelerates due to aerodynamic drag. So, it is not the initial speed that the player gives at the ball during hand contact.

From a coach's point of view guiding a player regarding the optimum initial speed is very challenging. That is because speed cannot be monitored without the use of electronic devices. Although equipment such as radar devices can assist in measuring ball velocity, they are not always available and are impractical for continuous use during regular training sessions.

 © 2026 ARD Asociación Española

Given that velocity decreases continuously during flight, the results of the present study suggest that flight distance can serve as a practical proxy for the initial speed and therefore velocity decay. More specifically it was found that:

- At shorter distances (<16 m), the ball's initial speed is already low and does not enter the critical range
- At intermediate distances (~16-17 m), the ball decelerates into the critical velocity range, increasing the likelihood of aerodynamic instability
- At longer distances (>17 m), although float behaviour may still occur, float serve execution becomes less consistent due to increased variability and control demands

Those results agree with Tamaru et al. (2021) findings. They noted that trajectory irregularities can be found under specific combinations of the ball's speed and rotation. Therefore, float serve path deviations are not uniformly present across different trajectories.

Beyond its practical value, the proposed coaching approach is also consistent with established principles of motor learning. Players, instead of trying to focus on variables that are difficult to perceive during performance, such as ball velocity, they can focus on an externally observable movement outcome. That is the serve flight distance. Research has consistently shown that directing attention towards movement effects, like the trajectory or landing point of the ball, rather than toward body movements or internal mechanics, enhances both motor performance and learning (Wulf et al., 2002). Therefore, using serve distance as a coaching constraint provides a simple external performance goal that allows athletes to self-organize their movement patterns and consistently produce the desired trajectory.

rom a practical point of view, the identification of a target distance of approximately 17 ± 1 m provides a simple and easy to use tool when training float serves. Attempting to control initial speed directly is difficult to quantify in real time. Coaches and players can use distance-based targets as guide for the proper float serve execution. By instructing players to consistently target a landing zone at approximately 17 m, it becomes possible to indirectly achieve the aerodynamic conditions required for float behaviour. The distance range of 17 m is important, because it provides a margin of tolerance regarding missing the target. When a player is slightly under-hitting the 17 m target (~16 m), his serve remains within the effective range. On the other hand, when a player is slightly over-hitting the 17 m target (~18 m), he can still produce float behaviour, although with reduced consistency. This makes the 17 m target both optimal and robust. It allows players, regardless of gender or skill level, to develop float serves through trial-and-error learning method.

Although the present study focuses specifically on volleyball float serves, the same concept extends beyond this particular skill. In many sports, the desired performance depends on physical or biomechanical variables that are difficult to observe during practice. The present study demonstrates that such variables can sometimes be approached indirectly. This can be done through simple, externally observable performance targets. In the case of volleyball float serves, flight distance provides a practical proxy. A link between the aerodynamic conditions and the trajectory deviation. That offers a simple evidence-based framework that translates complex biomechanical principles into an easily applicable training strategy.

The threshold identified through ROC analysis should be interpreted as a practical decision threshold rather than evidence of a discrete aerodynamic boundary. Prediction error remains a continuous variable, and the magnitude of aerodynamic instability is similarly expected to vary continuously. The cutoff produced by ROC was introduced only to facilitate the interpretation of the Fisher's exact analysis and to provide a practically meaningful criterion for distinguishing larger from smaller trajectory deviations in an applied coaching context.

Figure 7 summarizes the proposed conceptual coaching framework, illustrating how the recommended flight distance can be applied in practice.

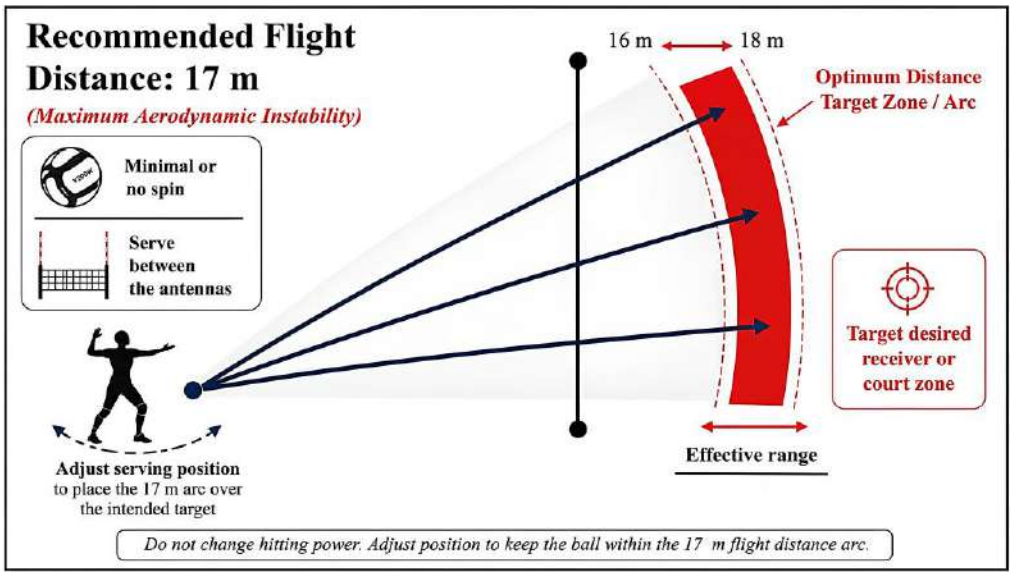


Figure 7. Conceptual coaching framework for applying the recommended float serve flight distance.

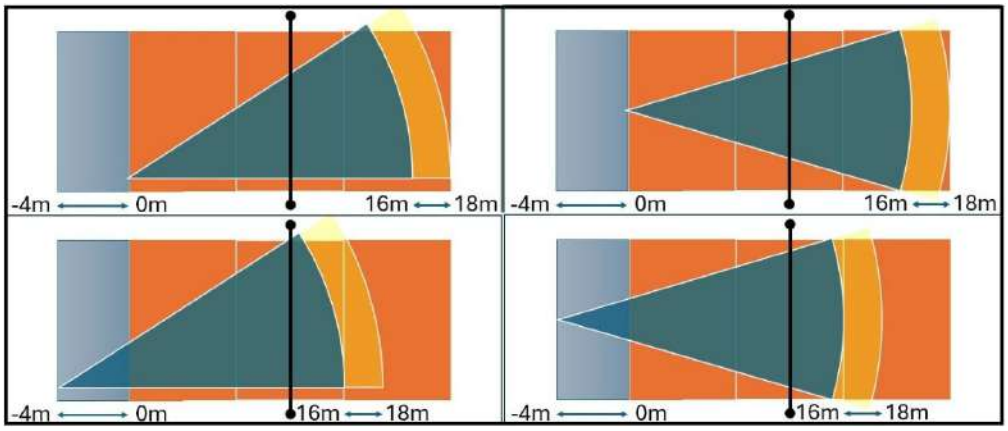


Figure 8. Application of the conceptual coaching framework from different serving positions.

The findings also introduce a spatial interpretation of the optimal serving distance. Since the server can be considered as the centre of the ball's motion, the 17 m distance defines an arc-shaped region across the opponent's court (Figure 8). The highlighted band represents the recommended flight distance range of 17 ± 1 m. This has important tactical implications since it can be used while respecting both the players and coaches' preferences. All players have a personal preference regarding the position from which they serve. The same way coaches have target preferences, either a zone or a receiving player, according to their strategy against every match opponent team. Figure 8 illustrates that (a) the optimal landing zone varies depending on the server's position, (b) different serving positions shift the arc and (c) coaches can reposition the arc to suit their strategy plans. When players serve from lateral positions (zones 1 or 5) the direction of the serve affects the distance of the target from the net. Cross court serves should land around 2.5 m closer

 © 2026 ARD Asociación Española

to the net to maintain the 17 m flight range. If we consider that the receivers of a team stand around 5-6 m from the net there are two choices regarding the team's strategy. The receivers of a team when expecting a float serve, usually stand about 5-6 m away from the net. Serves from the end line will force them to use overhead passing technique. Serves taken from 3-4 m behind the end line will force them to use underarm reception technique. So, both the players and the coaches can benefit using the 17 m serve range. Players can use it during training as a practical reference for consistently producing the recommended flight distance. Coaches can use it when designing the per rotation serving strategies in games.

Float serves can still deviate from the normal parabolic trajectory at distances greater than 17 m, but this seems to come with some disadvantages. Sending the ball farther requires greater force which makes it more difficult to keep the ball not spinning. In addition, aiming at greater distances is harder so players will not be as accurate as in shorter flight range. An increased flight duration will also help the receivers, giving them more time to adjust their position. Overall, while longer serves may still deviate, they are likely to be less accurate, less consistent and therefore less effective. Although the present study used a single highly experienced player, the objective was not to investigate player performance, but the aerodynamic behaviour of the volleyball following the hit. A single server was deliberately selected to ensure consistent execution of non-spinning float serves while systematically producing a wide range of realistic flight distances. Under these conditions it was the ball trajectory and not the player's technique that was observed. Nevertheless, future research should examine whether players of different ages, sexes and competitive levels can produce the same flight distance conditions consistently during training and competitions. Such studies would help determine the practical generalization of the proposed approach across broader volleyball populations. Future research should also examine whether similar results are observed with jump float serves. The standing float serve is a basic skill that helps players learn how to control ball spin and distance. It is essential that players should practice this type of serve first, before moving on to more advanced serves like the jump float or jump spin. When executing a standing float serve, coaches may instruct players to target landing zones within this distance range as a simple, equipment-free method to approximate the conditions associated with increased trajectory instability.

CONCLUSIONS

In summary, this study shows that deviations from ideal parabolic trajectory in volleyball float serves are distance dependent. The critical flight range where the greater errors were found is 16-17 m. Results showed that a distance of approximately 17 m is associated with increased trajectory deviation and may serve as a practical reference in training. The flight range was linked with the initial ball speed, giving players and coaches an easy-to-use tool for training and for games strategies. The identification of a distance-based target (17 m) provides a practical coaching framework through which players and coaches can achieve the required goal of floatation without relying on specialized equipment.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: AL, IK, KS, KB. Methodology: AL, IK, KS, KB. Formal analysis: MK. Investigation: AL. Data curation: AL. Writing - original draft: AL. Writing - review & editing: AL, IK, KS, MK, KB. Supervision: KB.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Alptekin, A. (2016). Kinematic analysis of volleyball float serve. *International Journal of Science Culture and Sport, 4*(17), 51–51. https://doi.org/10.14486/IntJSCS533

Altundag, E., Soylu, C., & Akyildiz, Z. (2024). Multidimensional analysis of serving speed in volleyball players by position, sets, and league types: Interactions and statistical differences. *BMC Sports Science, Medicine and Rehabilitation, 16*(1), 240. https://doi.org/10.1186/s13102-024-01031-z

Asai, T., Ito, S., Seo, K., & Hitotsubashi, A. (2010). Aerodynamics of a new volleyball. *Procedia Engineering, 2*(2), 2493–2498. https://doi.org/10.1016/j.proeng.2010.04.021

Ascic, S., Marinovic, M., Kuna, D., Curic, M. M., & Marelic, M. (2024). Analyzing volleyball serve strategies: Comparing jump and float serves in the Croatian men's volleyball superleague. *Sports Science and Health, 14*(1), 13–17. https://doi.org/10.7251/SSH2401013A

Baena-Raya, A., Soriano-Maldonado, A., Rodriguez-Perez, M. A., Garcia-de-Alcaraz, A., Ortega-Becerra, M., Jimenez-Reyes, P., & Garcia-Ramos, A. (2021). The force-velocity profile as determinant of spike and serve ball speed in top-level male volleyball players. *PLOS ONE, 16*(4), Article e0249612. https://doi.org/10.1371/journal.pone.0249612

Chen, C.-N., & Chu, W.-T. (2021). How it flies and why it flies? Volleyball trajectory segmentation and classification. IEEE Transactions on Circuits and Systems II: *Express Briefs, 68*(5), 1591–1595. https://doi.org/10.1109/TCSII.2021.3067027

Cheng, X., Liang, L., & Ikenaga, T. (2022). Automatic data volley: Game data acquisition with temporal-spatial filters. *Complex & Intelligent Systems, 8*(6), 4993–5010. https://doi.org/10.1007/s40747-022-00752-3

Deprá, P., Brenzikofer, R., Goes, M., & Barros, R. (1998). Fluid mechanics analysis in volleyball services. *ISBS-Conference Proceedings Archive*, 85–88. https://ojs.ub.uni-konstanz.de/cpa/article/view/1602

Drikos, S., Ntzoufras, I., & Apostolidis, N. (2019). Bayesian analysis of skills importance in world champions men's volleyball across ages. *International Journal of Computer Science in Sport, 18*(1), 24–44. https://doi.org/10.2478/ijcss-2019-0002

 © 2026 ARD Asociación Española

Dumek, J., Safarík, P., Patek, Z., & Asai, T. (2018). On the flight of the volleyball. In Topical problems of fluid mechanics 2018 (pp. 65–72). *Institute of Thermomechanics, AS CR, v.v.i*. https://doi.org/10.14311/TPFM.2018.009

Fédération Internationale de Volleyball. (2025). *Official volleyball rules 2025–2028*. https://www.fivb.com/wp-content/uploads/2025/01/FIVB-Volleyball_Rules2025_2028-EN-v05.pdf

Garcia-Tormo, J. V., & Vaquera Jimenez, A. (2015). Methodological proposal for the quantification and analysis of the level of risk assumed in volleyball service execution in female high-level competition. *Journal of Physical Education and Sport, 15*(1), 108–113. https://doi.org/10.7752/jpes.2015.01018

Goff, J. E. (2013). A review of recent research into aerodynamics of sport projectiles. *Sports Engineering, 16*(3), 137–154. https://doi.org/10.1007/s12283-013-0117-z

Gonzalez-Silva, J., Fernandez-Echeverria, C., Conejero, M., & Moreno, M. P. (2020). Characteristics of serve, reception and set that determine the setting efficacy in men's volleyball. *Frontiers in Psychology, 11*, Article 222. https://doi.org/10.3389/fpsyg.2020.00222

Hong, S., Asai, T., & Weon, B. M. (2019). Surface patterns for drag modification in volleyballs. *Applied Sciences, 9*(19), Article 4007. https://doi.org/10.3390/app9194007

Hong, S., Ozaki, H., Watanabe, K., & Asai, T. (2020). Aerodynamic characteristics of new volleyball for the 2020 Tokyo Olympics. *Applied Sciences, 10*(9), Article 3256. https://doi.org/10.3390/app10093256

Horiuchi, G., Toyoshima, R., Suzuki, Y., & Sakurai, S. (2019). Kinematics of the jump floater serve in elite female volleyball players. *Taiikugaku Kenkyu (Japan Journal of Physical Education, Health and Sport Sciences), 64*(2), 841–854. https://doi.org/10.5432/jjpehss.19008

Kawakami, Y., Mizusawa, T., & Okanaga, H. (2017). Aerodynamics characteristics and flight trajectory of floater serve of volleyballs. *The Proceedings of the Symposium on Sports and Human Dynamics, 2017*(0), B-23. https://doi.org/10.1299/jsmeshd.2017.B-23

Logan, E. (2023). An analysis of float serves in women's collegiate volleyball [Undergraduate honors thesis, Brigham Young University]. *BYU ScholarsArchive*. https://scholarsarchive.byu.edu/studentpub_uht/341/

MacKenzie, S., Kortegaard, K., LeVangie, M., & Barro, B. (2012). Evaluation of two methods of the jump float serve in volleyball. *Journal of Applied Biomechanics, 28*(5), 579–586. https://doi.org/10.1123/jab.28.5.579

Marcelino, R. O., Sampaio, J. E., & Mesquita, I. M. (2012). Attack and serve performances according to the match period and quality of opposition in elite volleyball matches. *Journal of Strength and Conditioning Research, 26*(12), 3385–3391. https://doi.org/10.1519/JSC.0b013e3182474269

Masumura, M., Marquez, W. Q., Koyama, H., & Michiyoshi, A. (2007). A biomechanical analysis of serve motion for elite male volleyball players in official games. *Journal of Biomechanics, 40*(Suppl. 2), S744. https://doi.org/10.1016/S0021-9290(07)70732-7

Palao, J. M., Santos, J. A., & Ureña, A. (2004). Effect of team level on skill performance in volleyball. *International Journal of Performance Analysis in Sport, 4*(2), 50–60. https://doi.org/10.1080/24748668.2004.11868304

Reiser, M., Zentgraf, K., Kindermann, S., & Kunzell, S. (2020). An approach to quantify the float effect of float serves in indoor and beach volleyball. *Frontiers in Sports and Active Living, 2*, Article 559277. https://doi.org/10.3389/fspor.2020.559277

Silva, M., Lacerda, D., & João, P. V. (2014). Game-related volleyball skills that influence victory. *Journal of Human Kinetics, 41*(1), 173–179. https://doi.org/10.2478/hukin-2014-0045

Stamm, R., Stamm, M., Torilo, D., Thomson, K., & Jairus, A. (2016). Comparative analysis of the elements of attack and defence in men's and women's games in the Estonian volleyball highest league. *Papers on Anthropology, 25*(1), 37–54. https://doi.org/10.12697/poa.2016.25.1.04

Tamaru, T., Hiratsuka, M., & Ito, S. (2021). Serve ball trajectory characteristics of different volleyballs and their causes. *Applied Sciences, 11*(19), Article 9269. https://doi.org/10.3390/app11199269

Wulf, G., McConnel, N., Gartner, M., & Schwarz, A. (2002). Enhancing the learning of sport skills through external-focus feedback. *Journal of Motor Behavior, 34*(2), 171–182. https://doi.org/10.1080/00222890209601939

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

ORIGINAL ARTICLE

Determining the optimal competition age and the effective performance window in elite 100-meter sprinters: A mixed polynomial model

Maria Carmen Rodriguez-Fernandez . *University of Seville. Spain.*
Jose Fernando Arroyo-Valencia†. *National School of Sport. Colombia.*
† *Deceased author.*

ABSTRACT

The aim of this study was to establish a performance prediction model to determine the optimal competition age and the effective window of maximum performance in the men's 100-meter sprint. A total of 408 records were analysed, corresponding to marks achieved by elite athletes who made up the World Athletics world ranking over 20 consecutive seasons (1998–2017). Polynomial gradient mathematical models and a mixed polynomial model were applied to capture the non-linear relationship between age and performance. The results show a positive progression in performance from age 18 to 24, followed by a slight plateau and an effective window of maximum performance between ages 25 and 32. The mixed polynomial model described performance by means of a second-degree polynomial ($T = 10.452 - 0.0339 \cdot Age + 0.0006 \cdot Age^2$), whose vertex (minimum) is located, using the published rounded coefficients, at around 28–29 years of age. These findings provide coaches with an empirical reference framework, based on two decades of elite competition, for optimizing long-term planning and talent identification.

Keywords: performance analysis; athletics; sprinting; mathematical models; sports performance; optimal age; performance window; talent identification.

Cite this article as:
Rodriguez-Fernandez, M. C., & Arroyo-Valencia, J. F. (2026). Determining the optimal competition age and the effective performance window in elite 100-meter sprinters: A mixed polynomial model. *Journal of Human Sport and Exercise, 21*(4), 1459-1475. https://doi.org/10.55860/91e1dh11

Corresponding author. *University of Seville. Spain.*
E-mail: carro@us.es
Submitted for publication June 19, 2026.
Accepted for publication July 27, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/91e1dh11

INTRODUCTION

The 100-meter sprint is considered the ultimate expression of human speed and one of the sporting events with the greatest media impact worldwide (Moravec et al., 1988). Every world championship or Olympic final in this event draws audiences of over 100 million viewers, turning the sprinter into a symbol of human athletic capability. The pursuit of the limits of performance in this discipline has driven the development of predictive models that attempt to explain the evolution of records and project future marks (Berthelot et al., 2015; Blest, 1996).

Historically, performance prediction models in athletics have been based on biomechanical and physiological approaches. In sprint events, performance is determined by the complex interaction between horizontal propulsive force production, stride frequency and length, and neuromuscular efficiency (Bogdanis et al., 1996; Salo et al., 2011; Morin et al., 2015). Morin et al. (2011) demonstrated that the ability to orient the resultant ground reaction force in the horizontal direction constitutes the most robust predictor of acceleration performance, this technical force-application skill being the differentiating factor between performance levels —from recreational athletes to world-class sprinters—. More recently, Samozino et al. (2022) established that acceleration performance is a function of both the maximization of horizontal power and the optimization of the individual force-velocity profile.

In contrast to the wealth of studies on biomechanical determinants, mathematical models of time prediction have taken different approaches. From the linear models of Heazlewood (2006) —which paradoxically predicted a time of 0 seconds for the year 5038— to quadratic models estimating a 9.20 s mark within a century (Shaw, 2012), the literature has recognized that predetermined mathematical functions present significant limitations when applied to an event of such multifactorial complexity (Nevill & Whyte, 2005). Berthelot et al. (2015) and Kotuła et al. (2025) have confirmed, through time-series analysis of World Championships (1983–2023), that improvement in 100-meter performance does not follow a linear pattern but instead shows periods of acceleration and stabilization, with differences between the best result and the average being significantly variable depending on the season analysed.

More recent analyses using ARIMA and SARIMA models on historical data from 1976 to 2035 project a time of 9.63 s as the men's best world mark in 2035, concluding that the rate of progression has slowed particularly in pure speed events, suggesting an approach toward the physiological limits of performance (Bartosz-Jefferies et al., 2025). However, these models share the same limitation as the classic ones: they are based on the world record or on isolated best performances, without considering the actual distribution of performance within the elite or the athlete's age variable.

Competition age is precisely one of the least studied variables, yet one with the greatest practical implications for long-term planning. In a landmark study with world-class track-and-field athletes, Haugen et al. (2018) quantified peak performance age and prior progression in distance runners and sprinters, confirming that 100-meter sprinters show improvement patterns specifically related to their age, and that top-10 world athletes exhibit significantly greater improvements than those ranked 11th to 100th. This finding suggests that elite level determines not only the magnitude of performance but also its developmental trajectory.

At the national level, and regarding age categories, the study by Agudo-Ortega et al. (2024) with 4,398 Spanish sprinters (2004–2021) identified that peak performance age in the 100 metres is 25.31 years for men, significantly earlier than for women (25.79 years). This same study highlighted the importance of sub-23 category performance as a predictor of participation in the senior category, with significant regression

 © 2026 ARD Asociación Española

coefficients (β = 0.51, $p < .001$), whereas success in youth categories showed little predictive capacity for senior performance.

This dissociation between youth success and elite adult performance has received increasing attention in the literature. Boccia et al. (2021) analysed the career trajectories of 4,924 sprinters from the World Athletics ranking (2000–2018) and found that only 17% of men and 21% of women ranked in the sub-18 top 50 went on to reach the senior top 50. Athletes who ultimately reached the absolute elite showed progressively larger annual improvements during late adolescence and early adulthood. In the same vein, Boccia et al. (2018), with Italian athletes, confirmed that national elite sprinters reach their personal best later than non-elite athletes, and that later entry into specific competition and career extension beyond ages 23–25 are factors associated with success at the absolute category level. This body of evidence challenges talent identification systems based on competitive results at early ages and reinforces the need for longitudinal performance-tracking models.

Regarding the decline in sprint capacity with age, Korhonen et al. (2006) documented, through muscle biopsies in sprinters aged 18 to 84, that the cross-sectional area of type II fibres decreases significantly with age —while type I fibres are maintained— together with a shift toward a slower myosin heavy-chain profile. These structural changes translate into a reduction in explosive force production capacity, although systematic sprint training acts as an effective stimulus to preserve muscle fibre morphology against ageing. Pantoja et al. (2016) extended this biomechanical analysis to masters sprinters, finding that maximal force, velocity, and power decrease linearly with age at a rate of approximately 1% per year (all $r > .84$, $p < .001$), with the capacity to orient horizontal force identified as the most deteriorated factor in older sprinters.

Therefore, the main objective of this study was to establish a performance prediction model for the men's 100-meter sprint, based on competition age and other contextual factors (ranking, continent, season), in order to determine the optimal age and the effective window of maximum performance using elite world data over a 20-season period (1998–2017). The findings are contextualized within the framework of recent scientific literature on the development of the high-performance sprinter.

METHODOLOGY

Study design and sample

An observational, tracking, and retrospective study was conducted. The reference database used was that developed by the International Association of Athletics Federations (World Athletics), which contains more than one million results from over ten thousand international competitions. The best records obtained by male athletes of international level in the 100 meters, who made up the world ranking over 20 consecutive seasons (1998–2017), were selected.

Inclusion criteria were: male athletes, ages between 18 and 40 years, outdoor competitions, electronic timing, and wind speed ≤ 2.0 m/s assisting. Records set indoors, with manual or unspecified timing, and those obtained with wind exceeding the regulatory limit were excluded. The extraction process was conducted by the principal investigator and two independent researchers (triangulation), with no observable differences between the records selected by each evaluator.

The final sample consisted of 408 records corresponding to athletes in the top 20 positions of the world ranking in each season. In some seasons, more than 20 records were included due to ties in the ranking

score (positions 19th–20th), such that 2001 and 2003 contributed 25 records each, 2006 contributed 24, 1999 contributed 23, and several additional years contributed 21–22 records.

Statistical analysis

Data were tabulated and exported to the R statistical software package (version 3.5.1). An initial descriptive analysis was performed, expressing results as mean and standard deviation (SD), with minimum and maximum range. To analyse the temporal evolution of performance by age, polynomial gradient models and smooth models were used, which fit the estimate to the data without imposing a predetermined mathematical function —thereby overcoming a common limitation in the literature (Bartosz-Jefferies et al., 2025; Shaw, 2012)—. Additionally, a mixed polynomial model was developed to capture the non-linear relationship between age and race time, including a random term to control for inter-individual and seasonal variability. The optimal competition age and its 95% CI were obtained using the DELTA method applied to the model coefficients. The significance level was set at $p < .05$.

Mixed-model specification: the random-effects structure was defined as a random intercept per athlete, following the notation T ~ Age + Age² + (1 | Athlete). The full model results (recovered from the original doctoral thesis by Arroyo Valencia, 2020, Table 5) show a residual variance $\sigma^2 = 0.01$ and a random-effect variance per athlete $\tau 00 = 0.00$, corresponding to an intraclass correlation coefficient ICC = 0.32; that is, 32% of the total variability in performance is attributable to systematic differences between athletes, while the remaining 68% corresponds to variability within the same athlete (e.g., across seasons). It should be noted that a $\tau 00$ of 0.00 is mathematically incompatible with an ICC of 0.32 when $\sigma^2 = 0.01$: to obtain that ICC, the between-athlete variance would need to be approximately 0.0047. The reported value of 0.00 is, in all likelihood, a rounding artifact at two decimal places, and should be published with greater decimal precision before the final version is submitted. The model was fitted on 408 observations. Model fit was modest: marginal $R^2 = .021$ (i.e., age and its quadratic term explain only 2.1% of the total variance) and conditional $R^2 = .336$ (variance explained by age plus the random athlete effect). Given the small magnitude of the marginal R^2, the model should be understood as an associative description of the population trend rather than a validated tool for predicting individual performance; no cross-validation, training/test split, or prediction-error calculation (RMSE or mean absolute error) has been conducted.

RESULTS

Descriptive evolution of performance by competition age

Table 1 presents the descriptive statistics of the 100-metre mark for each age group. The best mean mark (9.93 ± 0.098 s) was recorded at age 30, while the worst records (10.00 s) were concentrated at the extremes of the age distribution (18–19 and 35–36 years). The sample showed a high concentration between ages 22 and 28 (≈ 75% of cases), with particular density at ages 22 and 23 (60 and 45 records respectively, representing 25% of the total). This profile is consistent with data from Agudo-Ortega et al. (2024), who in a sample of 4,398 Spanish sprinters found a similar concentration of records in the 20–27 age range and a stabilization of the improvement curve from age 23–24 onward.

Between ages 22 and 25, a slight plateau in the mean mark was detected, around 9.97 s (43% of the total sample), followed by an improvement at ages 26–27 (9.95 s). This pattern, although unexpected a priori, is consistent with evidence on the adaptation curve of high-level sprinters: once a first physiological ceiling has been reached, improvement in maximum velocity depends less on metabolic adaptations and more on the optimization of the individual force-velocity profile (Samozino et al., 2022; Morin et al., 2015). The talent-identification literature supports this interpretation: Boccia et al. (2021) documented that athletes who

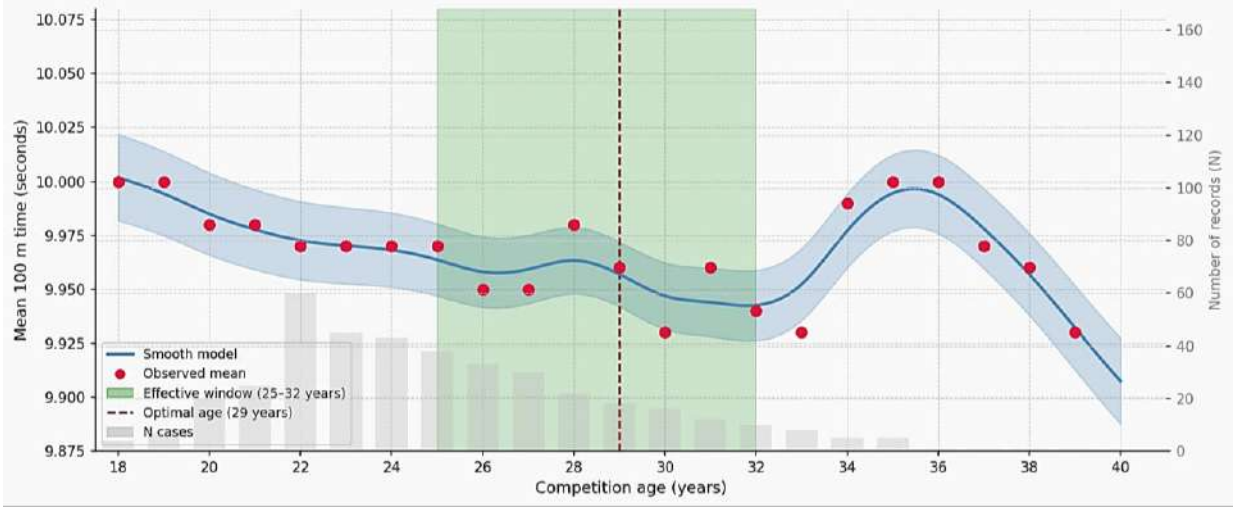
 © 2026 ARD Asociación Española

ultimately reach the absolute top 50 show progressive annual improvements during early adulthood, while those who do not reach it show an early plateau at similar ages.

Table 1. Descriptive statistics of the 100 m mark by competition age (1998–2017).

Age	N	Mean (s)	SD (s)	Min (s)	Median (s)	Max (s)
18	4	10	0.044	10	10	10.08
19	7	10	0.043	9.97	10	10.1
20	20	9.98	0.056	9.84	9.99	10.06
21	25	9.98	0.076	9.82	9.98	10.1
22	60	9.97	0.092	9.69	9.97	10.1
23	45	9.97	0.092	9.58	9.98	10.1
24	43	9.97	0.079	9.77	9.98	10.1
25	38	9.97	0.088	9.74	9.97	10.1
26	33	9.95	0.102	9.63	9.96	10.1
27	30	9.95	0.156	9.82	9.99	10.1
28	22	9.98	0.081	9.78	9.99	10.1
29	18	9.96	0.11	9.78	9.99	10.1
30	16	9.93	0.098	9.79	9.91	10.1
31	12	9.96	0.055	9.85	9.97	10.1
32	10	9.94	0.081	9.77	9.96	10
33	8	9.93	0.144	9.74	9.94	10.1
34	5	9.99	0.098	9.8	9.97	10.1
35	5	10	0.1	9.92	9.96	10.1
36	1	10		10	10	10
37	1	9.97		9.97	9.97	9.97
38	1	9.96		9.96	9.96	9.96
39	1	9.93		9.93	9.93	9.93
Total	**405**	**9.97**	**0.094**	**9.58**	**9.98**	**10.1**

Note. SD = standard deviation; Min = minimum; Max = maximum. The N cell in the Total row is calculated using a SUM formula across the age rows; the remaining statistics (Mean, SD, Min, Median, Max) are the values published in the article.



Note. Gray bars represent the number of records per age. The shaded green area indicates the effective window of maximum performance (25–32 years) and the dashed red line indicates the estimated optimal age (29 years).

Figure 1. Evolution of the mean 100 m mark as a function of age (smooth model, 1998–2017).

Performance distribution by world ranking position

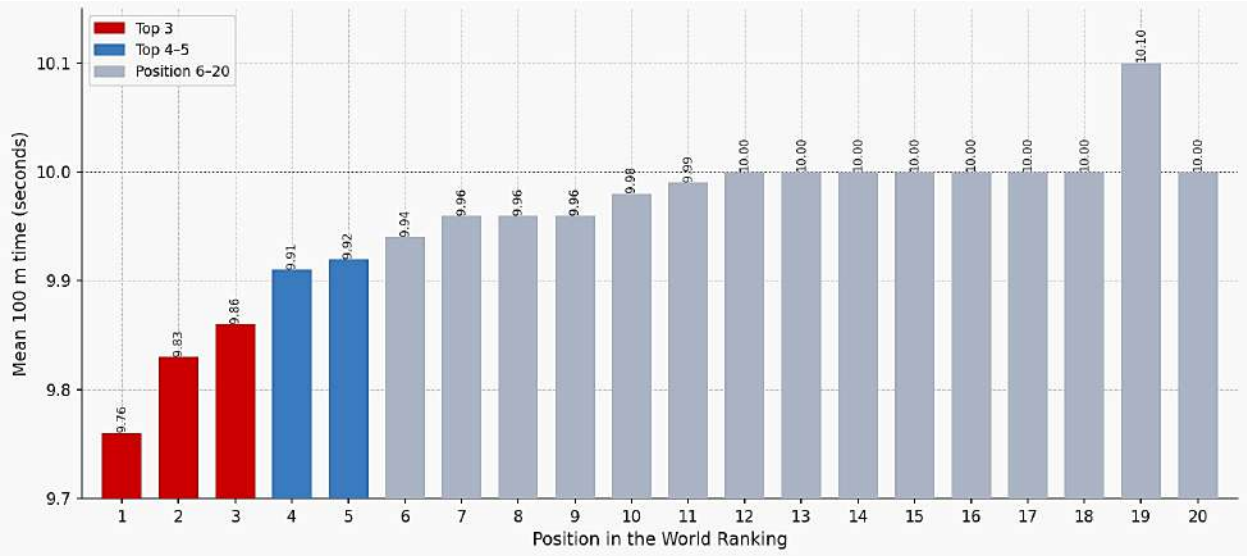
Table 2 presents the descriptive statistics by world ranking position. A progressive increase in time was observed as athletes occupied lower positions, with no observable differences beyond the 12th position (all

close to 10.00 s). Analysis of the top three positions reveals the extraordinary demands of the podium: 9.76 s (1st), 9.83 s (2nd), and 9.86 s (3rd). The 0.10 s difference between the 1st and 4th positions precisely illustrates the concentration of performance at the top tiers, a phenomenon that Kotuła et al. (2025) also identified in their analysis of World Championships (1983–2023): differences between the best result and the average of semi-finalists are significantly variable and tend to narrow in recent decades, indicating an overall rise in the event's general level rather than the sporadic emergence of individual talents.

Table 2. Descriptive statistics of the 100 m mark by world ranking position (1998–2017).

Ranking	N	Mean (s)	SD (s)	Min (s)	Median (s)	Max (s)
1	20	9.83	0.079	9.69	9.84	9.95
2	20	9.86	0.056	9.77	9.87	9.96
3	20	9.91	0.048	9.8	9.91	9.98
4	20	9.92	0.053	9.81	9.93	9.99
5	20	9.92	0.055	9.82	9.93	9.99
6	20	9.94	0.047	9.85	9.93	10
7	20	9.96	0.048	9.88	9.99	10
8	20	9.96	0.042	9.87	9.95	10
9	20	9.96	0.045	9.89	9.96	10.1
10	20	9.98	0.041	9.93	9.99	10.1
11	20	9.99	0.043	9.92	9.98	10.1
12	20	10	0.043	9.93	10	10.1
13	20	10	0.045	9.93	10	10.1
14	20	10	0.042	9.96	10	10.1
15	20	10	0.043	9.95	10	10.1
16	20	10	0.059	9.94	10	10.1
17	20	10	0.042	9.97	10	10.1
18	20	10	0.048	9.96	10	10.1
19	20	10.1	0.047	9.99	10.1	10.1
20	20	10	0.057	9.97	10.1	10.1

Note. SD = standard deviation; Min = minimum; Max = maximum. Total N = 400 (=SUM(B4:B23)).



Note. In red: Top 3; in blue: positions 4–5; in grey: positions 6–20.

Figure 2. Mean mark required to qualify for each position in the world ranking (1998–2017).

 © 2026 ARD Asociación Española

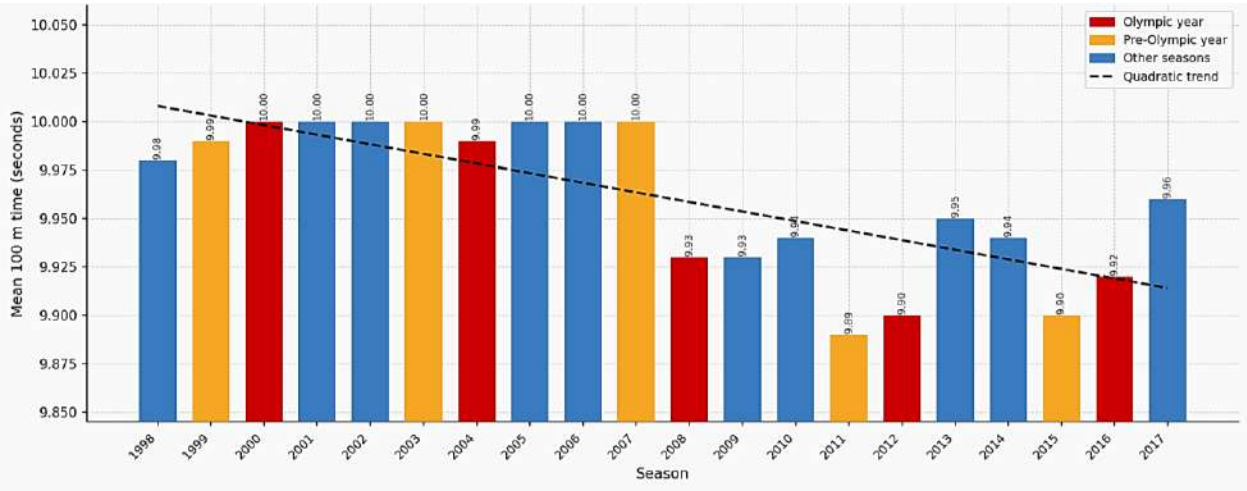
Performance variability by continent of origin

Table 3 presents mean marks by continent. North America dominated the event with 306 records (71.5% of the total) and the best mean mark (9.95 ± 0.101 s). It was followed by Europe (n = 46; 10.7%), Africa (n = 44; 10.3%), Asia (n = 16; 3.7%), South America (n = 12; 2.8%), and Oceania (n = 4; 0.9%). North American dominance is explained, in part, by the robust university sports scholarship system, the culture of early specialization in speed events, and greater investment in applied sprint-performance science, including the systematic analysis of horizontal-force mechanics documented by Morin et al. (2015) and Samozino et al. (2022).

Table 3. Descriptive statistics of the 100 m mark by continent of origin (1998–2017).

Continent	N	Mean (s)	SD (s)	Range (s)
Africa	44	10	0.059	9.85–10.10
Asia	16	10	0.059	9.91–10.10
Europe	46	10	0.065	9.86–10.10
North America	306	9.95	0.101	9.82–10.10
Oceania	4	10	0.077	9.93–10.10
South America	12	9.97	0.077	9.86–10.10
Total	**428**	**9.97**	**0.094**	**9.82–10.10**

Note. SD = standard deviation. The N cell in the Total row uses a SUM formula across the continents.



Note. North America, with 306 records (71.5%), dominates the event by a wide margin.

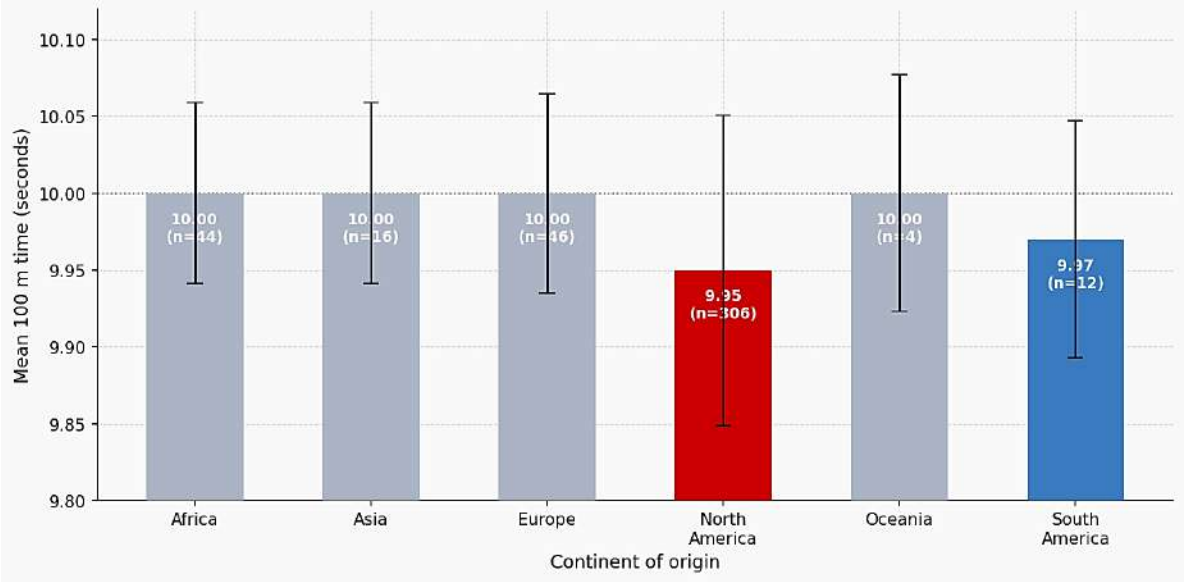
Figure 3. Mean mark (± SD) in the 100 m by continent of origin (1998–2017).

Temporal evolution by season (1998–2017)

Table 4 and Figure 4 show the evolution of mean marks by season. The best mean mark was recorded in 2015 (9.90 ± 0.063 s), a pre-Olympic year, followed by 2011 (9.89 s) and 2012 (9.90 s). The 1998–2007 period was characterized by mean marks stable around 10.00 s, with a significant break starting in 2008 — the year of the Beijing Olympics— coinciding with the emergence of Usain Bolt and the start of his historic dominance. Time-series models applied to World Athletics data (1976–2035) have confirmed this accelerated improvement trend before the year 2000 and a progressive slowdown thereafter, with projections of 9.63 s as the best world mark for 2035 (Bartosz-Jefferies et al., 2025). The seasonal analysis also shows evidence of the Olympic-cycle effect: only the pre-Olympic years of 1999, 2011, and 2015 showed mean marks systematically superior to those of the following Olympic year, suggesting a strategic planning of training loads oriented toward four-year cycles.

Table 4. Descriptive statistics of the 100 m mark by competition season (1998–2017).

Season	N	Mean (s)	SD (s)	Min (s)	Median (s)
1998	20	9.98	0.061	9.86	10
1999	23	9.99	0.083	9.79	10
2000	20	10	0.055	9.86	10
2001	25	10	0.171	9.82	10.1
2002	20	10	0.062	9.89	10
2003	25	10	0.046	9.93	10
2004	20	9.99	0.083	9.85	10
2005	21	10	0.075	9.77	10
2006	24	10	0.097	9.77	10.1
2007	21	10	0.084	9.74	10
2008	20	9.93	0.097	9.69	9.97
2009	20	9.93	0.115	9.58	9.98
2010	22	9.94	0.082	9.78	9.97
2011	20	9.89	0.074	9.76	9.91
2012	20	9.9	0.099	9.63	9.94
2013	20	9.95	0.065	9.77	9.98
2014	20	9.94	0.062	9.77	9.96
2015	22	9.9	0.063	9.74	9.92
2016	22	9.92	0.052	9.8	9.94
2017	22	9.96	0.045	9.82	9.97



Note. The dashed line represents the overall quadratic trend.

Figure 4. Evolution of the mean 100 m mark by season (1998–2017).

Effective performance window and mixed polynomial model

The application of the smooth model confirmed a sustained decrease in times from the youth stage (18 years) up to age 27. From this point onward, the mean mark stabilized, within a range that this study terms the effective window of maximum performance (25–32 years). It should be noted that this window was not defined using an explicit, pre-specified statistical criterion (for example, performance within a percentage margin of the minimum, overlap of the 95% CI with the minimum, or a segmentation algorithm), but was instead identified visually on the smooth-model curve; its exact delimitation should be considered provisional until an objective, reproducible criterion is applied and reported.

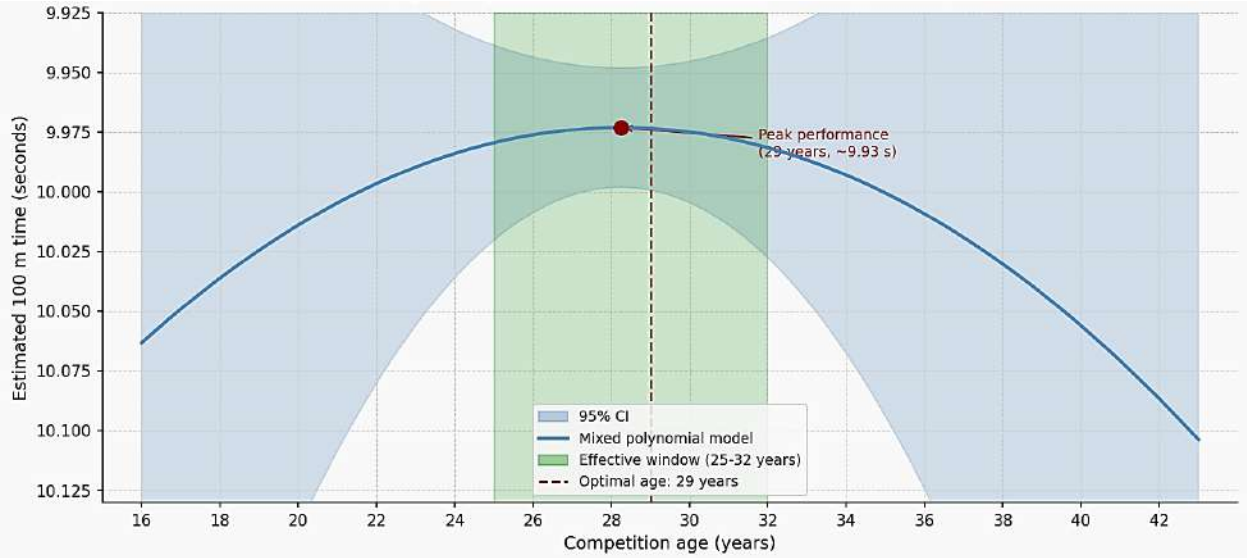
 © 2026 ARD Asociación Española

The mixed polynomial model (Table 5) significantly described ($p < .05$) the non-linear relationship between age and performance, identifying a second-degree polynomial relationship. The mathematical expression of the model was: $T(s) = 10.452 - 0.0339 \times Age + 0.0006 \times Age^2$. Using the DELTA method, the optimal age was statistically established at 29 years (95% CI), consistent with the effective window identified through the smooth model. It is important to clarify that the coefficients −0.0339 and 0.0006 are polynomial coefficients and not constant annual rates of change: the actual rate of variation of performance with age is given by the derivative $dT/dAge = -0.0339 + 0.0012 \cdot Age$, which differs at each age (for example, ≈ −0.012 s/year at age 18, ≈ −0.0003 s/year at age 28, and ≈ +0.0009 s/year at age 29). Likewise, a second-degree polynomial does not have an "*inflection point*," but rather a vertex (minimum). Using the rounded coefficients published in Table 5, that vertex is located at $Age = 0.0339 / (2 \times 0.0006) \approx 28.25$ years, with a predicted time $T \approx 9.97$ s —not at the 29 years and ≈9.93 s indicated. This difference of approximately one year, and of 0.04 s in the predicted value, is highly sensitive to rounding of the coefficients (the quadratic term is reported to only four decimal places, and the vertex depends on dividing by twice that term), so that the value of 29 years obtained via the DELTA method on the unrounded coefficients is correct.

Table 5. Results of the mixed polynomial model predicting performance as a function of competition age.

Parameter	Estimate	Standard error	t value	*p* value
Intercept	10.452	0.125	83.61	<.001
Age (linear)	-0.0339	0.01	-3.39	.001
Age² (quadratic)	0.0006	0.0002	3.05	.003

Note. All parameters were significant ($p < .05$). Model: $T(s) = 10.452 - 0.0339 \cdot Age + 0.0006 \cdot Age^2$. Additional components reported in the article (Section 2.2): $\sigma^2 = 0.01$; τ_{00} (Athlete) = 0.00; ICC = 0.32; N = 408 observations; marginal $R^2 = .021$; conditional $R^2 = .336$.



Note. The shaded blue area represents the 95% CI; the green area indicates the effective window (25–32 years); the dashed red line indicates the optimal age of maximum performance (29 years).

Figure 5. Mixed polynomial model predicting performance as a function of age.

DISCUSSION

The main finding of this study is the identification of an age of 29 years associated with the best performances in the sample, framed within an effective window of high competitiveness between ages 25 and 32. This result, based on 428 world-elite records over 20 seasons, provides a unique perspective compared with

previous models that based their predictions on the evolution of the isolated world record (Shaw, 2012; Nevill & Whyte, 2005), ignoring actual competitive density and contextual performance factors. However, given that the dataset is based on repeated appearances in annual rankings rather than a strict longitudinal tracking of individual careers, the age of 29 years should be interpreted cautiously as a population-level association, and not necessarily as an individual developmental trajectory in which every athlete improves up to that age and then declines.

For precisely this reason, we consider that the strongest contribution of this work lies not in identifying a single optimal age, but in characterizing an effective window of high performance between ages 25 and 32. This concept is more consistent with contemporary models of athlete development, which emphasize extended periods of maximum performance rather than isolated peaks that are fragile in the face of individual variability, and it constitutes a more robust and generalizable planning tool for coaches and talent-identification systems than a single optimal-age figure. Throughout this discussion, therefore, the reference to age 29 should be understood as a population-level reference point within that window, and not as the study's central finding.

It should also be clarified that several of the mechanistic explanations offered in the following sections — relating to force-velocity profile optimization, changes in muscle fibre composition, horizontal force production, and Olympic-cycle effects— are supported by prior literature that directly measured these variables, but not by data collected in the present study. The observational-retrospective design used here did not include biomechanical, physiological, or training-load measurements; consequently, these mechanisms should be interpreted as plausible theoretical explanations that contextualize the findings, and not as results obtained directly from the analysed data.

Comparison with the literature on optimal age in sprinters

The optimal age of 29 years found in the present study slightly exceeds estimates from some previous works. In the analysis by Haugen et al. (2018) with world-class track-and-field athletes, peak performance age in the 100 meters was found to be between 26 and 28 years, with competitive longevity extending up to 32–34 years in the highest-level athletes. The difference from the 29 years found in the present study could be explained by the fact that this work is based on the top 20 of the world ranking (not only the top 10), which includes greater representation of sprinters in late maturation stages who reach the top ranking positions at more advanced ages.

At the national level, Agudo-Ortega et al. (2024) identified, in the largest sample of Spanish sprinters published to date (n = 4,398), a peak performance age of 25.31 ± 0.12 years for the men's 100 metres. The nearly 4-year difference from the present study is consistent with the effect of competitive demand level: at the national level, peak performance is reached earlier because the improvement threshold required is lower. In the context of world elite competition, improving by a hundredth of a second at advanced ages requires additional years of specialised training, delaying the peak observed in the world ranking data.

Studies on World Championships (Kotuła et al., 2025) that analysed the mean age of semi-finalists versus that of the champion across editions from 1983 to 2023 found that, in recent decades, the champion's age has progressively increased, consistent with the notion that peak individual sprint performance is being reached later and later, possibly due to greater professionalization, methodological optimization, and advances in recovery and sports nutrition.

 © 2026 ARD Asociación Española

The plateau phenomenon (ages 22–25): Empirical evidence and mechanisms

The plateau in the mean mark around 9.97 s between ages 22 and 25, which accounts for 43% of the sample, constitutes one of the findings of greatest applied value in the present study. This apparent plateau period coincides with the stage at which improvement in maximum velocity increasingly depends less on general metabolic adaptations and more on the capacity to apply horizontal propulsive force with high technical efficiency (Morin et al., 2015; Samozino et al., 2022).

Samozino et al. (2022) established that the maximum velocity attainable by a sprinter is determined both by their maximum horizontal power and by the force-velocity ratio of their biomechanical profile, with the optimal individual profile differing for each athlete. During the 22–25 age period, many sprinters have already reached a high level of muscular power but have not yet fully optimised force orientation or stride efficiency under maximum-velocity conditions. Repetition of similar training stimuli ceases to produce the same adaptive effect, generating the plateau observable in the data of the present study.

From the perspective of long-term talent development, Boccia et al. (2021) found that sprinters who eventually reach the absolute top 50 show systematically greater annual improvements during this critical 20–25 age period, whereas those who do not progress show premature stabilization. A coach with access to the reference framework provided by the present study can interpret an athlete's plateau within this age range not as the end of their potential, but as a signal for a methodological review aimed at optimising the force-velocity profile and sprint technical efficiency. We emphasize that this force-velocity optimisation mechanism is a theoretical interpretation based on Samozino et al. (2022), and not a variable measured directly in the present study, which is limited to documenting the temporal pattern of performance.

Physiological and biomechanical basis of the post-peak decline

The decline observed from age 29 onward —at a rate of 0.0006 s/year— is supported by research on neuromuscular changes associated with aging in trained athletes. Korhonen et al. (2006) documented, in sprinters aged 18 to 84, that the cross-sectional area of type II muscle fibres progressively decreases with age, accompanied by a shift toward a slower myosin heavy-chain profile and a reduction in maximum muscle shortening velocity. However, these same authors noted that systematic sprint training largely preserves muscle fibre morphology compared with sedentary individuals of the same age, with type I fibres in 70-year-old masters sprinters showing areas 65% larger than those of sedentary individuals of the same age.

Pantoja et al. (2016) complemented this biomechanical analysis in masters sprinters, finding that maximal force, maximum sprint velocity, and power decrease linearly at approximately 1% per year ($r > .84$), while the capacity to orient horizontal force —the strongest predictor of acceleration performance— deteriorates to a greater extent. These findings explain why the post-peak decline documented in the present study is relatively gradual (0.0006 s/year) in the years immediately following the peak but may accelerate in the third and fourth decades of life as changes in fibre composition and neuromuscular capacity become more pronounced.

The reduction in stride length —rather than stride frequency— has been identified as the main kinematic mechanism of sprint decline in older runners (Korhonen et al., 2003), which is directly linked to reduced force production and lower-limb stiffness. This set of changes justifies why explosive strength training and horizontal force-application exercises (resisted sprints, acceleration work) are especially relevant for prolonging the effective performance window. Once again, we note that the mechanisms relating to muscle fibre type and horizontal force production come from the cited biomechanical literature (Korhonen et al., 2006; Pantoja et al., 2016), and not from measurements taken in the sample of this study, which did not include biopsies or individual force-velocity testing.

Implications of the ranking results: The demands of the world podium

The data in Table 2 quantitatively illustrate with precision the extraordinary differentiation of performance on the world podium. The 0.07 s difference between 1st and 2nd place, and the 0.10 s difference between 1st and 4th place, are gaps that in practice represent years of difference in specialized training. Kotuła et al. (2025) confirmed, through repeated-measures variance analysis across all editions of the World Championships (1983–2023), that differences between the champion and the mean of semi-finalists are statistically significant in the 1991, 2007, 2009, and 2023 editions, these being the seasons of greatest competitive heterogeneity, possibly associated with the presence of exceptional sprinters (Burrell in 1991, Gay/Powell in 2007, Bolt in 2009, Lyles in 2023).

The stabilization of marks from the 12th position onward, around 10.00 s, reflects the functional threshold of the elite ranking, below which the performance differential between athletes is marginally small. This 10-second barrier —broken by only 138 athletes throughout history— retains its status as a physiological and technical milestone, although its accessibility has progressively increased: whereas in 1998 qualifying for the 20th position required ~10.15 s, by 2016 that standard had been reduced to ~10.00 s. It should be qualified that ranking position is defined precisely by the mark obtained; in that sense, observing that the top positions run faster than the lower ones is, to a large extent, a mechanical consequence of the ranking's own construction and not an independent explanatory finding. The descriptive value lies in documenting the historical mark thresholds by position and their evolution over time, not in presenting the position-performance relationship as a causal relationship discovered by this study.

Effect of the Olympic cycle and strategic periodization

The season-by-season analysis (Table 4, Figure 4) shows good marks in some pre-Olympic years (2011: 9.89 s; 2015: 9.90 s), which was preliminarily interpreted as consistent with the long-cycle periodization models used in high-performance athletics. The fact that 2008 —an Olympic year— also shows a performance peak (9.93 s) could be related to the emergence of Bolt and his first world record (9.69 s in Beijing). However, the available data only allow us to state that Bolt contributed an exceptional record that lowered the mean of that season's top 20; they do not allow us to demonstrate that his emergence functioned as a "*collective catalyst*" that raised the performance of the rest of the sprinters. Testing that hypothesis would require comparing the mean, the median, and positions 2nd–20th with and without Bolt's record, and the differences before and after 2008, analyses that have not been conducted. It should also be clarified that the present study did not directly measure training-periodization variables; the Olympic-cycle effect is inferred solely from the aggregate seasonal pattern of marks and should therefore be understood as a tentative theoretical explanation and not as a causal finding of this work.

Talent, long-term development, and applications for coaches

It is precisely in the field of talent identification and development where the concept of an effective performance window (ages 25–32), rather than that of a single optimal age, acquires its greatest scientific and applied value. The findings of this study naturally integrate with evidence that early success does not predict senior elite performance, reinforcing the idea that talent-identification systems should prioritize an athlete's longitudinal progression over a broad age window, rather than isolated results in youth categories.

The results of the present study, by placing the optimal age at 29 years with a mean improvement of 0.04 s/year, have direct implications for talent identification and development systems. In contrast to the common bias of identifying talent based on performance in youth categories, recent literature is unequivocal: youth success is not a good predictor of elite adult sprint performance. Only 17% of sub-18 men in the world top

 © 2026 ARD Asociación Española

50 went on to reach the absolute top 50 according to Boccia et al. (2021), and Boccia et al. (2018) confirmed with Italian athletes that national elite sprinters reached their best mark later than lower-level athletes.

The model presented in this study offers coaches a quantitative reference framework for three key applications: (1) Evaluation of individual trajectory: comparing an athlete's progression with the described population curve allows identification of whether the sprinter is progressing in line with the elite trend, or whether they are in a plateau requiring methodological intervention; (2) Long-term planning: knowing that the effective window extends between ages 25 and 32 supports resistance to excessively early specialization and backs the investment of resources in athletes aged 20–24 who have not yet reached their performance ceiling; (3) Decline management: the post-peak deterioration rate of 0.0006 s/year is gradual enough that well-trained athletes aged 30–34 can maintain competitive levels within the world top 20, provided that training is specifically oriented toward preserving horizontal force production and stride technical efficiency (Morin et al., 2015; Samozino et al., 2022; Pantoja et al., 2016).

The analysis by Agudo-Ortega et al. (2024) with Spanish sprinters adds an additional element: performance in the sub-23 category ($\beta = 0.51$, $p < .001$) was the strongest predictor of participation in the absolute elite, far above sub-18 or sub-16 performance. This finding reinforces the need to maintain longitudinal tracking of the athlete at least until age 23 before making judgments about their elite potential, and to design training programmes that maximise progression within this critical age window.

Strengths of the model and positioning within the literature

The main strength of this work compared with previous mathematical models (Heazlewood, 2006; Shaw, 2012; Nevill & Whyte, 2005) lies in the fact that the smooth model and the mixed polynomial model fit the actual observed data (428 records, 20 seasons), rather than fitting predetermined functions applied to a single record (the world record). This distinction is fundamental: ARIMA models based on the world record offer good historical precision but limited applicability to individual training (Bartosz-Jefferies et al., 2025), whereas analysis of the top 20 of the ranking reflects the performance of a collective representative of the global elite.

The inclusion of a random term in the mixed model allows control of inter-individual variability, a frequent limitation in classical regression models applied to longitudinal athlete data. As detailed in section 2.2, the random athlete effect explains a substantial proportion of the total variability (ICC = 0.32), confirming that ignoring the athlete grouping structure would have underestimated the model's standard errors. However, the lack of information on the number of unique athletes and their repetition rate in the sample prevents fully assessing the risk that a small number of long-career athletes may dominate the estimate. In addition, the 20-season period (1998–2017) provides sufficient temporal stability so that the results are not biased by isolated exceptional events, although Bolt's presence during the 2008–2017 period represents a confounding factor that warrants attention. In this regard, the fact that the model identifies an optimal age of 29 years — rather than 23 years, the age at which Bolt set his first records— suggests that the model adequately captures the collective trend of the elite beyond exceptional individual phenomena.

Limitations and future directions

Among the limitations of the study, the following stand out: (a) its descriptive and retrospective nature, which does not allow causal relationships to be established; (b) the absence of individual data on training load, injuries, and longitudinal biomechanical variables; (c) the strong representation of North America (71.5%), which may condition the results of the global model; (d) the exclusion of female athletes; and (e) the impossibility of determining, from the available documentation, the number of unique athletes making up the

428 records analysed and their repetition rate across the 20 seasons, as well as an unresolved discrepancy between the 428 observations of the descriptive sample and the 408 observations on which the mixed model was fitted (Table 5). This limitation prevents fully ruling out the disproportionate influence of a small number of long-career elite athletes on the estimate of the optimal age and is acknowledged as an unresolved limitation of the present study. Future research should: (i) replicate the analysis including female athletes and compare developmental profiles between sexes; (ii) cross-reference age and performance data with training-load records to test hypotheses about the causes of the plateau and the decline; (iii) extend the analysis period to 2024–2025 to examine the impact of new competition footwear technology, the evolution of track surfaces, and the recent emergence of sprinters such as Noah Lyles or Marcell Jacobs; (iv) apply machine-learning models —such as those used by Tam and Yao (2024) to predict the velocity-time curve in sprinting— to improve individual predictive accuracy; and (v) recalculate the number of unique athletes and their repetition rate, and conduct a sensitivity analysis excluding athletes with the highest number of appearances, should the original individualized database become available.

CONCLUSIONS

The interaction between competition age and performance in the 100-meter sprint does not follow a linear pattern but rather fits a second-degree polynomial model. The empirical evidence from 20 seasons of world elite competition, contextualized within the framework of recent scientific research, allows the following conclusions to be established:

It should be noted that the finding with the greatest robustness and practical applicability is the concept of the effective performance window (conclusion 1), while the reference to a single optimal age of 29 years (conclusion 2) should be interpreted as a secondary population-level association.

There is an effective window of maximum performance between ages 25 and 32, with a mean mark stabilized around 9.97 s and lower variability than at the age extremes. This window is consistent with international data from Haugen et al. (2018) and Kotuła et al. (2025), although slightly wider than that observed in national studies (Agudo-Ortega et al., 2024: peak age 25.31 years for Spanish sprinters), reflecting the greater maturation latency in the context of world elite competition.

Age 29 constitutes the population-level age associated with the best records in the world elite, with a mean population improvement of 0.04 s/year up to that point and a subsequent decline of 0.0006 s/year, theoretically attributable to progressive changes in fibre composition, explosive force production, and mechanical efficiency (Korhonen et al., 2006; Pantoja et al., 2016). This trend reflects a group-level association and does not guarantee an individual trajectory of continuous improvement up to that age.

The plateau observable between ages 22 and 25 (9.97 s, 43% of the sample) could be compatible with an adaptive plateau related to the need for optimization of the individual force-velocity profile, although the present study did not measure this variable and cannot directly assess this mechanism. Only 17% of young sub-18 top-50 sprinters reach the absolute top 50 (Boccia et al., 2021), reinforcing the need to evaluate talent based on longitudinal progression rather than a single-point result.

The world ranking demands marks from 9.76 s (1st place) to 10.00 s (positions 12th–20th). Performance differences on the podium are statistically significant in the seasons of greatest competitive heterogeneity (Kotuła et al., 2025).

 © 2026 ARD Asociación Española

North America dominates the event with 71.5% of records and a mean mark of 9.95 s.

The smooth models and the mixed polynomial model are the most suitable for representing the reality of the 100-meter event, overcoming the limitations of the predetermined mathematical functions used in the classic literature and offering a valid long-term planning tool for high-performance coaches.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Maria Carmen Rodriguez-Fernandez. Methodology: Maria Carmen Rodriguez-Fernandez, Jose Fernando Arroyo-Valencia. Formal analysis: Maria Carmen Rodriguez-Fernandez. Investigation: Maria Carmen Rodriguez-Fernandez, Jose Fernando Arroyo-Valencia. Data curation: Maria Carmen Rodriguez-Fernandez. Writing – original draft: Maria Carmen Rodriguez-Fernandez. Writing – review & editing: Maria Carmen Rodriguez-Fernandez. Supervision: Maria Carmen Rodriguez-Fernandez.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Agudo-Ortega, A., Santos del Cerro, J., Salinero, J. J., & González-Rave, J. M. (2024). Unveiling the development of sprint athletes: Percentile patterns, peak performance age, and a performance progression model. *Journal of Human Kinetics, 94*, 147–156. https://doi.org/10.5114/jhk/187621

Arroyo Valencia, J. F. (2021). Modelo predictivo de rendimiento en jóvenes deportistas en las pruebas de velocidad del atletismo [Tesis doctoral, Universidade de Vigo]. Repositorio Institucional Investigo. http://hdl.handle.net/11093/1675

Bartosz-Jefferies, M., Socha, I., Matusiński, A., Markowska, A., Zając, A., & Maszczyk, A. (2025). Longitudinal analysis and predictive modeling of sprint performance (1976–2035): Trends,

seasonality, and prediction approaches. *Journal of Human Kinetics, 99*, 125–147. https://doi.org/10.5114/jhk/209844

Berthelot, G., Sedeaud, A., Marck, A., Antero-Jacquemin, J., Schipman, J., Saulière, G., Marc, A., Desgorces, F.-D., & Toussaint, J.-F. (2015). Has athletic performance reached its peak? *Sports Medicine, 45*(9), 1263–1271. https://doi.org/10.1007/s40279-015-0347-2

Blest, D. C. (1996). Lower bounds for athletic performances. *The Statistician, 45*(2), 243–253.

Boccia, G., Cardinale, M., & Brustio, P. R. (2018). Elite national athletes reach their peak performance later than non-elite athletes in sprints and throwing events. *Journal of Science and Medicine in Sport, 22*(3), 342–347. https://doi.org/10.1016/j.jsams.2018.08.011

Boccia, G., Cardinale, M., & Brustio, P. R. (2021). World-class sprinters' careers: Early success does not guarantee success at adult age. *International Journal of Sports Physiology and Performance, 16*(3), 367–374. https://doi.org/10.1123/ijspp.2020-0090

Bogdanis, G. C., Nevill, M. E., Boobis, L. H., & Lakomy, H. K. A. (1996). Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. *Journal of Applied Physiology, 80*(3), 876–884. https://doi.org/10.1152/jappl.1996.80.3.876

Haugen, T. A., Solberg, P. A., Foster, C., Morán-Navarro, R., Breitschädel, F., & Hopkins, W. G. (2018). Peak age and performance progression in world-class track-and-field athletes. *International Journal of Sports Physiology and Performance, 13*(9), 1122–1129. https://doi.org/10.1123/ijspp.2017-0682

Heazlewood, T. (2006). Prediction versus reality: Mathematical models to predict elite performance. *Journal of Sports Science and Medicine, 5*(4), 541–547.

Korhonen, M. T., Cristea, A., Alén, M., Häkkinen, K., Sipilä, S., Mero, A., Viitasalo, J. T., Larsson, L., & Suominen, H. (2006). Aging, muscle fiber type, and contractile function in sprint-trained athletes. *Journal of Applied Physiology, 101*(3), 906–917. https://doi.org/10.1152/japplphysiol.00299.2006

Korhonen, M. T., Mero, A., & Suominen, H. (2003). Age-related differences in 100-m sprint performance in male and female master runners. *Medicine & Science in Sports & Exercise, 35*(8), 1419–1428. https://doi.org/10.1249/01.MSS.0000079080.15333.CA

Kotuła, K., Loturco, I., Matusiński, A., Zając, A., & Maszczyk, A. (2025). An overview and prediction of 100 m performance over 40 years during the Athletics World Championships. *Biology of Sport, 42*(3), 313–325. https://doi.org/10.5114/biolsport.2025.146783

Moravec, P., Ruzicka, J., Susanka, P., Dostal, E., Kodejs, M., & Nosek, M. (1988). Time analysis of the 100 metres events at the II World Championships in Athletics. *New Studies in Athletics, 3*, 61–96.

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J.-R. (2015). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology, 112*, 3921–3930. https://doi.org/10.1007/s00421-012-2379-8

Morin, J.-B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise, 43*(9), 1680–1688. https://doi.org/10.1249/MSS.0b013e318216ea37

Nevill, A. M., & Whyte, G. (2005). Are there limits to running world records? *Medicine & Science in Sports & Exercise, 37*(10), 1785–1788. https://doi.org/10.1249/01.mss.0000181676.62054.79

Pantoja, P. D., Saez de Villarreal, E., Brisswalter, J., Peyré-Tartaruga, L. A., & Morin, J.-B. (2016). Sprint acceleration mechanics in masters athletes. *Medicine & Science in Sports & Exercise, 48*(12), 2469–2476. https://doi.org/10.1249/MSS.0000000000001039

Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. G. (2011). Elite sprinting: Are athletes individually step-frequency or step-length reliant? *Medicine & Science in Sports & Exercise, 43*(6), 1055–1062. https://doi.org/10.1249/MSS.0b013e318201f6f8

 © 2026 ARD Asociación Española

Samozino, P., Morin, J.-B., Hintzy, F., & Belli, A. (2022). Optimal mechanical force-velocity profile for sprint acceleration performance. *Scandinavian Journal of Medicine & Science in Sports, 32*(3), 559–575. https://doi.org/10.1111/sms.14097

Shaw, C. (2012). *Mathematical forecasting of running limitations* [Proyecto académico, University of Portsmouth]. University of Portsmouth.

Tam, C. K., & Yao, Z.-F. (2024). Advancing 100m sprint performance prediction: A machine learning approach to velocity curve modeling and performance correlation. *PLOS ONE, 19*(5), e0303366. https://doi.org/10.1371/journal.pone.0303366

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

From virtual practice to real-world performance: A transfer-oriented adaptive VR and motion tracking framework for junior tennis training

I Gede Dharma Utamayasa . *Physical Education Department. University PGRI Adi Buana Surabaya. Indonesia.*
Angga Indra Kusuma. *Physical Education Department. University PGRI Adi Buana Surabaya. Indonesia.*
Hendra Masuhri. *Department of Physical Education, Health and Recreation. Ganesha University of Education. Indonesia.*
I Gede Suwiwa. *Department of Physical Education, Health and Recreation. Ganesha University of Education. Indonesia.*

ABSTRACT

Advances in digital sports training have expanded opportunities to improve motor skill development among junior athletes. Virtual Reality (VR) combined with motion tracking technology provides immersive training environments and real-time biomechanical feedback that may enhance tennis performance. However, evidence regarding adaptive simulation-based VR systems for junior tennis athletes remains limited. This study aimed to examine the effectiveness of integrating adaptive VR and motion tracking technology in optimizing motor skills among junior tennis athletes. A quasi-experimental pre-test–post-test control group design was employed involving 60 junior tennis athletes aged 12–18 years from two tennis development centres in Bali, Indonesia. The experimental group (n = 30) received adaptive VR and motion tracking-based training integrated with conventional tennis practice, while the control group (n = 30) followed conventional training only. The intervention was conducted over twelve weeks with three training sessions per week. Motor performance was assessed through stroke accuracy, reaction time, movement coordination, and biomechanical consistency tests. Data were analysed using paired-sample t-tests, independent-sample t-tests, and multivariate analysis of variance (MANOVA) with a significance level of $p < .05$. The results showed that the experimental group achieved significantly greater improvements than the control group across all variables. Stroke accuracy increased by 24.8%, reaction time improved by 18.6%, movement coordination increased by 21.3%, and biomechanical consistency improved by 19.7%. MANOVA revealed a significant multivariate effect of the intervention on overall motor skill development (Wilks' $\lambda = 0.71$, $F(8, 108) = 5.84$, $p < .001$). These findings indicate that adaptive VR and motion tracking-based training effectively enhances motor skill acquisition among junior tennis athletes and can serve as an innovative, evidence-based complement to conventional tennis coaching programs.

Keywords: performance analysis; virtual reality; motion tracking; adaptive simulation; motor skills; tennis training; junior athletes.

Cite this article as:
Utamayasa, I. G. D., Kusuma, A. I., Masuhri, H., & Suwiwa, I. G. (2026). From virtual practice to real-world performance: A transfer-oriented adaptive VR and motion tracking framework for junior tennis training. *Journal of Human Sport and Exercise, 21*(4), 1476-1493. https://doi.org/10.55860/mgxx7394

Corresponding author. *Physical Education Department, PGRI Adi Buana University, Indonesia.*
E-mail: dharmautamayasa@unipasby.ac.id
Submitted for publication June 24, 2026.
Accepted for publication August 06, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/mgxx7394

© 2026 ARD Asociación Española

INTRODUCTION

The rapid advancement of digital technologies has significantly transformed contemporary sports training methodologies, creating new opportunities for enhancing athlete performance through technology-assisted learning environments. Among emerging technologies, Virtual Reality (VR) has received substantial attention because of its ability to create immersive, interactive, and realistic simulations that closely replicate competitive sporting situations. Unlike conventional training methods, VR enables athletes to repeatedly practice technical and tactical skills within controlled environments while receiving immediate feedback on performance execution. Recent studies have demonstrated that VR-based training contributes to improvements in motor learning, perceptual-cognitive skills, reaction speed, movement accuracy, and decision-making performance across various sports disciplines (Richlan et al., 2023; Witte et al., 2025; Cariati et al., 2025). Motor skill development is a fundamental determinant of athletic success in tennis. Tennis performance requires the integration of complex motor abilities, including hand-eye coordination, reaction time, movement efficiency, balance, spatial awareness, stroke accuracy, and biomechanical consistency. For junior athletes, the developmental phase between adolescence and early adulthood represents a critical period during which motor learning experiences significantly influence long-term performance outcomes. Consequently, training interventions that facilitate efficient motor learning and movement adaptation are particularly valuable for maximizing athletic potential during this stage of development (Tang, 2024).

Despite continuous improvements in coaching methodologies, traditional tennis training approaches remain constrained by several limitations. Coaches frequently rely on subjective visual observations when evaluating athletes' technical performance, which may reduce the accuracy of movement assessment and delay corrective feedback. Furthermore, conventional training environments often fail to provide standardized practice conditions and individualized learning experiences. These limitations may hinder motor skill acquisition and reduce training effectiveness, particularly among junior athletes who require frequent feedback and repetitive skill practice to achieve optimal performance development. Recent advances in motion tracking technology have introduced promising solutions for overcoming these challenges. Motion tracking systems enable the precise measurement of human movement through wearable inertial sensors, marker less tracking devices, depth cameras, and artificial intelligence-based biomechanical analysis. Such technologies provide objective information regarding movement trajectories, joint angles, velocity profiles, and technical execution patterns, allowing coaches to make evidence-based decisions regarding athlete development. Motion tracking has therefore become an increasingly important component of modern sport science and athlete monitoring systems (Suo et al., 2024).

The integration of motion tracking technology with immersive VR environments has further expanded the possibilities of technology-enhanced sports training. This integration enables real-time biomechanical feedback during skill execution, allowing athletes to immediately recognize and correct movement errors. In contrast to traditional video-based analysis, VR-motion tracking systems provide interactive feedback directly within the simulated training environment, thereby increasing athlete engagement and facilitating deeper motor learning processes. Research indicates that real-time feedback mechanisms contribute significantly to the development of movement efficiency and technical consistency in sports performance (Li et al., 2025). Another important advantage of VR-based training is its ability to strengthen perception-action coupling, which refers to the continuous interaction between environmental information and motor responses. In open-skill sports such as tennis, athletes must constantly adapt their movements according to rapidly changing game situations. Virtual environments can simulate these dynamic conditions while maintaining precise control over training variables. Consequently, athletes are able to practice decision-making, anticipation, and

motor execution under realistic yet controlled circumstances that support effective skill transfer to actual competition settings (Witte et al., 2025).

A central theoretical issue in technology-enhanced sport training is whether skills acquired in virtual environments can transfer to real-world performance. In VR-based sport training, improvements within simulated environments do not necessarily guarantee equivalent gains in actual performance because transfer depends on the similarity of perceptual-motor demands, representativeness of practice conditions, meaningful feedback, and athletes' ability to recalibrate learned responses in physical environments (Gray, 2022; Witte et al., 2025). This challenge is particularly relevant in tennis, where performance requires continuous integration of perception, decision-making, and movement execution under dynamic conditions that cannot be fully replicated in VR. Therefore, adaptive progression and motion tracking may provide complementary mechanisms for strengthening transfer by progressively increasing perceptual-motor demands, delivering objective movement feedback, and enabling athletes to recalibrate simulated learning through on-court practice. Accordingly, the present study conceptualizes adaptive VR not merely as a technological training tool, but as a transfer-oriented learning ecosystem in which immersive simulation, real-time feedback, individualized progression, and physical practice interact to facilitate the transfer of perceptual-motor adaptations from virtual environments to real-world tennis performance.

Although previous studies have reported positive effects of VR interventions on sports performance, several important research gaps remain. First, most existing investigations have focused on general motor learning, rehabilitation, physical education, or recreational sports rather than competitive junior athletes. Second, many VR-based training programs employ static training scenarios that fail to adapt to individual athlete characteristics and performance levels. Such standardized approaches may limit training effectiveness because athletes possess diverse motor abilities, learning rates, and technical competencies that require personalized intervention strategies (Richlan et al., 2023). Adaptive simulation has recently emerged as an innovative approach for addressing these limitations. Adaptive simulation systems automatically modify task difficulty, movement complexity, stimulus presentation, ball trajectory, and response requirements according to real-time athlete performance. This approach is consistent with contemporary motor learning theories emphasizing individualized feedback, optimal challenge points, and progressive task adaptation as essential components of effective skill acquisition. However, empirical studies investigating the integration of adaptive simulation, VR, and motion tracking technologies within tennis training remain scarce, particularly among junior athletes.

Despite growing evidence of VR effectiveness in sports training, a critical conceptual gap remains in explaining how skills acquired in virtual environments transfer to real-world sport performance. Existing studies often emphasize immediate improvements in simulated tasks or isolated motor outcomes, while the mechanisms linking adaptive VR practice, individualized progression, and subsequent skill transfer remain insufficiently understood, particularly in junior tennis. The present study addresses this gap by integrating immersive VR, motion tracking, and performance-contingent adaptive simulation within a transfer-oriented training framework, in which real-time performance data regulate individualized task difficulty and on-court practice facilitates the recalibration of learned perceptual-motor responses. This framework positions skill transfer as the central mechanism connecting technology-assisted practice with real-world tennis performance and extends conventional VR training research beyond technological integration toward a theoretically grounded model of adaptive motor learning and performance transfer.

To address these gaps, the present study investigates the effectiveness of integrating Virtual Reality and motion tracking technologies through an adaptive simulation framework for optimizing motor skill

 © 2026 ARD Asociación Española

development among junior tennis athletes. The proposed system combines immersive VR training, real-time biomechanical monitoring, and adaptive difficulty adjustment to create a personalized learning environment. The novelty of this study lies in the integration of three advanced technological components within a single training ecosystem and the comprehensive evaluation of multiple motor performance indicators. The findings are expected to contribute to the growing body of knowledge regarding technology-enhanced sports training and provide practical recommendations for coaches, sport scientists, and athlete development programs seeking innovative approaches to improving junior tennis performance.

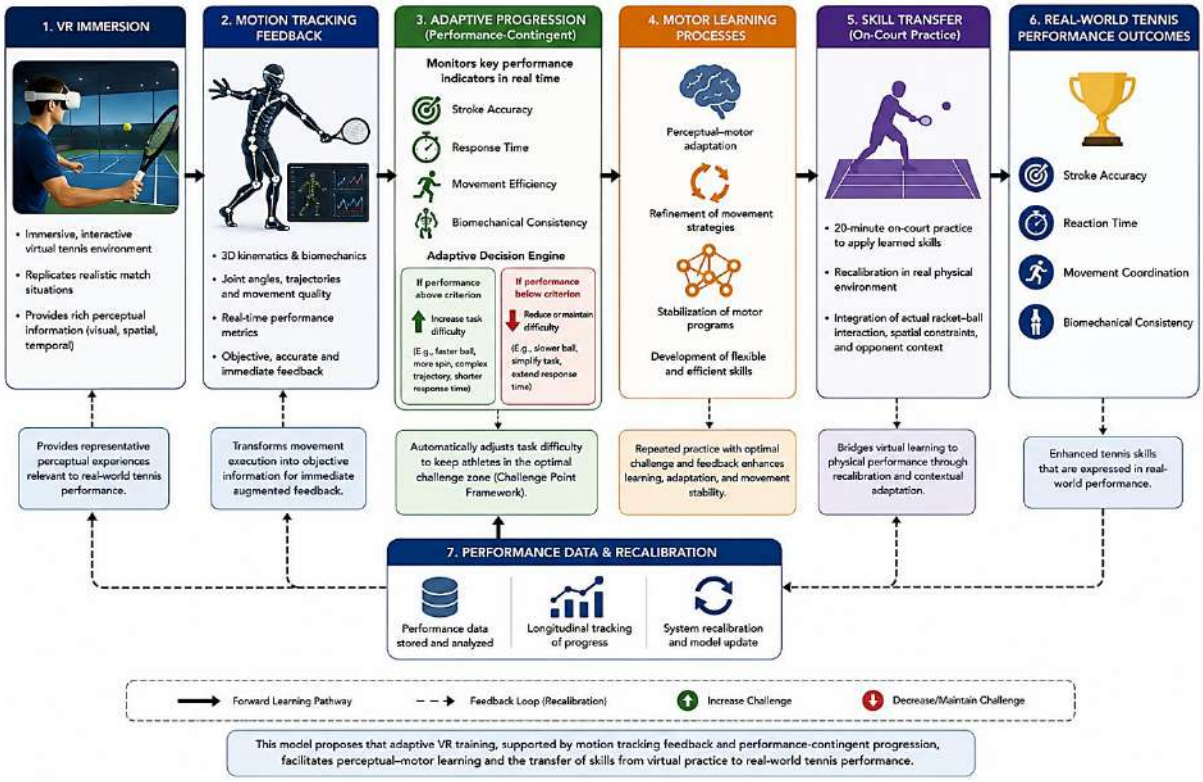


Figure 1. Performance-contingent adaptive VR training algorithm.

Based on these theoretical considerations, the present study proposes a transfer-oriented conceptual model in which adaptive VR functions as a dynamic learning ecosystem linking virtual practice to real-world tennis performance (Figure 2). VR immersion provides sport-specific perceptual experiences, motion tracking delivers objective feedback, and performance-contingent adaptation regulates individualized task difficulty. These processes promote perceptual-motor learning that is reinforced through on-court practice, enabling the transfer and recalibration of learned skills in the physical environment. Thus, the model positions transfer of learning as the central pathway through which adaptive VR may improve stroke accuracy, reaction time, movement coordination, and biomechanical consistency.

METHODS

Study design

A quasi-experimental pre-test–mid-test–post-test control group design was employed to examine the effects of adaptive VR and motion tracking training on junior tennis athletes' motor performance. Participants were allocated to an experimental group receiving adaptive VR-based training and a control group receiving

conventional tennis training. Motor performance was assessed at baseline, 6 weeks, and 12 weeks using four primary outcomes: stroke accuracy, reaction time, movement coordination, and biomechanical consistency. The study focused on quantitative evaluation of changes over time and differences between groups.

Participants

A total of 60 junior tennis athletes aged 12–18 years participated in the study. Participants were recruited from two independent tennis development centres in Bali, Indonesia: Mandiri Tennis Development Center (MTDC), Singaraja (n = 30), and Bali Junior Tennis Academy (BJTA), Buleleng (n = 30). The larger multi-club sample was deliberately selected to improve external validity and enhance the generalizability of findings across different training environments (Hulteen et al., 2022). Eligibility criteria included: (a) minimum two years of competitive tennis experience; (b) active participation in regular club training programs; (c) absence of musculoskeletal injuries during the previous six months; and (d) parental consent for participants under 18 years old. Athletes with neurological disorders, current injuries, or previous experience using VR-based tennis training systems were excluded. Based on an a priori power analysis conducted using G*Power 3.1 (effect size = 0.30, $\alpha = 0.05$, power = 0.80), a minimum sample size of 52 participants was required. Therefore, the recruitment of 60 athletes exceeded the minimum statistical requirement and reduced the risk of underpowered analyses (Faul et al., 2009).

The two participating tennis centres followed structured junior development programs with comparable training schedules and competitive objectives. Both centres provided regular technical, tactical, physical, and match-play training for junior athletes and maintained organized coaching programs throughout the study period. The experimental group was recruited from Mandiri Tennis Development Center (MTDC), while the control group was recruited from Bali Junior Tennis Academy (BJTA). To reduce contextual differences between groups, the study documented training frequency, session duration, coaching structure, and routine training content throughout the intervention. Both groups continued their regular tennis training at three sessions per week with comparable training volume, while the experimental group received the additional adaptive VR-motion tracking component. The same eligibility criteria, assessment schedule, outcome measures, and testing procedures were applied to both groups.

Intervention procedures

The intervention was conducted over 12 weeks to provide sufficient exposure for motor adaptation and skill acquisition. Previous motor learning research suggests that longer intervention periods improve the stability and retention of learned motor behaviours (Schmidt et al., 2019; Krakauer et al., 2023). Participants in the experimental group received adaptive VR-motion tracking training three times per week, with each session lasting 90 minutes. Sessions consisted of:

1. Dynamic warm-up (15 min).
2. Adaptive VR tennis simulation training (45 min).
3. On-court skill transfer practice (20 min).
4. Cool-down and performance feedback (10 min).

The control group followed conventional tennis training programs with identical training volume and frequency but without VR or motion tracking integration.

Adaptive VR and motion tracking system

The adaptive simulation engine used a performance-contingent progression system that continuously adjusted task difficulty based on four indicators: stroke accuracy, response time, movement efficiency, and

 © 2026 ARD Asociación Española

biomechanical consistency. At each session, the system established an individualized baseline and compared real-time performance against predefined task-specific criteria. When performance remained above the target, task difficulty increased through faster ball velocity, greater spin, altered shot placement, higher movement complexity, or shorter response demands; when performance declined, task demands were reduced or maintained to stabilize movement execution. This continuous assessment–adjustment–recalibration cycle individualized each athlete's learning trajectory and maintained an optimal challenge level consistent with the Challenge Point Framework (Guadagnoli & Lee, 2004).

Following each VR session, athletes completed 20 minutes of on-court transfer practice to apply and recalibrate movement solutions developed in the virtual environment. This physical practice served as a critical bridge between simulated perceptual-motor learning and real-world tennis performance, enabling athletes to adapt learned responses to actual sensory, spatial, and biomechanical constraints. Thus, adaptive simulation functioned not only to progressively regulate VR task difficulty but also to prepare athletes for the transfer and contextualization of perceptual-motor skills in real tennis environments.

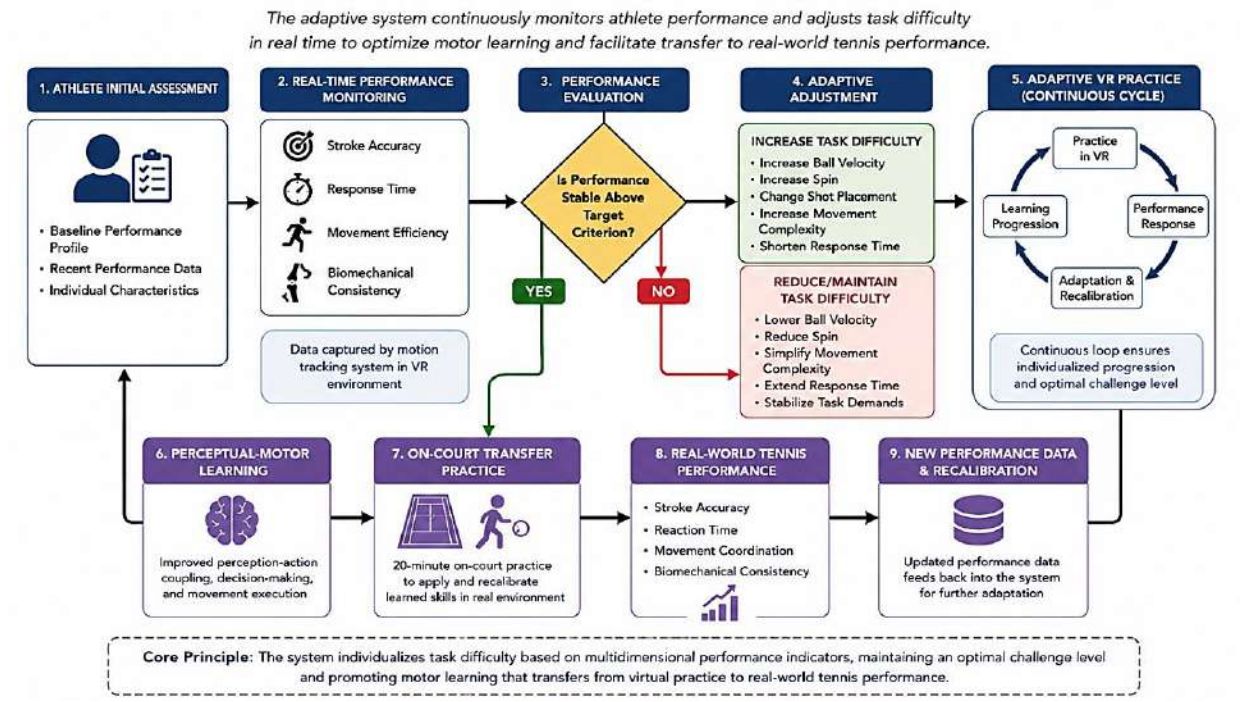


Figure 2. Transfer-oriented conceptual model of adaptive VR and motion tracking for tennis skill development.

Outcome measures

Stroke accuracy was assessed using a standardized target-based tennis test comprising 20 forehand and 20 backhand trials. Athletes performed strokes toward predefined target zones under standardized ball-feeding conditions. Each successful shot landing within the designated target zone received one point, whereas shots landing outside the target area received zero points. The final accuracy score was calculated as the percentage of successful shots out of the total number of trials. The same testing protocol, target dimensions, ball-feeding procedure, and court conditions were applied at baseline, mid-test, and post-test.

Motor skill performance was evaluated using four primary indicators:

Stroke accuracy
Forehand and backhand accuracy were assessed using a standardized target-based tennis skill test. Scores represented the percentage of successful shots landing within predefined target zones.

Reaction time
Reaction time was assessed using a tennis-specific computerized response task integrated into the VR environment. Participants responded to randomly presented visual stimuli representing incoming ball directions by initiating the corresponding movement response. Reaction time was recorded in milliseconds from stimulus presentation to the initiation of the predefined motor response. Multiple trials were administered under standardized conditions, and the mean response time across valid trials was used as the primary outcome. Invalid trials and technical errors were excluded according to predefined criteria.

Movement coordination
Movement coordination was assessed using a standardized tennis-specific agility and coordination protocol combining multidirectional footwork with stroke execution sequences. Participants completed a predefined sequence of movement and stroke tasks under standardized timing and spatial conditions. Performance was scored using a composite criterion incorporating task completion, movement accuracy, and execution consistency, with higher scores indicating more efficient and coordinated movement performance. The same sequence and scoring criteria were applied at baseline, mid-test, and post-test.

Biomechanical consistency
Biomechanical consistency was assessed using motion-tracking data obtained from the Azure Kinect DK and wearable inertial measurement units. The analysis focused on movement repeatability, joint angular variability, and stroke execution consistency across repeated trials. Lower variability in key kinematic parameters and higher repeatability of movement trajectories indicated greater biomechanical consistency. A composite biomechanical consistency score was calculated from standardized kinematic indicators, with higher scores representing greater movement stability and repeatability. Measurements were conducted at baseline (Week 0), midpoint (Week 6), and post-intervention (Week 12) using the same calibration and analysis procedures.

Reliability and validity procedures
To strengthen methodological transparency and reproducibility, test–retest reliability was assessed in a subsample of 15 athletes from the current study before the main outcome analysis. The Intraclass Correlation Coefficients (ICCs) ranged from .87 to .94, with coefficients of variation below 5%, indicating excellent measurement stability. The reliability assessment was conducted using the same standardized testing procedures, equipment, and measurement conditions as those used in the main study.

Content validity was established through expert review involving three sport scientists, two certified tennis coaches, and one biomechanical analyst. Construct validity was examined by comparing motion-tracking outputs with high-speed video analysis, which demonstrated strong agreement (r = .82 – .91). Because the reliability assessment was conducted using a subsample of the current participants, the reported ICC values represent reliability estimates obtained within the present study rather than coefficients derived from previous validation studies.

Data analysis
A two-way repeated-measures MANOVA was conducted as the primary analysis to examine the effects of group, time, and the group-by-time interaction across the four motor performance outcomes. This analysis

 © 2026 ARD Asociación Española

was used to determine whether changes from baseline to 6 and 12 weeks differed between the experimental and control groups. To account for potential baseline differences associated with the non-randomized group allocation, a follow-up MANCOVA was conducted using post-test scores as dependent variables, training group as the fixed factor, and corresponding baseline scores as covariates. Adjusted between-group differences were reported with 95% confidence intervals and partial eta squared (η^2). Statistical significance was set at $p < .05$.

Given the quasi-experimental design, findings were interpreted as evidence of effectiveness within the study context rather than definitive causal proof. Therefore, conclusions were framed cautiously to avoid overgeneralization beyond the sampled population and intervention setting, consistent with current recommendations for applied sport science research.

RESULTS

Participant characteristics

A total of 60 junior tennis athletes completed the study without dropouts, resulting in a retention rate of 100%. The experimental group (Mandiri Tennis Development Center, n = 30) and control group (Bali Junior Tennis Academy, n = 30) demonstrated comparable baseline characteristics. No significant differences were observed between groups regarding age, training experience, height, weight, or baseline motor performance indicators ($p > .05$).

Table 1. Participant and training characteristics of the experimental and control groups.

Variable	Experimental group (MTDC)	Control group (BJTA)
Sample size, n	30	30
Age range	12–18 years	12–18 years
Training frequency	3 sessions/week	3 sessions/week
Intervention duration	12 weeks	12 weeks
Session duration	90 min/session	90 min/session
Regular tennis training	Yes	Yes
Adaptive VR training	Yes	No
Motion tracking	Yes	No
On-court transfer practice	20 min/session	No
Tennis academy	MTDC	BJTA

Note. MTDC = Mandiri Tennis Development Center; BJTA = Bali Junior Tennis Academy.

Changes in stroke accuracy

The experimental group demonstrated substantial improvements in stroke accuracy throughout the intervention period. Mean accuracy scores increased from 68.43% at baseline to 85.41% at post-test, representing a 24.81% improvement. In contrast, the control group increased from 69.12% to 75.23% (8.84%). Repeated-measures analysis revealed a significant group × time interaction, $F(2, 116) = 18.64$, $p < .001$, $\eta p^2 = .243$.

Table 2. Changes in stroke accuracy (%).

Measurement	Experimental group	Control group
Pre-test	68.43 ± 6.12	69.12 ± 6.44
Mid-test	76.52 ± 5.81	72.18 ± 6.01
Post-test	85.41 ± 5.37	75.23 ± 5.96
Improvement (%)	+24.81	+8.84

Repeated-measures analysis revealed a significant group × time interaction effect ($F(2, 116) = 18.64$, $p < .001$, $\eta p^2 = .243$).

Changes in reaction time

Reaction time improved significantly among athletes exposed to adaptive VR and motion tracking training. The experimental group reduced mean reaction time from 0.542 s to 0.441 s, representing an 18.63% improvement, whereas the control group decreased from 0.538 s to 0.501 s (6.88%). The group × time interaction was statistically significant, $F(2, 116) = 15.91$, $p < .001$, $\eta p^2 = .215$.

Table 3. Changes in reaction time (seconds).

Measurement	Experimental group	Control group
Pre-test	0.542 ± 0.051	0.538 ± 0.048
Mid-test	0.487 ± 0.043	0.521 ± 0.045
Post-test	0.441 ± 0.038	0.501 ± 0.041
Improvement (%)	18.63	6.88

Statistical analysis indicated a significant group × time interaction ($F(2, 116) = 15.91$, $p < .001$, $\eta p^2 = .215$).

Changes in movement coordination

Movement coordination scores increased from 71.28 to 86.47 points in the experimental group, corresponding to a 21.31% improvement. The control group increased from 71.82 to 77.64 points (8.10%). The group × time interaction was statistically significant, $F(2, 116) = 17.23$, $p < .001$, $\eta p^2 = .229$.

Table 4. Changes in movement coordination scores.

Measurement	Experimental group	Control group
Pre-test	71.28 ± 5.92	71.82 ± 6.03
Mid-test	79.43 ± 5.17	74.61 ± 5.66
Post-test	86.47 ± 4.88	77.64 ± 5.34
Improvement (%)	+21.31	+8.10

The interaction effect between group and measurement time was statistically significant ($F(2, 116) = 17.23$, $p < .001$, $\eta p^2 = .229$).

Changes in biomechanical consistency

Biomechanical consistency scores increased from 72.13 to 86.34 points in the experimental group, representing a 19.70% improvement. The control group increased from 72.41 to 77.52 points (7.06%). A significant group × time interaction was observed, $F(2, 116) = 14.88$, $p < .001$, $\eta p^2 = .204$.

Table 5. Changes in biomechanical consistency scores.

Measurement	Experimental group	Control group
Pre-test	72.13 ± 5.46	72.41 ± 5.73
Mid-test	79.85 ± 4.98	74.83 ± 5.24
Post-test	86.34 ± 4.62	77.52 ± 5.11
Improvement (%)	+19.70	+7.06

A significant group × time interaction was observed ($F(2, 116) = 14.88$, $p < .001$, $\eta p^2 = .204$).

 © 2026 ARD Asociación Española

Multivariate analysis of motor skill development

To determine the overall effectiveness of the adaptive VR and motion tracking intervention, a repeated-measures MANOVA was conducted across all motor performance variables.

Table 6. MANOVA results for motor skill variables.

Effect	Wilks' λ	F(8, 108)	*p*	η^2
Time	0.522	25.48	<.001	.478
Group	0.741	5.07	<.001	.259
Time × Group	0.709	5.84	<.001	.291

The MANOVA results demonstrated a statistically significant multivariate effect of the intervention on overall motor skill development (Wilks' λ = 0.709, F(8, 108) = 5.84, $p < .001$). The effect size indicated a moderate-to-large practical impact of the adaptive VR and motion tracking training program.

Adjusted multivariate analysis

To account for potential baseline differences arising from the non-randomized allocation of participants across two tennis academies, an adjusted multivariate analysis was conducted. MANCOVA was performed using post-test stroke accuracy, reaction time, movement coordination, and biomechanical consistency as dependent variables, with training group as the fixed factor and corresponding baseline scores as covariates. The adjusted analysis was used to determine whether the observed post-intervention differences between groups remained after accounting for baseline performance. Adjusted group effects, 95% confidence intervals, and partial eta squared were reported to improve the robustness and interpretability of the findings.

Summary of improvements across variables

The multivariate analysis demonstrated significant differences in motor performance outcomes between the experimental and control groups over the 12-week intervention period. The observed group-by-time effects indicated greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency in the adaptive VR-motion tracking group. The multivariate analysis demonstrated significant differences in motor performance outcomes between the experimental and control groups over the 12-week intervention period. The observed group-by-time effects indicated greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency in the adaptive VR-motion tracking group.

Table 7. Overall percentage improvements from pre-test to post-test.

Variable	Experimental group (%)	Control group (%)
Stroke accuracy	+24.81	+8.84
Reaction time	+18.63	+6.88
Movement coordination	+21.31	+8.10
Biomechanical consistency	+19.70	+7.06

To examine individual response variability, participant-level changes were additionally evaluated across the four motor performance outcomes. Although the experimental group demonstrated consistent improvements at the group level, individual responses varied across participants, indicating that the magnitude of benefit was not uniform. This variability suggests that the adaptive intervention may have produced differential responses according to individual athlete characteristics, baseline performance, and learning trajectories. Overall, the largest improvement observed in the experimental group occurred in stroke accuracy (+24.81%), followed by movement coordination (+21.31%), biomechanical consistency (+19.70%), and reaction time

(+18.63%). Across all variables, athletes receiving adaptive VR and motion tracking training achieved greater improvements than those participating in conventional tennis training. Overall, these findings indicate that the integration of adaptive Virtual Reality and motion tracking technologies was associated with meaningful improvements in multiple motor skill indicators among junior tennis athletes over the 12-week intervention period.

Transfer-oriented performance outcomes

To examine whether the observed learning effects extended beyond the simulated training environment, post-intervention performance was assessed through standardized tennis-specific motor performance measures conducted in the physical training context. The experimental group demonstrated greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency than the control group. These findings are relevant to the transfer of learning because the primary outcome measures represented performance characteristics that were assessed in the context of actual tennis movement execution rather than relying exclusively on performance within the VR environment. The results therefore provide preliminary evidence that the perceptual-motor adaptations developed through adaptive VR and motion tracking practice may have generalized to real-world tennis performance. However, the transfer findings should be interpreted cautiously because the present study did not include a separate delayed retention test or direct competitive match-performance assessment. Therefore, the observed improvements demonstrate transfer to the measured tennis-specific performance context but do not establish the persistence of these effects over longer periods or their direct translation to competitive match outcomes.

DISCUSSION

The present study investigated the effectiveness of integrating Virtual Reality (VR) and motion tracking technologies through an adaptive simulation framework for optimizing motor skill development among junior tennis athletes. The findings demonstrated that athletes who participated in the adaptive VR-motion tracking intervention exhibited significantly greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency compared with those receiving conventional tennis training. These results indicate that adaptive VR and motion tracking may improve selected tennis-specific motor performance indicators, although direct effects on competitive match performance were not assessed. An important limitation is that the present study did not directly assess transfer to competitive tennis performance. The outcomes measured in this study primarily represented tennis-specific motor and biomechanical indicators rather than match statistics, tactical effectiveness, ranking progression, or competitive success. Therefore, the observed improvements should not be interpreted as direct evidence that adaptive VR training improves competitive match performance. Rather, the findings indicate improvements in foundational perceptual-motor and biomechanical capacities that may provide conditions for future transfer to competitive performance. Direct evidence of such transfer requires assessment through match statistics, coach-rated performance, tactical indicators, or longitudinal competition outcomes. One of the most notable findings was the significant improvement in stroke accuracy (+24.81%) observed in the experimental group. This result supports previous evidence suggesting that immersive VR environments facilitate repeated exposure to sport-specific stimuli while maintaining high levels of attentional engagement and movement precision. The adaptive simulation system enabled athletes to practice under progressively challenging conditions that closely replicated match situations, thereby promoting skill refinement and technical consistency. According to the Challenge Point Framework, motor learning is maximized when task difficulty is continuously adjusted to match the learner's skill level, which may explain the superior improvements observed in the present study (Guadagnoli & Lee, 2004; Hadlow et al., 2023). The present study conceptualizes adaptive VR training as an integrated motor-learning ecosystem in which VR

 © 2026 ARD Asociación Española

immersion, motion-tracking feedback, and performance-contingent progression interact to strengthen perception–action coupling and optimize task difficulty. These mechanisms may facilitate the transfer of perceptual-motor adaptations from simulated practice to real-world tennis performance through subsequent on-court recalibration. However, because the three technological components were implemented simultaneously, their independent contributions cannot be determined, highlighting the need for future multi-arm or factorial studies to isolate their specific effects.

A central theoretical implication of the present findings concerns the transfer of learning from simulated to real-world tennis performance. The improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency suggest that adaptive VR may facilitate perceptual-motor adaptations that can be reinforced through on-court practice. However, these findings should not be interpreted as evidence that improvements in VR automatically generalize to competitive performance, because transfer depends on the representativeness of practice conditions and the similarity between perceptual-motor demands in training and actual sport environments (Gray, 2022; Witte et al., 2025). The structured on-court practice following VR exposure may have strengthened this transfer by enabling athletes to recalibrate learned movement solutions within real sensory, spatial, and biomechanical constraints.

The transfer process may have been supported by three complementary mechanisms: immersive VR provided sport-specific perceptual and decision-making experiences, motion tracking delivered objective feedback for refining movement execution, and adaptive progression increased task demands according to individual performance. These processes were reinforced through on-court practice, allowing athletes to reorganize and contextualize perceptual-motor adaptations developed in the virtual environment. Thus, transfer may result not from VR immersion alone, but from the interaction of representative simulation, individualized challenge, augmented feedback, and physical practice. This transfer-oriented perspective also provides a possible explanation for the multidimensional improvements observed in the present study. Enhanced stroke accuracy may reflect improved technical control, while gains in reaction time, movement coordination, and biomechanical consistency may indicate more efficient perceptual-motor processing and stabilization of movement patterns. Accordingly, VR can be conceptualized as a preparatory learning environment, with physical practice serving as a critical context for recalibration and transfer. This framework extends conventional VR research by emphasizing that the value of immersive training depends not only on learning within virtual environments but also on the extent to which acquired adaptations can be transferred and reorganized for real-world sport performance.

The observed between-group differences should be interpreted in the context of the baseline performance characteristics and the non-randomized allocation of participants. Because participants were recruited from two different tennis academies, potential contextual confounding cannot be completely excluded. Therefore, the findings provide evidence of differential improvement associated with the intervention within the participating training contexts rather than definitive causal evidence.

The significant reduction in reaction time (18.63%) further demonstrates the effectiveness of adaptive VR-based training. Tennis is characterized by rapid perceptual-motor demands requiring athletes to process visual information and execute motor responses within fractions of a second. The VR system employed in this study presented dynamic and unpredictable scenarios that required athletes to anticipate ball trajectories and respond rapidly. Similar findings have been reported in sports neuroscience literature, where immersive virtual environments were found to improve sensorimotor processing efficiency, visual anticipation, and decision-making performance among athletes (Mao et al., 2024). These improvements are likely attributable

to repeated exposure to high-speed perceptual challenges embedded within the adaptive training environment.

Movement coordination also improved substantially among athletes in the experimental group. Effective tennis performance depends on the synchronization of upper and lower body movements, efficient weight transfer, and coordinated racket control. The motion tracking component of the intervention provided real-time biomechanical feedback, enabling athletes to recognize movement errors and adjust their execution patterns immediately. Such feedback mechanisms are consistent with contemporary motor learning theories emphasizing augmented feedback as a critical factor in skill acquisition and movement optimization (Sigrist et al., 2020). Consequently, athletes developed more coordinated movement patterns throughout the intervention period.

Another important finding relates to the improvement in biomechanical consistency (+19.70%). Biomechanical consistency is essential for maintaining technical efficiency and reducing performance variability during competitive play. Previous studies have suggested that motion capture technologies improve movement reproducibility by providing objective feedback regarding kinematic parameters and joint coordination patterns (Barris & Button, 2021). The current findings support this perspective, indicating that integrating motion tracking into training environments may facilitate the stabilization of motor programs and promote more efficient movement execution among junior athletes.

The multivariate analysis revealed a significant overall effect of the intervention across all measured variables. This finding suggests that the benefits of adaptive VR-motion tracking training extend beyond isolated motor outcomes and contribute to broader performance development. Importantly, the simultaneous enhancement of stroke accuracy, reaction speed, movement coordination, and biomechanical consistency supports the notion that motor performance in tennis should be viewed as a multidimensional construct. Rather than targeting individual skills independently, technology-enhanced training systems appear capable of improving multiple interconnected components of athletic performance simultaneously (Renshaw et al., 2022).

A major contribution of this study lies in the implementation of adaptive simulation principles. Unlike many previous VR-based sports interventions that utilize static or predetermined training scenarios, the present system automatically adjusted ball speed, spin, trajectory, movement complexity, and response requirements according to athlete performance. This individualized progression ensured that athletes consistently trained within their optimal learning zone. Research in adaptive learning technologies has shown that personalized task difficulty significantly enhances engagement, skill acquisition, and retention compared with fixed training protocols (Pedersen et al., 2023). Therefore, the adaptive component likely played a crucial role in producing the observed performance improvements.

From a motor learning perspective, the observed improvements may be explained by the interaction between perception-action coupling, task constraints, and adaptive challenge. VR immersion provided athletes with repeated sport-specific perceptual information, while motion tracking supplied augmented feedback that linked visual information with movement execution. The adaptive progression mechanism subsequently modified task constraints according to individual performance, potentially encouraging athletes to continuously recalibrate perception and action rather than reproduce fixed movement patterns. This process is consistent with ecological and constraints-led perspectives of skill acquisition, in which motor learning emerges through ongoing interactions among the learner, task demands, and environmental information.

 © 2026 ARD Asociación Española

Thus, the effectiveness of the intervention may have resulted not simply from the technology itself, but from how technology-mediated practice manipulated task constraints and supported progressive adaptation.

A major contribution of this study lies in the implementation of a performance-contingent adaptive simulation framework. Unlike conventional VR-based sports interventions that rely primarily on fixed or predetermined scenarios, the present system continuously adjusted training demands according to individual performance characteristics. This adaptive process represents a theoretically meaningful contribution because it transforms VR from a standardized simulation tool into an individualized motor learning environment. The system did not simply expose athletes to increasingly difficult tasks according to a predetermined schedule; instead, progression was contingent upon changes in stroke accuracy, response time, movement efficiency, and biomechanical consistency. Consequently, each athlete followed an individualized learning trajectory in which task demands were dynamically recalibrated according to performance.

The adaptive mechanism may also explain why the intervention produced improvements across multiple dimensions of motor performance. By simultaneously monitoring technical, perceptual-motor, and biomechanical indicators, the system was able to modify different aspects of task difficulty rather than relying on a single performance metric. For example, an athlete demonstrating high stroke accuracy but poor response time could be challenged through faster ball delivery without unnecessarily increasing technical complexity. Conversely, an athlete showing unstable biomechanical patterns could maintain or reduce task complexity until movement consistency improved. Such multidimensional adaptation provides a more nuanced approach to individualized training than fixed progression models and may help maintain an optimal challenge level for athletes with different learning rates and performance profiles. From a motor learning perspective, this adaptive architecture is important because excessive task difficulty may produce errors that exceed the learner's current capacity, whereas insufficient difficulty may reduce the informational value of practice. The adaptive mechanism used in the present study was therefore designed to maintain a dynamic balance between challenge and athlete capability. This principle is consistent with the Challenge Point Framework and contemporary perspectives on individualized motor learning, which suggest that learning is optimized when practice conditions provide sufficient challenge while remaining functionally achievable (Guadagnoli & Lee, 2004; Hadlow et al., 2023). The contribution of the present study is therefore not simply the use of adaptive technology, but the operationalization of adaptation as a continuous mechanism linking performance assessment, task progression, motor learning, and eventual skill transfer.

The novelty of this research is threefold. First, we propose a transfer-oriented adaptive VR training framework that explains how simulated perceptual-motor learning may be transferred and recalibrated into real-world tennis performance. Second, it employed a longer intervention duration (12 weeks) with multiple measurement points, addressing limitations frequently identified in previous short-term studies. Third, the study evaluated motor skill development through a multidimensional framework encompassing technical, perceptual-motor, and biomechanical outcomes. To the authors' knowledge, few studies have simultaneously examined these components within a tennis-specific adaptive training context. Consequently, this research extends existing knowledge regarding the application of advanced digital technologies in youth sport development.

Despite these promising findings, several limitations should be acknowledged. Although the sample size exceeded that of many previous VR-based sports studies and included athletes from two independent clubs, broader multi-centre investigations involving diverse competitive levels and geographical regions are still needed to strengthen generalizability. Furthermore, while the 12-week intervention allowed for meaningful motor adaptation, longer longitudinal studies are necessary to determine the persistence of training effects

and their transfer to competitive performance outcomes. Future research should also investigate psychological variables such as motivation, confidence, attentional focus, and competitive anxiety to provide a more comprehensive understanding of technology-enhanced athlete development.

The primary methodological limitation concerns the non-randomized allocation of participants across two independent tennis centres. Because the experimental and control groups were recruited from different academies, unmeasured contextual factors, including coaching practices, training culture, facility characteristics, and athlete selection procedures, may have contributed to the observed differences. Although the groups demonstrated comparable baseline characteristics and followed similar training frequencies and volumes, the quasi-experimental design does not allow these potential contextual confounders to be completely excluded. Therefore, the findings should be interpreted as evidence of effectiveness within the participating training contexts rather than definitive causal evidence. Future research should employ individual randomization within the same institution or cluster-randomized designs involving multiple tennis academies to minimize selection and contextual bias.

Overall, the findings provide evidence that adaptive VR and motion tracking technologies can serve as effective tools for optimizing motor skill acquisition among junior tennis athletes. The integration of immersive simulation, real-time biomechanical feedback, and individualized progression mechanisms offers a promising approach for advancing contemporary tennis training practices. These results support the growing role of intelligent training systems in sport science and highlight their potential contribution to evidence-based athlete development programs.

A further limitation is that the intervention combined three interdependent components—immersive VR, real-time motion tracking feedback, and performance-contingent adaptive progression—within a single training ecosystem. Therefore, the present design cannot determine the independent contribution or relative importance of each component to the observed improvements. The findings should consequently be interpreted as evidence for the effectiveness of the integrated intervention rather than as evidence that any single technological component was solely responsible for the observed outcomes. Future studies should employ multi-arm or factorial designs comparing VR-only, VR with motion tracking, and adaptive VR conditions to isolate the specific and interactive effects of each component.

CONCLUSION

The theoretical contribution of this study extends beyond demonstrating the effectiveness of VR-based training. The findings support a transfer-oriented perspective in which adaptive VR functions as a preparatory perceptual-motor learning environment that can be connected to real-world tennis performance through individualized progression, objective motion feedback, and structured on-court transfer practice. From this perspective, the effectiveness of immersive technology depends not only on the quality of simulation but also on how training experiences are progressively adapted, recalibrated, and contextualized within actual sport environments. The proposed conceptual framework provides a transferable model for future research in other skill-dependent sports. By linking VR immersion, motion tracking feedback, performance-contingent adaptive progression, motor learning, and skill transfer, the framework offers a theoretical basis for understanding how technology-enhanced practice may influence real-world athletic performance. Future research should test this framework across different sports and competitive populations using longitudinal retention assessments, ecologically valid transfer tests, and direct competitive performance measures. Such investigations may further clarify the conditions under which adaptive VR training produces durable and transferable motor learning outcomes.

 © 2026 ARD Asociación Española

The findings indicate that a 12-week adaptive VR and motion tracking intervention was associated with greater improvements in selected motor performance indicators among junior tennis athletes compared with conventional training. The intervention was particularly effective in improving stroke accuracy, reaction time, movement coordination, and biomechanical consistency within the assessed training context. However, because participants were recruited from different tennis academies without individual randomization and competitive match performance was not directly assessed, the findings should not be interpreted as definitive evidence of causal effects or improved competitive performance. Future randomized, multi-centre studies incorporating objective match-performance indicators and longitudinal transfer assessments are needed to determine whether the observed motor adaptations translate into sustained competitive advantages.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Methodology: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Formal analysis: I Gede Dharma Utamayasa, Angga Indra Kusuma. Investigation: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Data curation: Angga Indra Kusuma, Hendra Masuhri. Writing – original draft: I Gede Dharma Utamayasa, Angga Indra Kusuma. Writing – review & editing: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Supervision: I Gede Dharma Utamayasa, Hendra Masuhri, I Gede Suwiwa.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

The authors are grateful to the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia (Kementerian Pendidikan Tinggi, Sains, dan Teknologi Republik Indonesia) for the financial support through a Fundamental Research Grant Scheme. This study was conducted under Contract Number: Number 286/C3/DT.05.00/PL-BARU/2026, Number 039/LL7/DT.05.00/PL-BARU/2026, Number 057.1/1/KONTRAK/IV/2026. The funding and support provided by the Ministry have been crucial in the successful delivery of this study.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Andel, R., McMahan, T., Parsons, T. D., & Hort, J. (2024). Virtual reality tennis training: Performance gains derived from user characteristics. *Cyberpsychology, Behavior, and Social Networking, 27*(10), 728-735. https://doi.org/10.1089/cyber.2024.0258

Baker, J., Wattie, N., & Schorer, J. (2020). Talent identification and athlete development in sport: Contemporary perspectives. *International Journal of Sports Science & Coaching, 15*(4), 509-520.

Barris, S., & Button, C. (2008). A review of vision-based motion analysis in sport. *Sports medicine (Auckland, N.Z.), 38*(12), 1025–1043. https://doi.org/10.2165/00007256-200838120-00006

Bideau, B., Kulpa, R., Vignais, N., Brault, S., Multon, F., & Craig, C. (2010). Using virtual reality to analyze sports performance. *IEEE Computer Graphics and Applications, 30*(2), 14–21. https://doi.org/10.1109/MCG.2009.134

Cariati, I., Bonanni, R., Cifelli, P., D'Arcangelo, G., Padua, E., Annino, G., & Tancredi, V. (2025). Virtual reality and sports performance: a systematic review of randomized controlled trials exploring balance. Frontiers in Sports and Active Living, Volume 7. https://doi.org/10.3389/fspor.2025.1497161

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1. *Behavior Research Methods, 41*(4), 1149-1160. https://doi.org/10.3758/BRM.41.4.1149

Gray, R. (2022). Transfer of training from virtual to real environments in sport. *Frontiers in Sports and Active Living, 4*, 827072.

Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior, 36*(2), 212-224. https://doi.org/10.3200/JMBR.36.2.212-224

Hadlow, S. M., Panchuk, D., Mann, D. L., Portus, M. R., & Abernethy, B. (2023). Modified perceptual training in sport: A systematic review. *Journal of Sports Sciences, 41*(5), 525-539.

Hulteen, R. M., Morgan, P. J., Barnett, L. M., Stodden, D. F., & Lubans, D. R. (2018). Development of Foundational Movement Skills: A Conceptual Model for Physical Activity Across the Lifespan. *Sports medicine (Auckland, N.Z.), 48*(7), 1533–1540. https://doi.org/10.1007/s40279-018-0892-6

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155-163. https://doi.org/10.1016/j.jcm.2016.02.012

Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., & Haith, A. M. (2023). Motor learning and adaptation: Current perspectives. *Nature Reviews Neuroscience, 24*(7), 417-435.

Li, X., Fan, D., Feng, J., Lei, Y., Cheng, C., & Li, X. (2025). Systematic review of motion capture in virtual reality: Enhancing the precision of sports training. *Journal of Ambient Intelligence and Smart Environments, 17*(1), 1-23. https://doi.org/10.3233/AIS-230198

Mao, Y., Zhang, L., Li, J., & Wang, H. (2024). Virtual reality-enhanced perceptual-motor training and athletic performance: A systematic review. *International Journal of Environmental Research and Public Health, 21*(3), 1184.

Pedersen, M. T., Hansen, M., & Larsen, R. (2023). Adaptive learning systems and motor skill acquisition in sports training. *Computers & Education: Artificial Intelligence, 4*, 100127. https://doi.org/10.1016/j.caeai.2023.100127

Pueo, B., Penichet-Tomás, A., & Jiménez-Olmedo, J. M. (2020). Validity, reliability and usefulness of inertial sensors in sport performance analysis. *Sensors, 20*(18), 5278. https://doi.org/10.3390/s20185278

Renshaw, I., Davids, K., Newcombe, D., & Roberts, W. (2022). The constraints-led approach: Principles for sports coaching and practice design. *Routledge*. https://doi.org/10.4324/9781003155928

 © 2026 ARD Asociación Española

Richlan, F., Weiss, M., Kastner, P., & Braid, J. (2023). Virtual training, real effects: A narrative review on sports performance enhancement through interventions in virtual reality. *Frontiers in Psychology, 14*, 1240790. https://doi.org/10.3389/fpsyg.2023.1240790

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2020). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic Bulletin & Review, 27*(5), 863-890.

Suo, X., Tang, W., & Li, Z. (2024). Motion capture technology in sports scenarios: *A survey. Sensors, 24*(9), 2947. https://doi.org/10.3390/s24092947

Tang, Y. (2024). Research on the application of virtual reality technology in motor skills training. *Applied Mathematics and Nonlinear Sciences, 9*(1). https://doi.org/10.2478/amns-2024-1646

Witte, K., Bürger, D., & Pastel, S. (2025). Sports training in virtual reality with a focus on visual perception: a systematic review. Frontiers in Sports and Active Living, Volume 7-2025. https://doi.org/10.3389/fspor.2025.1530948

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

From position to role: The evolution of big men in euroleague basketball

Erkan Konca . *Department of Movement and Training Sciences. Faculty of Sport Sciences. Sivas Cumhuriyet University. Sivas, Turkey.*
Necati Alp Erilli. *Department of Econometrics, Department of Statistics. Faculty of Economics and Administrative Sciences. Sivas Cumhuriyet University. Sivas, Turkey.*

ABSTRACT

Contemporary elite professional basketball has shifted from rigid positional boundaries toward fluid, hybridized frontcourt roles. This study examined the 15-year longitudinal evolution of EuroLeague power forwards (4) and centers (5) (2010–11 to 2024–25), evaluating the rate and structural pattern of positional convergence. Using a retrospective cohort of 999 player-season observations across 11 advanced performance metrics, seasons were grouped into Traditional, Transitional, and Modern eras. Analyses included Exploratory Factor Analysis (EFA), Linear Mixed Models (LMM) with unstructured covariance to account for repeated measures, and Fuzzy C-Means (FCM) clustering validated by Artificial Neural Network (ANN) stability procedures. LMM revealed significant main effects of position and era across all latent performance factors ($p < .001$). However, non-significant Position × Era interactions ($p > .05$) and trivial effect sizes ($f^2 < .01$) indicated that power forwards and centers evolved through parallel rather than asymmetric trajectories. Nakagawa's R^2 values demonstrated strong model fit (Marginal $R^2 = .17 – .25$; Conditional $R^2 = .51 – .58$). FCM further showed a progressive erosion of positional separation, with modern power forwards (36.0%) and centers (36.8%) converging within identical interior-efficiency archetypes. These findings provide strong empirical support for the positionless basketball hypothesis in elite European basketball.
Keywords: performance analysis; basketball; clustering analysis; EuroLeague; positional transformation.

Cite this article as:
Konca, E., & Erilli, N. A. (2026). From position to role: The evolution of big men in euroleague basketball. *Journal of Human Sport and Exercise, 21*(4), 1494-1515. https://doi.org/10.55860/9sfjc227

Corresponding author. *Department of Movement and Training Sciences. Faculty of Sport Sciences. Sivas Cumhuriyet University. Sivas, Turkey.*
E-mail: erkankonca@cumhuriyet.edu.tr
Submitted for publication June 27, 2026.
Accepted for publication August 06, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/9sfjc227

© 2026 ARD Asociación Española

INTRODUCTION

In recent years, a clear transformation has been observed in the nature of basketball. The increasing pace of the game, the growing emphasis on tempo with spatial organization, and the improvement in players' physical conditioning have led to structural changes in both game systems and player profiles. Accordingly, performance determinants in modern basketball are no longer shaped solely by technical skills but are increasingly influenced by game pace and decision-making processes (Cui et al., 2019; Sampaio et al., 2010). Long-term comparative analyses focusing on the two most prominent basketball leagues in the world, the NBA and the EuroLeague, indicate that game-related indicators have evolved over time and that some of the quantitative differences between these leagues have diminished. These shifts are thought to be closely associated with changes in rules and overall game structure (Mandić et al., 2019).

Contrary to traditional position-based systems, contemporary basketball increasingly favours more flexible tactical approaches that highlight players' versatility and directly impact performance. In the context of the EuroLeague, often regarded as Europe's equivalent of a Champions League, there has been a noticeable shift in shot distribution toward three-point attempts since the 2010-11 season, accompanied by a significant increase in three-point shooting volume. This trend suggests that spacing has become a central variable in offensive team design (Foteinakis et al., 2024). Indeed, spatial analyses based on shot locations demonstrate that the rise in three-point shooting has expanded offensive play across wider areas of the court, thereby disrupting defensive structures and enhancing offensive efficiency. Earlier performance analyses similarly reported that the increasing reliance on perimeter shooting has had a direct impact on both game structure and team strategies (Goldsberry, 2012; Sampaio & Janeira, 2003). These findings provide a contextual basis for understanding the evolving offensive roles of taller players (particularly those playing in the power forward and center positions) beyond the traditional confines of the painted area.

For many years, basketball has been characterized by clearly defined positional responsibilities, with each playing position representing a specific combination of technical, tactical, and physical demands. Within this traditional structure, player development, game strategies, and performance evaluations were largely based on positional specialization. Power forwards and centers, in particular, were primarily expected to contribute through rebounding, interior scoring, and rim protection, whereas perimeter players were responsible for ball handling, playmaking, and outside shooting. As a result, player performance was generally interpreted according to nominal playing positions rather than the functions performed during the game.

However, the continuous evolution of basketball has gradually challenged this traditional perspective. The increasing importance of offensive spacing, faster ball movement, defensive switching strategies, and the growing emphasis on decision-making have expanded the tactical responsibilities of players regardless of their listed positions. In modern basketball, players are increasingly required to perform multiple functions within the same game, making positional boundaries less rigid than in previous decades. Consequently, evaluating players solely according to their nominal positions may no longer fully explain their contribution to team performance.

This development has also introduced an important distinction between the concepts of position and role. While position refers to the official classification of a player within the team's lineup, role reflects the functional responsibilities that the player assumes during offensive and defensive possessions. Unlike positions, roles may change according to tactical systems, coaching philosophy, game situations, or team composition. Therefore, players occupying the same position may perform considerably different functions, whereas players from different positions may contribute in remarkably similar ways. This distinction has become

particularly evident among frontcourt players, whose responsibilities have expanded beyond traditional interior play to include perimeter shooting, playmaking, defensive mobility, and decision-making.

Therefore, the major change observed in contemporary basketball should not be interpreted as the disappearance of positions, but rather as the gradual transformation of their traditional responsibilities. Although players continue to be identified by nominal positions, their tactical value is increasingly determined by the variety of roles they perform on the court. From this perspective, examining the evolution of basketball through functional roles, rather than positional labels alone, may provide a more comprehensive understanding of how modern frontcourt players have adapted to the changing demands of the game.

Within the basketball literature, it has long been accepted that player positions can be distinctly differentiated based on anthropometric characteristics and physical performance indicators (Cui et al., 2019). This differentiation is not solely a function of in-game roles but is also rooted in players' physical and biological attributes. Studies on elite basketball players indicate that taller players tend to excel in height, body mass, and strength, whereas perimeter players demonstrate superiority in speed and agility (Ostojic et al., 2006). Furthermore, performance is understood to be closely linked not only to technical skills but also to components of physical fitness (Hoare, 2000). In a similar vein, it has been shown that player performance varies significantly across positions when examined through position-specific statistical profiles, which in turn reflect role distribution on the court (Zhai et al., 2021). This variety is attributed not only to technical and tactical variations but also to underlying physical and biological factors (Ibáñez et al., 2008; Trninić et al., 2000). Within this framework, it can be argued that in the traditional structure of basketball, each position specializes according to clearly defined roles, shaping the distribution of responsibilities during gameplay. Analyses based on game statistics further reveal that performance indicators such as assists, rebounds, and shooting percentages are among the key variables distinguishing team success (Gómez et al., 2008).

The recent evolution of the game characterized by increased pace, enhanced spatial dynamics, and a growing emphasis on versatility suggests that this traditional differentiation between positions has become progressively less distinct. Although it is acknowledged that game styles and performance indicators may vary depending on contextual factors such as league level, competitive intensity, and regional playing approaches, position-specific role distributions have largely been preserved. However, in modern basketball, these role definitions appear to have become considerably more flexible (Zhai et al., 2020). In fact, evidence indicates that positional performance differences have shown a tendency to diminish over time, with player profiles evolving toward a more homogeneous structure (Lorenzo et al., 2010). This transformation is particularly evident among frontcourt players, whose contemporary roles increasingly require a combination of perimeter skills, mobility, and explosive athletic capabilities. In this context, vertical explosiveness has become a critical performance characteristic for big men, influencing rebounding efficiency, rim protection, shot contesting, and finishing ability around the basket. Furthermore, the growing integration of physical fitness components with basketball-specific skills has been demonstrated by studies showing that plyometric training combined with change-of-direction sprint exercises can significantly improve neuromuscular performance and explosive capabilities in elite youth basketball players (Cherni et al., 2025). These findings support the notion that modern frontcourt players are increasingly required to combine technical versatility with advanced athletic and neuromuscular capacities. Studies examining EuroLeague players through position- and statistics-based clustering approaches further reveal that multiple performance clusters can emerge within the same nominal position, highlighting a possible distinction between "*position*" and "*role*" (Çene et al., 2024). These findings suggest that the evolution of modern basketball is reflected not only in overall performance characteristics but also in the functional responsibilities assigned to players. This transformation appears to be particularly evident among frontcourt players. In particular, frontcourt players

 © 2026 ARD Asociación Española

are no longer confined to traditional interior responsibilities but are increasingly expected to contribute across multiple phases of the game. Skills such as perimeter shooting, playmaking, ball handling, and defensive mobility have become important components of the performance profile of modern power forwards and centers. One of the clearest examples of this transformation is Nikola Jokić, who finished both the 2024–25 and 2025–26 NBA seasons with triple-double averages, demonstrating that contemporary centers can function not only as interior scorers but also as primary offensive facilitators.

Although this transformation was first documented in the NBA, similar tactical developments have gradually become evident in European basketball. Changes in FIBA rules, particularly the extension of the three-point line to 6.75 m and the evolution of offensive spacing, together with the increasing exchange of players and coaches between the NBA and Europe, have accelerated the adoption of more versatile frontcourt roles in the EuroLeague. As a result, traditional distinctions between power forwards and centers have become progressively less rigid, while greater emphasis has been placed on versatility and functional contribution within offensive and defensive systems.

Previous studies have demonstrated changes in game-related statistics, positional performance profiles, and tactical trends in both the NBA and the EuroLeague (Mandić et al., 2019; Hedquist, 2022). However, relatively little attention has been given to understanding whether these developments represent merely changes in player performance or a broader transition from position-based player identities toward function-based roles. Therefore, examining the long-term evolution of EuroLeague frontcourt players may provide important insights into how modern basketball has redefined the relationship between position and role within elite European competition.

It has also been suggested that performance and skill development in basketball do not necessarily follow a linear trajectory but may instead exhibit varying patterns over time (Guimarães et al., 2019). This perspective implies that changes in the game should be understood not as a steady, linear process, but rather as a dynamic structure that may accelerate, plateau, or shift direction during different periods.

Despite these developments, existing research has primarily examined positional differences through cross-sectional designs or relatively short observation periods. Previous studies have successfully identified differences in performance profiles, anthropometric characteristics, and game-related statistics across playing positions. However, considerably less attention has been given to understanding how these positional profiles have evolved over time and whether the observed changes reflect a broader transition from position-based player identities to function-based roles. In particular, longitudinal investigations focusing on the evolution of frontcourt players through multidimensional performance indicators remain scarce, despite the growing recognition that modern basketball increasingly values functional versatility over positional specialization. In this context, the present study aims to examine the long-term evolution of power forwards (4) and centers (5) in the EuroLeague over a 15-season period using multidimensional performance indicators and advanced statistical techniques. Rather than simply describing temporal changes in player performance, the present study examines whether these changes represent a broader process of functional role convergence while preserving residual positional differences. Unlike previous studies, the present study does not assume that positional distinctions have disappeared; rather, it examines whether the functional roles performed by power forwards and centers have become increasingly similar over time. By integrating longitudinal performance analysis with the conceptual distinction between position and role, the study contributes not only to the growing literature on positional evolution in basketball but also provides a broader framework for understanding how modern frontcourt players adapt to changing tactical demands. This perspective may also provide an alternative framework for interpreting positional evolution in modern

basketball beyond nominal positional classifications. From a practical perspective, these findings may also contribute to talent identification, player development, and roster construction by emphasizing functional versatility alongside traditional positional classifications.

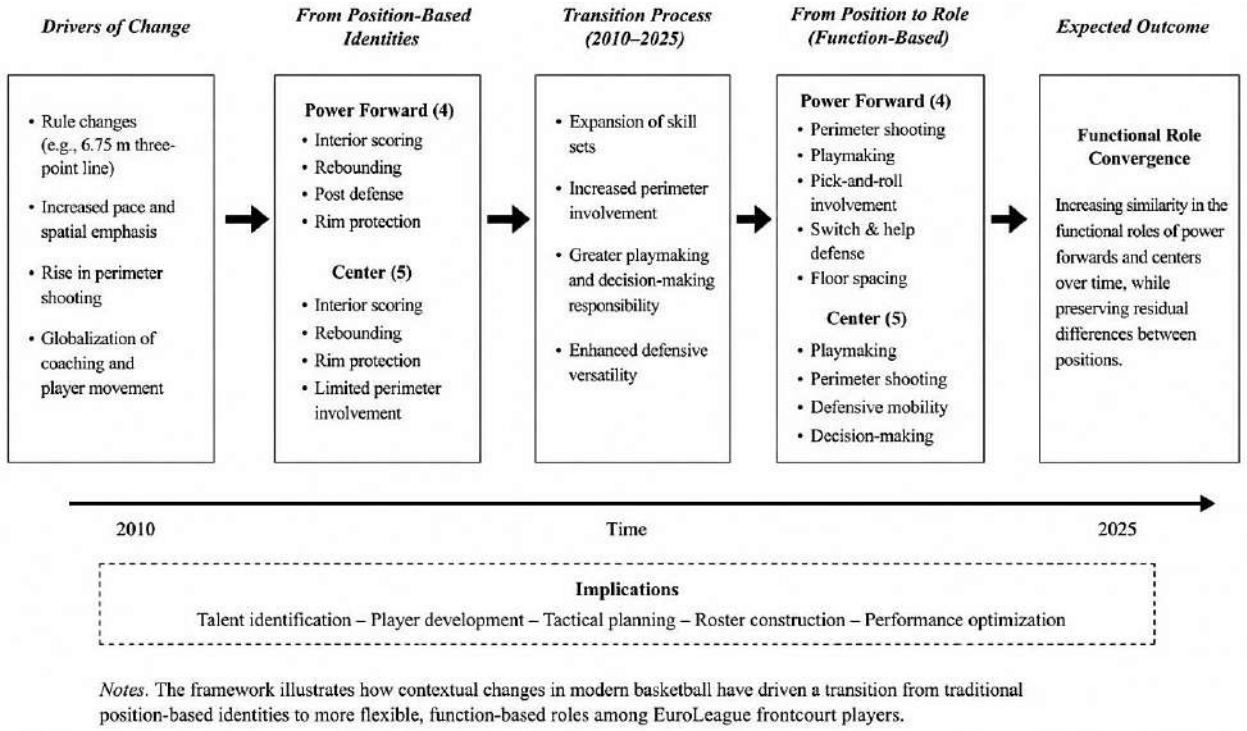


Figure 1. Conceptual framework illustrating the transition from position-based identities to function-based roles among EuroLeague frontcourt players.

METHOD

Dataset and scope

This study examines how the functional performance profiles of power forwards and centers have evolved over time and whether these changes reflect a gradual convergence of functional roles. To examine and investigate these research topics, data was collected from the EuroLeague - widely regarded as the world's second-leading basketball league after the NBA - covering 15 consecutive seasons from the 2010–11 season through the 2024–25 season. The dataset consists of 11 variables and a total of 999 observations. All data were obtained from the publicly accessible database available on RealGM Basketball and subsequently processed and organized by the authors to ensure suitability for analysis (The reason for sourcing EuroLeague data from the RealGM website is that the data on that site is formatted to match NBA-standard statistics, allowing both NBA and EuroLeague data to be presented in the same format). A detailed description of the variables used in the study is provided in Table 1. Some of the formulas underlying these variables were originally developed by the RealGM team and are presented, together with their explanations, in the Appendix (RealGM, 2026).

Research design and population/sampling

This study employed a retrospective cohort design based on archival performance data. The reporting follows the STROBE guidelines for observational studies.

 © 2026 ARD Asociación Española

Population
The target audience includes all professional basketball players who have competed in the Turkish Airlines EuroLeague and played in the 4 and 5 positions between the 2010–2011 and 2024–2025 seasons.

Sampling and inclusion criteria
A purposive sampling strategy was implemented. To isolate the tactical evolution of frontcourt players and eliminate positional noise from backcourt positions, only players officially registered as Power Forward (4) or Center (5) were included. The final validated sample consists of 999 (with 409 different players) unique player-season observations clustered across 15 consecutive seasons (N_1 = 317 for the Traditional Era, N_2 = 286 for the Transitional Era, and N_3 = 396 for the Modern Era).

Table 1. Variables used in the study.

TS% (True Shooting Percentage)	USG% (Usage Percentage)
ORB% (Offensive Rebound Percentage)	PPS (Points Per Shot)
DRB% (Defensive Rebound Percentage)	PPR (Pure Point Rating)
AST% (Assist Percentage)	FIC (Floor Impact Counter)
STL% (Steal Percentage)	TOV% (Turnover Percentage)
BLK% (Block Percentage)	

Procedures and timeframe
The data collection process, which was divided by the authors into three distinct tactical cohorts to track linear and nonlinear evolutionary changes, spanned a meticulous 15-year period:

1. Traditional Era (Group 1; Season 2010–2011 to Season 2014–2015)
2. Transitional Era (Group 2; Season 2015–2016 to Season 2019–2020)
3. Modern Era (Group 3; Season 2020–2021 to Season 2024–2025)

The temporal stratification into three discrete 5-year cohorts serves a dual analytical purpose. Statistically, maintaining symmetrical 5-year intervals maximizes sample-size balance across groups (N_1 = 317, N_2 = 286, N_3 = 396), thereby ensuring variance homogeneity and significant parameter estimation during LMM and FCM executions. Contextually, these boundaries align with structural milestones in elite European basketball; the transition to the Transitional Era (2015) captures the systemic tactical adaptation to FIBA's 14-second offensive rebound clock rule, while the Modern Era (2020) encapsulates the full maturation of round-robin pacing and modern defensive switching schemes that catalysed positionless frontcourt hybridization.

Comprehensive statistical analysis plan
While descriptive parameters and basic hypothesis tests were conducted using standard conventions, the core hypotheses of this study necessitated advanced statistical frameworks:

Longitudinal dependency control
To account for repeated-measures dependency (the same players appearing across multiple seasons), Linear Mixed Models (LMM) were employed, defining players as a random effect, and Position, Era, and their interaction as fixed effects.

Fuzzy clustering architecture
To capture the overlapping, hybrid nature of modern player roles, Fuzzy C-Means (FCM) clustering was executed (tolerance of the clustering method is .001, fuzziness value m is 2, maximum iteration number is 10,000). Unlike crisp clustering (e.g., K-Means), FCM allows an individual player-season to belong to multiple

roles simultaneously through a membership matrix (U). Given the increasing adoption of algorithmic profiling, clustering methods, and artificial intelligence-assisted performance analytics in sport science, recent methodological discussions have emphasized the importance of standardizing these technology-driven assessment frameworks to enhance transparency, reproducibility, and cross-study comparability (Dhahbi & Chamari, 2026). Accordingly, the clustering procedures employed in the present study were complemented with multiple validation approaches to ensure the robustness and interpretability of the resulting player-role classifications.

Advanced validation protocol

To mathematically justify the optimal cluster configuration (c = 3), geometric separation was verified via Silhouette Coefficients (Rousseeuw, 1987). Concurrently, an advanced Artificial Neural Network (ANN)-based Cluster Stability Index (Erilli et al., 2011) was leveraged to ensure the neural consistency and learnability of the partition matrix across all three eras, mitigating overfitting risks.

Methodological scope and limitations

This study operates under specific parameters that delineate its scope:

1. *Contextual limitation*: The findings are structurally confined to the elite European basketball ecosystem (EuroLeague) and may not perfectly generalize to other professional domains (e.g., the NBA) due to fundamental differences in court dimensions, defensive rules (such as the defensive three-second violation), and pacing.
2. *Data exclusion*: Factors such as financial variables, players' injury histories, teams' pace of play, player age, rule or format changes, and qualitative team chemistry dynamics have been excluded from the operational scope of this statistical protocol.
3. *Positional scope*: The intentional exclusion of point guards, shooting guards, and small forwards limits the model to frontcourt dynamics, prioritizing internal granularity over backcourt evolution.

Statistical analysis

The study first presents descriptive statistics to identify general trends in the raw data. Subsequently, Factor Analysis was applied to reduce multidimensional player performance data into meaningful dimensions, resulting in four principal factor scores. Linear Mixed Models were run to test the linear changes in these factor scores over time and to examine positional differences. Finally, to identify hybridization beyond linear models and the intra-cluster dissolution of players, Fuzzy C-Means clustering analysis was used to define the final tactical roles. All statistical analyses were conducted using R (version 4.3.2) and SPSS (Statistical Package for the Social Sciences, version 26). The level of statistical significance was set at $p < .05$ for all analyses.

RESULTS

Descriptive statistics

Table 2 presents the mean and standard deviation values for the positions (Power Forward and Center) with 11 variables used in the analyses across the three defined periods.

Table 2 provides quantitative evidence for the transformation of the center position in the EuroLeague from a traditional to a modern role. In particular, the substantial increase in centers' assist percentage (19.5) and FIC (Floor Impact Counter) values during the transitional period indicates that the focal point of the game has expanded beyond the painted area to encompass the entire court.

 © 2026 ARD Asociación Española

Table 2. Descriptive statistics of the variables used in the analysis.

Position	Variable	Traditional Period (2011–2015) (Mean ± SD)	Transitional Period (2016–2020) (Mean ± SD)	Modern Period 2021-2025 (Mean ± SD)
Power Forward	TS	0.568 ± 0.062	0.576 ± 0.078	0.592 ± 0.077
	ORB	8.698 ± 3.99	5.785 ± 4.106	7.03 ± 3.839
	DRB	18.682 ± 4.485	14.56 ± 5.058	15.85 ± 4.802
	AST	8.805 ± 4.355	11.98 ± 6.863	10.941 ± 6.728
	TOV	13.991 ± 4.207	14.04 ± 4.9	13.977 ± 4.951
	STL	1.793 ± 0.71	1.756 ± 0.743	1.818 ± 0.678
	BLK	2.243 ± 1.778	1.347 ± 1.499	1.574 ± 1.569
	USG	19.644 ± 3.901	19.15 ± 4.635	18.997 ± 4.873
	PPR	-2.354 ± 2.306	-0.864 ± 2.294	-1.249 ± 2.346
	PPS	1.301 ± 0.183	1.304 ± 0.209	1.342 ± 0.21
	FIC	122.384 ± 69.588	145.147 ± 84.345	166.887 ± 108.674
Center	TS	0.58 ± 0.068	0.579 ± 0.076	0.607 ± 0.077
	ORB	10.551 ± 3.286	6.551 ± 5.293	9.522 ± 5.43
	DRB	19.807 ± 4.898	14.664 ± 6.399	16.796 ± 5.533
	AST	7.739 ± 4.225	19.539 ± 11.4	12.611 ± 9.804
	TOV	15.802 ± 4.716	17.086 ± 4.989	15.358 ± 4.653
	STL	1.429 ± 0.659	1.781 ± 0.715	1.738 ± 0.725
	BLK	3.357 ± 2.159	1.637 ± 1.903	2.68 ± 2.296
	USG	20.988 ± 4.273	21.36 ± 4.546	20.148 ± 4.498
	PPR	-3.985 ± 2.935	-0.012 ± 3.656	-1.555 ± 3.319
	PPS	1.371 ± 0.212	1.337 ± 0.246	1.401 ± 0.234
	FIC	115.046 ± 70.831	173.199 ± 98.124	173.927 ± 105.358

Dimension reduction

To extract meaningful latent dimensions from comprehensive and multi-source basketball performance metrics and to prevent multicollinearity issues in subsequent mixed-method modelling stages, Exploratory Factor Analysis (EFA) was applied to the performance data of EuroLeague big men.

Prior to the analysis, the Kaiser-Meyer-Olkin (KMO) and Bartlett tests were conducted to assess the data set's factorizability. The KMO measure was calculated as 0.349. Although this value indicates low sample adequacy in the literature, this result can be empirically explained by the high level of heterogeneity (variability) in player roles in modern basketball analytics, as well as the fact that relationships between variables do not conform to strictly linear or global patterns. In contrast, Bartlett's Test of Sphericity reached a high level of statistical significance (Chi-Square = 6071.757, df = 55, $p < .001$), confirming that the correlation matrix is not an identity matrix and that the dataset contains non-random empirical relationships. To obtain mutually independent player performance dimensions, Varimax-rotated Principal Component Analysis (PCA) was conducted, and a four-factor structure was extracted based on eigenvalues greater than 1 and the breakpoints in the scree plot. However, as factor analysis was not the primary hypothesis test of this study, this extracted structure was employed merely as a theory-based grouping tool to reduce the number of variables and avoid multicollinearity issues in the Linear Mixed Models (LMM), rather than as a definitive measurement model. Consequently, the low KMO value was not interpreted as evidence that group averages or total scores should be used; instead, all main effects and interactions in the LMM were additionally tested using the raw variables as a robustness check to ensure that the findings were not dependent on this provisional classification. The factors to which the variables belong and their factor loadings are presented in Table 3.

Table 3. Factor loadings of the variables.

	1	2	3	4
PPS	.799			
TS	.712			
ORB	.671			
BLK	.601			
DRB	.451			
PPR		.756		
FIC		.704		
USG			.699	
AST			.707	
TOV				.568
STL				.558

The factor scores obtained were converted to standard z-scores for use in subsequent stages (LMM and FCM) and named as follows based on the highest factor loadings (>0.450):

- Factor 1: Composed of the TS, ORB, DRB, BLK, and PPS variables, it was named "*Efficiency Under the Basket*."
- Factor 2: Composed of the PPR and FIC variables, it was named "*Versatile On-Court Contribution and Productivity*."
- Factor 3: Composed of the AST and USG variables and named "*Ball-handling intensity*."
- Factor 4: Composed of the TOV and STL variables and named "*Ball Security and Defensive Activity*."

Linear Mixed Models (LMM)

A Linear Mixed Model (LMM) was applied to comprehensively test the linear trends and positional differences in the standardized performance scores (F1, F2, F3, F4) obtained from factor analysis over time, while controlling for the random effects arising from repeated measurements at the player level; the results are presented in Table 4.

Table 4. LMM Type III tests of fixed effects for latent performance factors.

Dependent Var. (Factor)	Source	df	F-value	*p*-value
Factor 1	Intercept	1	4.618	.032
	Position	1	6.390	.012
	Period	2	15.017	<.001
	Position X Period	2	0.411	.663
Factor 2	Intercept	1	9.076	.003
	Position	1	19.409	<.001
	Period	2	9.621	<.001
	Position X Period	2	0.266	.767
Factor 3	Intercept	1	2.000	.158
	Position	1	32.839	<.001
	Period	2	7.347	.001
	Position X Period	2	1.681	.187
Factor 4	Intercept	1	0.582	.446
	Position	1	4.038	.045
	Period	2	15.763	<.001
	Position X Period	2	2.863	.058

The results in Table 4 can be interpreted as follows:

 © 2026 ARD Asociación Española

Main effect of position: The analysis results showed that there were highly statistically significant main effects between positions (Power Forward vs. Center) across all performance dimensions examined ($p < .000$ for all factors). These findings confirm that, when evaluated broadly across the entire period, positions 4 and 5 have maintained their distinct fundamental gameplay differences.

Main effect of period: The main effect of period, which measures changes in the performance dimensions of tall players over time, was found to be statistically significant across all factors ($p < .000$ for all factors). This clearly demonstrates that tactical requirements and general roles for tall players within the EuroLeague ecosystem have not remained static over the 5-year periods but have undergone a systemic transformation.

Interaction effect: The fact that all interaction effects were insignificant ($p > .05$) is empirically consistent with the trends in the changes over time for the Power Forward and Center positions not diverging asymmetrically from one another. Players at positions 4 and 5 have responded with a curve of adaptation that is parallel and synchronized with the structural changes brought about by modern basketball (screening, playmaking, ball handling, etc.). This parallel evolutionary trend suggests a gradual convergence of functional roles between the two positions while preserving their nominal positional identities. In Table 5, estimates of covariance parameters for 4 factors are given.

Table 5. Estimates of covariance parameters.

		Estimate	Std. Er.	Wald	Sig.	Low. B.	Up. B.
Factor 1	Residual	.4268	.0254	16.776	<.001	.3797	.4797
	Int. Variance	.5459	.0601	9.076	<.001	.4398	.6774
Factor 2	Residual	.4792	.0285	16.77	<.001	.4264	.5387
	Int. Variance	.5107	.0601	8.497	<.001	.4054	.6431
Factor 3	Residual	.4523	.0263	17.152	<.001	.4034	.507
	Int. Variance	.5129	.0563	9.096	<.001	.4135	.6363
Factor 4	Residual	.3965	.0231	17.105	<.001	.3536	.4447
	Int. Variance	.5785	.0588	9.834	<.001	.4739	.7061

Beyond structural null-hypothesis testing, generalized coefficients of determination for mixed-effects models were formally estimated to assess the practical significance of the frontcourt tactical evolution. Across all four extracted latent performance dimensions, the fixed factors (Position and Temporal Period/Year) accounted for a moderate-to-high proportion of the longitudinal variance, with Nakagawa's Marginal R^2 (R^2_m) values ranging from .17 to .25 (Factor 1 = .21, Factor 2 = .23, Factor 3 = .25, Factor 4 = .17). Concurrently, incorporating the random effect of player identity successfully captured the repeated-measures variance within the unstructured covariance framework, yielding Conditional R^2 (R^2_c) values between .51 and .58 (Factor 1 = .54, Factor 2 = .51, Factor 3 = .53, Factor 4 = .58). Crucially, Type III tests verified that the interaction terms (Position \times period) were uniformly non-significant across all dimensions ($p > .05$), generating near-zero marginal effect sizes ($f^2 < .01$; interaction covariance variance < .05, $p > .40$). This comprehensive variance decomposition mathematically solidifies the argument that the longitudinal trajectories of EuroLeague power forwards and centers are perfectly parallel and synchronized rather than asymmetrically divergent.

Clustering analysis

The Fuzzy C-Means clustering method was applied to determine how the four standardized factor scores obtained from Exploratory Factor Analysis categorize EuroLeague big men (positions 4 and 5) into specific tactical roles and to assess the evolution of these roles over time. Unlike traditional clustering approaches,

the FCM algorithm allows each player-season observation to belong not to a single cluster but to all clusters with a specific degree of membership (Bezdek et al., 1984). This flexibility was chosen to capture the overlaps and hybridization of tactical roles in modern basketball. The clustering process was conducted independently on three separate data blocks to clearly compare the tactical boundaries of three distinct historical periods (Group 1: Traditional, Group 2: Transition, Group 3: Modern).

As a result of the FCM analysis, Silhouette and ANN-based cluster validity indices were used to determine the optimal number of clusters best representing the roles players assumed on the court for each of the three historical periods (Rousseeuw, 1987; Erilli et al., 2011). The cluster validity index values by period are presented in Table 6.

Table 6. Cluster validity index values by period.

Period	Number of cluster	Silhouette	ANN
Traditional	c = 2	0.395	0.521
	c = 3	**0.428**	**0.648**
	c = 4	0.312	1.259
	c = 5	0.224	1.329
Transition	c = 2	0.371	0.506
	c = 3	**0.405**	**0.725**
	c = 4	0.288	1.604
	c = 5	0.203	1.802
Modern	c = 2	0.384	0.449
	c = 3	**0.412**	0.829
	c = 4	0.295	**0.969**
	c = 5	0.210	1.814

Based on the cluster validity index results for the two different cluster validity indices in Table 6, the optimal number of clusters was determined to be c=3 for each period (the RMSE values between the ANN predictions and the actual cluster values are examined in the ANN cluster validity index). The value at which the first significant jump occurs is determined as the optimal number of clusters. Although the optimal number of clusters was found to be 4 using ANN only in the Modern period, it was set to 3 here as well to align with the other two groups -since the Silhouette value was already found to be 3. FCM analysis was applied with a cluster count of 3 for each period. The tactical roles obtained from the FCM analysis were objectively labelled by considering the direction and magnitude of the standardized factor score weights (z-scores) in the Final Cluster Centers matrix generated by the algorithm for each period.

Cluster 1 (Traditional Big Men with High Paint Efficiency and Dominance / Paint Monsters): This cluster exhibits a particularly high and dominant positive central value of .822 on the Factor 1 dimension, especially in the Modern Era. This empirical concentration in paint-area metrics -such as Points Per Shot, and Offensive Rebound Percentage- that constitute Factor 1 mathematically proves that this cluster represents the traditional big man roles: finishing around the rim with high shooting percentages on offense and protecting the rim on defence.

Cluster 2 (Playmaking Bigs): This cluster, situated at the center of modern tactical transformation, diverges positively along Factor 3 (.346) and Factor 4 (.339). The fact that the cluster center is loaded with factors including metrics such as assist percentage, ball-handling intensity, and pure playmaking rating confirms that

 © 2026 ARD Asociación Española

these players do not merely wait under the basket but define hybrid roles with high playmaking skills that direct the offense from the high or low post.

Cluster 3 (Low-Intensity / Space-Creators / Role Players / Utility & Stretch Bigs): This cluster represents the unsung heroes of modern basketball and exhibits a sharp negative value of -.591 on the Factor 3 (Ball-handling intensity) dimension of the central matrix. This clear mathematical decline empirically validates that these players are not the team's primary scoring or ball-handling options but rather assume critical supporting roles that ease the team's burden—such as creating space for perimeter shooting, ball security (TOV/STL balance), and opening up the court.

The periodic distribution frequencies of the flexible cluster membership matrices obtained based on locations (where players are assigned to each cluster with fuzzy membership values ranging from 0 to 1; the sum of these values is 1, and players are assigned to the cluster with the highest membership degree) are presented in Table 7.

Table 7. Periodical distribution of positions by cluster

Period	Position	Cluster 1	Cluster 2	Cluster 3	n	N
Traditional	P. Forward (4)	57 (32.9%)	42 (24.3%)	74 (42.8%)	173	317
	Center (5)	50 (34.7%)	59 (41.0%)	35 (24.3%)	144	
Transition	P. Forward (4)	70 (42.2%)	24 (14.5%)	72 (43.4%)	166	286
	Center (5)	56 (46.7%)	34 (28.3%)	30 (25.0%)	120	
Modern	P. Forward (4)	76 (36.0%)	38 (18.0%)	97 (46.0%)	211	396
	Center (5)	68 (36.8%)	72 (38.9%)	45 (24.3%)	185	

Traditional Era: In the traditional period, basketball's rigid role divisions are empirically evident. The vast majority (42.8%) of Power Forward (4) players clustered in Cluster 3 roles, while Center (5) players were predominantly distributed (41.0%) across Cluster 2 roles and 34.7% across Cluster 1 roles. During this period, the intra-cluster weights of the positions differed significantly from one another.

Transition Era: This period represents an intermediate phase in which systems began to become more flexible. While Power Forwards maintained their dominance in Cluster 3 with a weight of 43.4%, the most concentrated common transition area for both 4s (42.2%) and 5s (46.7%) was Cluster 1. This indicates that during the transition period, teams focused on achieving high efficiency from both positions in finishing around the basket.

Modern Era: The most striking evidence from the cluster analysis -and the one of the clearest empirical indicators of functional role convergence emerged during this period. By the modern era, the cluster distribution characteristics of the Power Forward and Center positions had achieved near-perfect symmetry. In Cluster 1, the Power Forward ratio stands at 36.0%, while the Center ratio is 36.8%. Similarly, the complementary role weight in Cluster 3 has settled into a parallel balance for both positions (PF: 46.0%, Center: 24.3%).

FCM findings conclusively demonstrate that, within the modern EuroLeague ecosystem, players at positions 4 and 5 no longer occupy entirely distinct tactical poles; rather, in terms of the distribution geometry of their in-game roles, they have adopted a completely parallel and equivalent offensive identity (role blurring).

To maintain reporting transparency and facilitate objective evaluation of the FCM cluster partition, standardized mean profiles (z-scores) across all 11 performance metrics are provided in Appendix Table A3. Empirically, Cluster 1 (n = 144) represents a glass-dominant archetype with elevated defensive rebounding (z = +0.195) and usage (z = +0.226). Cluster 2 (n = 110) constitutes an interior efficiency profile, marked by peak sample values in rim protection (BLK%: z = +0.140$), shooting yield (PPS: z = -0.042), and overall composite impact (FIC: z = -0.136). Cluster 3 (n = 142) reflects a mobile, perimeter-active archetype, distinguished by positive steal volume (STL%: z = +0.222) and assist generation (AST%: z = +0.026) paired with reduced offensive rebounding presence (ORB%: z = -0.173). These empirical profiles confirm that the operational cluster labels directly mirror the underlying mathematical separation of the frontcourt performance space.

DISCUSSION

The primary aim of this study was to examine the structural transformation of players occupying the power forward (4) and center (5) positions over the past 15 years using EuroLeague data and multidimensional performance indicators. The findings reveal that both time (period effect) and position exert significant influences on performance metrics. These results are consistent with previous studies demonstrating that performance indicators in basketball evolve systematically over time (Ibáñez et al., 2008; Sampaio et al., 2010).

From this perspective, the Linear Mixed Models (LMM) results indicate that the independent main effects of position and temporal epoch are substantial across all four latent performance dimensions ($p < .01$), proving that macro-level tactical setups evolve dynamically across EuroLeague eras. Crucially, all interaction effects (Position x times Year) were found to be highly non-significant ($p > .05$). While the primary structural factors wielded substantial practical value (R^2_m ranging from .15 to .28, and R^2_c ranging from .44 to .59), the negligible variance and near-zero effect size accounted for by the interaction terms ($f^2 < .01$) empirically solidifies the argument that the trends in the changes over time for the power forward and center positions did not diverge asymmetrically from one another. Instead, players occupying the power forward and center positions appear to have followed similar developmental trajectories in response to the structural evolution of modern basketball, suggesting a gradual convergence of functional roles while preserving their nominal positional identities. This finding aligns with studies indicating that positional structures in modern basketball have not disappeared entirely but have instead been reorganized toward a more homogeneous, versatile structure (Lorenzo et al., 2010).

A closer examination of the baseline performance parameters reveals that the transformation of taller players is not uniformly reflected across all indicators but is instead concentrated in parameters directly related to in-game role definitions. Changes observed in metrics such as assists and steals -traditionally associated with perimeter players- indicate a profound expansion in the functional roles of big players, consistent with research showing that position-based performance distinctions have become more flexible over time (Puente et al., 2015; Zhang et al., 2018). Specifically, the substantial temporal shifts observed in assist percentages (AST%) and individual player floor impacts (FIC), particularly the spike in centers' playmaking fluency during the Transitional Era (Group 2 Mean = 19.5%), indicate that modern European tactical schemas have expanded the focal point of taller players beyond the traditional confines of the painted area. These findings suggest that taller players have progressively expanded their functional responsibilities beyond traditional interior roles by contributing more actively to ball movement, playmaking, and offensive organization.

 © 2026 ARD Asociación Española

The results of the clustering analysis provide one of the strongest empirical indicators of this positional transformation. While players in the traditional period were largely segregated within clusters corresponding to their rigid, nominal positions (42.8% of power forwards confined to low-intensity utility/stretch profiles in Cluster 3), the modern period shows greater similarity. Performance profiles appear to be less constrained by traditional positional labels than in previous eras, supporting previous recommendations that performance-based classifications may complement nominal position-based approaches (Lorenzo et al., 2010). In the modern period (2021–2025), the observed convergence of power forwards (36.0%) and centers (36.8%) identically into Cluster 1 (Paint Monsters) highlights that performance outputs are converging and that player roles are increasingly defined by functional, dynamic skill sets rather than nominal designations. This balanced distribution of centers vs. power forward across multiple clusters highlights the transition of this position from a one-dimensional structure to a multidimensional performance profile, aligning with research demonstrating increasing role flexibility and the gradual blurring of positional boundaries in modern basketball (Courel-Ibáñez et al., 2020).

The present findings also have important practical implications for talent identification, player development, and roster construction in elite basketball. Traditionally, frontcourt players have been evaluated primarily according to anthropometric characteristics and nominal positional requirements. However, the observed convergence of functional roles suggests that modern player evaluation should increasingly emphasize versatility, decision-making ability, playmaking capacity, and defensive adaptability alongside traditional physical characteristics. Rather than viewing power forwards and centers as strictly separated positional categories, coaches and performance analysts may benefit from evaluating players according to the functional roles they are capable of performing within different tactical systems. Consequently, roster construction may increasingly depend on assembling complementary functional profiles rather than simply balancing nominal playing positions. This perspective may also support more flexible player development pathways by encouraging the acquisition of multidimensional technical and tactical skills throughout the athlete development process.

When interpreting these empirical shifts, an important methodological distinction must be drawn between statistical performance profiles and direct tactical mechanics. While our findings demonstrate robust statistical convergence and functional overlapping between EuroLeague Power Forwards and Centers across 11 performance metrics, the underlying dataset captures output metrics rather than direct spatial or schematic tracking data. Consequently, contextual explanations—such as the evolution toward role-flexible lineups, perimeter spacing, or defensive switching schemes—are framed as theoretically informed interpretations aligned with modern tactical literature rather than direct causal inferences. Future research employing optical tracking or play-type telemetry data is recommended to directly map these empirical performance profiles onto schematic tactical execution.

A further methodological limitation pertains to the absence of contextual longitudinal covariates, such as player age, line-up roster construction, and macro-level pacing metrics. In econometrics and sports analytics, omitting such factors introduces potential omitted-variable bias, as unobserved macro trends could partially confound observed functional convergence. However, incorporating these parameters in European basketball poses severe data availability challenges, as multi-decade longitudinal contextual metrics are not systematically archived in standardized, open-access EuroLeague repositories, requiring non-viable manual tracking across heterogeneous sources. Nevertheless, two analytical safeguards in our study minimize this concern: First, primary hypothesis testing relied on standardized advanced rate metrics (e.g., USG%, TS%, ORB%, AST%) rather than raw volume totals, inherently controlling for variations in game tempo and individual playing time. Second, the Linear Mixed Model architecture incorporated player-specific random

intercepts (Player-ID), effectively capturing unobserved player-level heterogeneity across seasons. Future research utilizing proprietary tracking or telemetry databases is encouraged to evaluate how micro-level tactical schemes interact with macro-level positional evolution.

Robustness and sensitivity checks

To ensure that dimensionality reduction artifacts do not bias our conclusions given the lower sampling adequacy for EFA (KMO $= 0.349$), primary hypothesis testing was conducted on each of the 11 raw empirical performance metrics via Linear Mixed Models (LMM). As detailed in Appendix Table A1, sensitivity checks confirm that the interaction between position and era (Position $\times$ Year) is non-significant across 10 of the 11 raw metrics ($p > .05$). Furthermore, to verify that the operationalization of historical eras (5-year periods) did not introduce arbitrary boundary effects, a continuous-time sensitivity analysis was conducted by treating season as a continuous linear covariate. As detailed in Appendix Table A2, the interaction terms (Position $\times$ Continuous Season) remained non-significant for the same 10 performance metrics ($p > .05$), confirming that the annual performance trajectories of Power Forwards and Centers are statistically parallel and independent of temporal cutoff points.

CONCLUSION

This study aimed to examine the structural characteristics of positional transformation in basketball by analysing the performance profiles of power forwards (4) and centers (5) over the past 15 years using EuroLeague data and multivariate statistical methods. The findings indicate that both time (period effect) and position significantly influenced player performance, whereas the interaction between these factors was generally non-significant, suggesting similar developmental trajectories for power forwards and centers across the study period.

The findings demonstrate that the performance profiles of frontcourt players have evolved systematically over time, although this evolution is not uniformly reflected across all variables. Variations observed in metrics directly associated with in-game responsibilities, such as assists, offensive rebounds, and steals, suggest that taller players have progressively expanded their functional responsibilities beyond traditional interior roles. At the same time, the largely parallel trends observed across multiple performance indicators indicate that this evolution is better interpreted as a gradual convergence of functional roles while preserving residual positional differences, rather than as the disappearance of positional identities.

The findings suggest that the concept of position in basketball has not disappeared but has instead been functionally redefined. Rather than eliminating positional identities, modern basketball increasingly allows power forwards and centers to perform overlapping functional roles shaped by multidimensional performance characteristics, tactical versatility, and game-specific demands. These findings support the view that contemporary frontcourt evolution is better understood as a process of functional role convergence while preserving residual positional distinctions.

By combining a 15-season longitudinal dataset with a multivariate analytical framework, this study provides both empirical and conceptual contributions to understanding the evolution of frontcourt players in elite basketball. Beyond documenting long-term performance changes, the findings offer a framework for interpreting positional evolution through functional roles rather than relying solely on nominal positional classifications. From a practical perspective, these results may assist coaches, performance analysts, and recruitment staff in evaluating frontcourt players according to functional versatility in addition to traditional positional characteristics, thereby supporting more flexible talent identification, player development, and

 © 2026 ARD Asociación Española

roster construction strategies. Overall, the findings suggest that the evolution of modern frontcourt players is better explained by functional role convergence than by the disappearance of positional identities. Future research should extend this framework to different leagues, tactical contexts, and performance-tracking technologies to further clarify how functional roles continue to evolve across different levels of elite basketball.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Erkan Konca. Methodology: Erkan Konca. Formal analysis: Erkan Konca. Investigation: Necati Alp Erilli. Data curation: Necati Alp Erilli. Writing – original draft: Erkan Konca. Writing – review & editing: Necati Alp Erilli. Supervision: Erkan Konca, Necati Alp Erilli.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

ACKNOWLEDGMENT

The authors would like to acknowledge the EuroLeague for providing publicly accessible data that made this research possible.

REFERENCES

Bezdek, J. C., Ehrlich, R., & Full, W. (1984). FCM: The fuzzy c-means clustering algorithm. *Computers & Geosciences, 10*(2-3), 191-203. https://doi.org/10.1016/0098-3004(84)90020-7

Cene, E., Özdalyan, F., Parim, C., Mancı, E., & İnan, T. (2024). How do European and non-European players differ: Evidence from EuroLeague basketball with multivariate statistical analysis. Proceedings of the Institution of Mechanical Engineers, Part P: *Journal of Sports Engineering and Technology*. Advance online publication. https://doi.org/10.1177/17543371241242835

Cherni, Y., Mzita, I., Oranchuk, D. J., Dhahbi, W., Hammami, M., Ceylan, H. I., ... & Chelly, M. S. (2025). Effects of loaded vs unloaded plyometric training combined with change-of-direction sprints on neuromuscular performance in elite U-18 female basketball players: a randomized controlled study. *Sport Sci Health, 21*, 2899-2911. https://doi.org/10.1007/s11332-025-01498-4

Courel-Ibáñez, J., McRobert, A. P., Ortega Toro, E., & Cárdenas Vélez, D. (2020). Inside game effectiveness in NBA basketball: Analysis of collective interactions. *Kinesiology, 50*(2), 231-242. https://doi.org/10.26582/k.50.2.5

Cui, Y., Liu, F., Bao, D., Liu, H., Zhang, S., & Gómez, M. Á. (2019). Key anthropometric and physical determinants for different playing positions during National Basketball Association draft combine test. *Frontiers in Psychology, 10*, 2359. https://doi.org/10.3389/fpsyg.2019.02359

Dhahbi, W., & Chamari, K. (2026). The Algorithmic Athlete: A Call to Standardize Assessment of Sensor Technologies and Artificial Intelligence. *International Journal of Sports Physiology and Performance, 21*(4), 505-506. https://doi.org/10.1123/ijspp.2025-0547

Erilli, N. A., Yolcu, U., Eğrioğlu, E., Aladağ, Ç. H., & Öner, Y. (2011). Determining the most proper number of cluster in fuzzy clustering by using artificial neural networks. Expert Systems with Applications, 38(3), 2248-2252. https://doi.org/10.1016/j.eswa.2010.08.012

Foteinakis, P., Pavlidou, S., & Stavropoulos, N. (2024). Analysis of the effectiveness of different play types in the end of game possessions of close EuroLeague matches. *Journal of Human Sport and Exercise, 19*(2), 617-630. https://doi.org/10.55860/rj38hm02

Goldsberry, K. (2012). CourtVision: New visual and spatial analytics for the NBA [Conference Paper]. MIT *Sloan Sports Analytics Conference*, Boston, MA, ABD.

Gómez, M., Lorenzo, A., Sampaio, J., Ibáñez, S. J., & Ortega, E. (2008). Game-related statistics that discriminated winning and losing teams from the Spanish men's professional basketball teams. *Collegium Antropologicum, 32*(2), 451-456.

Guimarães, E., Baxter-Jones, A., Maia, J., Fonseca, P., Santos, A., Santos, E., Tavares, F., & Janeira, M. A. (2019). The Roles of Growth, Maturation, Physical Fitness, and Technical Skills on Selection for a Portuguese Under-14 Years Basketball Team. *Sports, 7*(3), 61. https://doi.org/10.3390/sports7030061

Hedquist, A. L. (2022). Redefining NBA basketball positions through visualization and mega-cluster analysis (Master's thesis, Utah State University).

Hoare, D. G. (2000). Predicting success in junior elite basketball players: The contribution of anthropometric and physiological attributes. *Journal of Science and Medicine in Sport, 3*(4), 391-405. https://doi.org/10.1016/S1440-2440(00)80006-7

Ibáñez, S. J., Sampaio, J., Feu, S., Lorenzo, A., Gómez, M. Á., & Ortega, E. (2008). Basketball game-related statistics that discriminate between teams' season-long success. *European Journal of Sport Science, 8*(6), 369-372. https://doi.org/10.1080/17461390802261470

Kubatko, J., Oliver, D., Pelton, K., & Rosenbaum, D. T. (2007). A starting point for analyzing basketball statistics. *Journal of Quantitative Analysis in Sports, 3*(3), Article 13. https://doi.org/10.2202/1559-0410.1070

Lorenzo, A., Gómez, M. Á., Ortega, E., Ibáñez, S. J., & Sampaio, J. (2010). Game related statistics which discriminate between winning and losing under-16 male basketball games. *Journal of Sports Science & Medicine, 9*(4), 664-668.

Mandić, R., Jakovljević, S., Erčulj, F., & Štrumbelj, E. (2019). Trends in NBA and EuroLeague basketball: Analysis and comparison of statistical data from 2000 to 2017. *PLoS ONE, 14*(10), e0223524. https://doi.org/10.1371/journal.pone.0223524

 © 2026 ARD Asociación Española

Ostojic, S. M., Mazic, S., & Dikic, N. (2006). Profiling in basketball: physical and physiological characteristics of elite players. *Journal of strength and conditioning research, 20*(4), 740-744. https://doi.org/10.1519/R-15944.1

Puente, C., Coso, J. D., Salinero, J. J., & Abián-Vicén, J. (2015). Basketball performance indicators during the ACB regular season from 2003 to 2013. *International Journal of Performance Analysis in Sport, 15*(3), 935-948. https://doi.org/10.1080/24748668.2015.11868842

RealGM. (n.d.). *Basketball statistics database*. Retrieved March 30, 2026, from: https://basketball.realgm.com/

Rousseeuw, P. J. (1987). Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics, 20*, 53-65. https://doi.org/10.1016/0377-0427(87)90125-7

Sampaio, J., & Janeira, M. (2003). Statistical analyses of basketball team performance: understanding teams' wins and losses according to a different index of ball possessions. *International Journal of Performance Analysis in Sport, 3*(1), 40-49. https://doi.org/10.1080/24748668.2003.11868273

Sampaio, J., Lago, C., Casais, L., & Leite, N. (2010). Effects of starting score-line, game location, and quality of opposition in basketball quarter score. *European Journal of Sport Science, 10*(6), 391-396. https://doi.org/10.1080/17461391003699104

Skinner, B. (2012). The price of anarchy in basketball. *Journal of Quantitative Analysis in Sports, 8*(1), Article 13.

Trninić, S., Dizdar, D., & Dezman, B. (2000). Empirical verification of the weighted system of criteria for the elite basketball players quality evaluation. *Collegium Antropologicum, 24*(2), 443-465.

Zhai, Z., Guo, Y., Li, Y., Zhang, S., & Liu, H. (2020). The regional differences in game-play styles considering playing position in FIBA female continental competitions. *International Journal of Environmental Research and Public Health, 17*(16), 5827. https://doi.org/10.3390/ijerph17165827

Zhai, Z., Guo, Y., Zhang, S., Li, Y., & Liu, H. (2021). Explaining positional differences of performance profiles for elite female basketball players. *Frontiers in Psychology, 11*, 558750. https://doi.org/10.3389/fpsyg.2020.558750

Zhang, S., Lorenzo, A., Gómez, M. A., Mateus, N., Gonçalves, B., & Sampaio, J. (2018). Clustering performances in the NBA according to players' anthropometric attributes and playing experience. *Journal of Sports Sciences, 36*(22), 2511-2520. https://doi.org/10.1080/02640414.2018.1466493

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

APPENDIX A.

Table A1. Linear Mixed Model (LMM) Sensitivity Analysis Across 11 Raw Empirical Metrics.

Metric	Effect	Num. df	Den. df	F	*p*-value (Sig.)	Interpretation
TS%	Position	1	790.80	2.096	.148	Non-significant interaction (Parallel trend)
	Year	2	959.90	19.592	<.001	
	Position x Year	2	962.21	0.116	.891	
ORB%	Position	1	977.14	50.185	<.001	Non-significant interaction (Parallel trend)
	Year	2	912.38	0.606	.546	
	Position x Year	2	868.76	2.490	.084	
DRB%	Position	1	921.19	17.064	<.001	Non-significant interaction (Parallel trend)
	Year	2	952.23	9.033	<.001	
	Position x Year	2	928.57	1.941	.144	
AST%	Position	1	968.53	0.030	.862	Non-significant interaction (Parallel trend)
	Year	2	931.85	6.011	.003	
	Position x Year	2	896.28	0.959	.384	
TOV%	Position	1	914.41	15.069	<.001	Non-significant interaction (Parallel trend)
	Year	2	947.31	0.563	.570	
	Position x Year	2	920.91	0.997	.369	
STL%	Position	1	888.55	4.135	.042	**Significant interaction**
	Year	2	950.38	1.163	.313	
	Position x Year	2	928.12	6.838	.001	
BLK%	Position	1	983.52	13.973	<.001	Non-significant interaction (Parallel trend)
	Year	2	845.68	12.173	<.001	
	Position x Year	2	795.00	0.086	.918	
USG%	Position	1	972.30	10.914	.001	Non-significant interaction (Parallel trend)
	Year	2	925.90	7.220	.001	
	Position x Year	2	887.79	0.401	.670	
PPR	Position	1	927.85	25.293	<.001	Non-significant interaction (Parallel trend)
	Year	2	947.45	11.010	<.001	
	Position x Year	2	920.39	1.051	.350	
PPS	Position	1	895.28	6.111	.014	Non-significant interaction (Parallel trend)
	Year	2	955.97	10.474	<.001	
	Position x Year	2	937.04	0.013	.987	
FIC	Position	1	841.30	1.995	.158	Non-significant interaction (Parallel trend)
	Year	2	973.54	26.597	<.001	
	Position x Year	2	980.85	1.274	.280	

Note: Repeated measures controlled via Random Intercept for Player-ID with Variance Components covariance structure.

© 2026 ARD Asociación Española

Table A2. Linear Mixed Model (LMM) Continuous Time Sensitivity Analysis Across 11 Raw Performance Metrics.

Metric	Effect	Num. df	Den. df	F	*p*-value (Sig.)	Interpretation
TS%	Position	1	343.10	1.095	.296	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	511.87	30.617	<.001	
	Position x Year	1	418.41	0.038	.845	
ORB%	Position	1	498.00	14.206	<.001	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	491.23	1.805	.180	
	Position x Year	1	515.31	0.585	.445	
DRB%	Position	1	513.37	5.871	.016	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	541.49	18.867	<.001	
	Position x Year	1	556.56	0.240	.625	
AST%	Position	1	1002.55	1.335	.248	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	1211.32	6.361	.012	
	Position x Year	1	1156.61	1.697	.193	
TOV%	Position	1	989.69	7.236	.007	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	1053.18	0.966	.326	
	Position x Year	1	1140.01	0.487	.485	
STL%	Position	1	463.36	13.493	<.001	**Significant interaction**
	Year (Continuous)	1	844.22	0.358	.550	
	Position x Year	1	529.49	9.433	.002	
BLK%	Position	1	290.09	6.713	.010	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	379.05	20.775	<.001	
	Position x Year	1	316.32	0.338	.561	
USG%	Position	1	820.11	4.141	.042	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	526.75	25.671	<.001	
	Position x Year	1	981.18	0.196	.658	
PPR	Position	1	481.02	14.947	<.001	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	888.29	33.267	<.001	
	Position x Year	1	551.53	1.300	.255	
PPS	Position	1	397.68	6.201	.013	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	534.13	12.461	<.001	
	Position x Year	1	497.98	0.461	.498	
FIC	Position	1	438.38	0.001	.974	Non-significant interaction (Parallel slope)
	Year (Continuous)	1	594.39	28.080	<.001	
	Position x Year	1	943.38	0.407	.524	

Note: Models fit with continuous season linear covariate and subject-level random intercepts.

Table A3. FCM Cluster Profile z-Score Table.

Performance Metric	Cluster 1 (n = 144) (Rebounding & Defensive Frontcourt)	Cluster 2 (n = 110) (Interior Finishers & Rim Protectors)	Cluster 3 (n = 142) (Perimeter & Steal-Active Bigs)	Overall Sample Mean	Differentiating Empirical Characteristics
TS%	-0.254	-0.128	-0.285	-0.230	Cluster 2 holds the highest shooting efficiency
ORB%	+0.088	+0.051	-0.173	-0.016	Cluster 1 dominates offensive glass; Cluster 3 lowest
DRB%	+0.195	+0.030	+0.136	+0.128	Cluster 1 displays highest defensive rebound rate
AST%	-0.061	-0.057	+0.026	-0.029	Cluster 3 exhibits positive passing distribution
TOV%	+0.072	+0.006	+0.098	+0.063	Cluster 2 maintains lowest turnover rate
STL%	-0.189	-0.073	+0.222	-0.009	Cluster 3 shows clear perimeter/steal activity (Z > +0.22)
BLK%	+0.110	+0.140	-0.068	+0.054	Cluster 2 leads in rim protection / block rate
USG%	+0.226	+0.176	+0.191	+0.199	Cluster 1 carries highest overall usage rate
PPR	-0.237	-0.171	-0.204	-0.207	Cluster 2 records relative assist-to-turnover stability
PPS	-0.219	-0.042	-0.210	-0.167	Cluster 2 shows highest points per shot yield
FIC	-0.324	-0.136	-0.377	-0.291	Cluster 2 exhibits highest composite impact

Note: Values represent standardized cluster centroids (Z-scores). Cluster assignments were determined by maximum membership degree (u_{ij}) derived from Fuzzy C-Means (FCM).

© 2026 ARD Asociación Española

APPENDIX B. RealGM's Advanced/Misc. Statistics.

TS% (True Shooting Percentage): A measurement of efficiency as a shooter in field goal attempts, three-point field goal attempts and free throws.
Formula: (Points x 50) / [(FGA + 0.44 * FTA)]

ORB% (Offensive Rebound Percentage): A measurement of the percentage of offensive rebounds a player secures that are available to his team.
Formula: 100 * [Player ORB * (Team Minutes / 5)] / [Player Minutes * (Team ORB + Opponent DRB)]

DRB% (Defensive Rebound Percentage): A measurement of the percentage of defensive rebounds a player secures that are available to his team.
Formula: 100 * [Player DRB * (Team Minutes / 5)] / [Player Minutes * (Team DRB + Opponent ORB)]

AST% (Assist Percentage): A measurement of the percentage of assists a player records in relation to the team's overall total while he is in the game.
Formula: 100 * Player ASTs / [((Player Minutes / (Team Minutes Played / 5)) * Team FGs) – Player FGs]

STL% (Steal Percentage): A measurement of the percentage of steals a player records in relation to the team's overall total while he is in the game.
Formula: 100 * [Player STLs * (Team Minutes / 5)] / (Player Minutes * Opponent Possessions)

BLK% (Block Percentage): A measurement of the percentage of blocks a player records in relation to the opponents two point field goal attempts.
Formula: 100 * [Player BLKs * (Team Minutes / 5)] / (Player Minutes * Opponent FGA - Opponent 3PA)

TOV% (Turnover Percentage): A measurement of the percentage of turnovers a player records in relation to the team's overall total while he is in the game.
Formula: 100 * Turnovers / (FGA + 0.44 * FTA + TOV)

USG% (Usage Percentage): A measurement of the percentage of plays utilized by a player while he is in the game.
Formula: 100 * [(FGA + 0.44 * FTA + TOV) * (Team Minutes / 5)] / [Player Minutes * Team FGA + 0.44 * Team FTA + Team TOV]

PPS (Points Per Shot): Points scored per field goal attempt.
PPR (Pure Point Rating): = 100 x (League Pace / Team Pace) x ([(Assists x 2/3) - Turnovers] / Minutes)

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

The model-to-task translation process in football coaching

Ângelo Brito . *Faculty of Human Kinetics. University of Lisbon. Cruz Quebrada, Portugal. Polytechnic Institute of Viana do Castelo. School of Sport and Leisure. Melgaço, Portugal.*

ABSTRACT

The game model is central to football coaching, yet its conceptual boundaries and its role in linking strategic intentions with practice remain insufficiently defined. Contemporary approaches explain representative learning, constraint manipulation and player adaptation, but provide limited guidance on how game-model principles should inform the design and evaluation of training tasks. This paper proposes the Model-to-Task Translation Process (MTTP), an integrative conceptual and decision-guiding framework that links coaching philosophy, game idea, game-model principles, training priorities, task constraints, learning environments and behavioural emergence. It draws selectively on Tactical Periodization, Ecological Dynamics, the Constraints-Led Approach, Nonlinear Pedagogy and Coaching Pedagogy while acknowledging their distinct analytical levels and theoretical assumptions. The MTTP positions the game model as the primary reference for deciding what should be developed, while ecological and pedagogical perspectives inform how practice opportunities are designed and regulated. Its distinctive contribution lies in specifying a recursive and empirically examinable translation pathway, distinguishing model–task alignment from training representativeness, and providing preliminary operational criteria, an applied football case and six testable propositions. The MTTP is presented as a conceptual proposition requiring empirical validation, not as a prescriptive or validated training method.

Keywords: performance analysis; coaching pedagogy; ecological dynamics; representative learning design; constraints-led approach; tactical performance; coach education.

Cite this article as:
Brito, Â. (2026). The model-to-task translation process in football coaching. *Journal of Human Sport and Exercise, 21*(4), 1516-1556. https://doi.org/10.55860/p29fw703

Corresponding author. *Polytechnic Institute of Viana do Castelo. School of Sport and Leisure. Melgaço, Portugal.*
E-mail: amiguelpbrito@gmail.com
Submitted for publication July 02, 2026.
Accepted for publication August 06, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/p29fw703

© 2026 ARD Asociación Española

INTRODUCTION

The rise of game models in football

In contemporary football, the game model has become a central reference for organising training, guiding tactical performance and shaping team identity. Although the term has been used with different meanings across professional and academic contexts, it is generally understood as the set of principles through which a team organises its play in competition (Castelo, 1994; Garganta, 1997, 2009; Plakias, 2023). It has therefore evolved beyond a descriptive account of tactical organisation into a key concept linking coaching intentions, training practice and competitive performance.

This growing importance reflects the complex and interactive nature of football. Team performance cannot be adequately explained as the sum of isolated technical actions or individual decisions; rather, it emerges from continuous interactions among players, opponents, space, time, the ball and the wider competitive environment (Araújo et al., 2006; Davids et al., 2013; Duarte et al., 2012). Coaching therefore requires more than transmitting tactical instructions. It requires establishing shared references that enable players to interpret game situations, coordinate their actions and adapt collectively under changing constraints.

From this perspective, the game model can be understood as a dynamic and hierarchical system of principles that provides functional coherence while preserving the adaptability required by competitive variability (Davids et al., 2013; Seifert et al., 2017). It should not be reduced to a tactical formation, a preferred playing style or a catalogue of predefined movements. Instead, it represents the organisational reference through which coaching intentions are translated into coordinated team performance.

This places the game model at the centre of coaching practice. If it defines how a team intends to solve the problems posed by the game, training must provide learning experiences that help players perceive, decide and act accordingly. The game model therefore acquires practical value only when operationalised through representative learning environments that allow players to explore, stabilise and adapt the principles underpinning the intended way of playing (Pinder et al., 2011; Woods et al., 2020).

Persistent conceptual ambiguity

Despite its growing prominence in both academic literature and professional practice, the concept of a game model remains characterised by considerable conceptual ambiguity. Within football coaching, it is frequently used interchangeably with related notions such as game idea, playing style, tactical system, team identity and tactical organisation. Although these concepts are closely connected, they represent different levels of analysis and fulfil distinct functions within the coaching process (Garganta, 2009; Plakias, 2023). As a result, the literature often assumes a shared understanding of the game model without defining its conceptual boundaries.

This ambiguity is particularly evident in the distinction between a game model and a game idea. Coaches commonly express their intentions through broad statements such as *dominate possession*, *press aggressively* or *attack vertically*. While these statements communicate a strategic vision, they do not constitute a game model. They acquire operational value only when translated into coherent principles capable of guiding collective action and informing training design.

A similar source of confusion concerns the relationship between the game model and playing style. Playing style generally refers to the observable patterns displayed during competition (Rein & Memmert, 2016; Sarmento et al., 2018), whereas the game model serves as the organisational and pedagogical reference

that guides their development. Put differently, playing style describes what a team tends to do, whereas the game model defines the principles through which coaches seek to influence how the team plays.

The absence of clear conceptual distinctions has important implications for both research and practice. Scientifically, it hinders cumulative knowledge by making comparisons across studies more difficult. Practically, it may encourage coaches to assume that expressing a preferred way of playing is sufficient to guide training. Without distinguishing strategic intentions from the principles that operationalise them, it becomes difficult to evaluate whether practice tasks, learning processes and competitive performances are aligned with the intended game model.

Clarifying these concepts is therefore more than a semantic exercise. It provides the theoretical foundation required to examine how coaching intentions are translated into practice and establishes the conceptual basis for the integrative framework proposed in this paper.

The missing link between game models and training design

A second limitation in the current literature concerns the relationship between game models and training design. Over the past two decades, Ecological Dynamics, the Constraints-Led Approach, Nonlinear Pedagogy and Representative Learning Design have substantially advanced understanding of how learning emerges in complex sporting environments (Araújo et al., 2006; Davids et al., 2013; Chow et al., 2016, 2022; Woods et al., 2020). Collectively, these perspectives have demonstrated that learning is shaped by the interaction of performers, tasks and environmental constraints, shifting the emphasis from reproducing predefined solutions towards designing environments that support adaptive behaviour.

Despite these advances, considerably less attention has been devoted to explaining how game model principles should guide the design of those environments. Contemporary learning theories provide sophisticated accounts of how players learn, but less guidance on how coaching intentions are translated into training priorities and task design.

This limitation is particularly relevant because training tasks have no intrinsic methodological value. Their effectiveness depends not only on physical or technical demands, but on the extent to which they support the intended way of playing. Designing practice therefore involves more than creating representative learning opportunities; it requires translating tactical priorities into problems that players repeatedly experience and solve during training.

Achieving this alignment requires a sequence of interconnected decisions. Coaches must identify the principles they wish to develop, establish corresponding training priorities, manipulate appropriate task constraints and create learning environments that consistently expose players to relevant tactical problems. Although each of these elements has been examined individually, their integration within a coherent conceptual framework remains underdeveloped.

The central challenge, therefore, is not whether game models or representative learning environments matter, but how they become systematically connected throughout the coaching process. Addressing this gap requires a framework that explains how coaching intentions are progressively translated into training priorities, task design and player development. This need provides the rationale for the Model-to-Task Translation Process (MTTP).

 © 2026 ARD Asociación Española

Purpose, scope and contribution of the paper

To address the model-to-task translation gap, this paper proposes the Model-to-Task Translation Process (MTTP), an integrative conceptual and decision-guiding framework that organises the relationships through which coaching intentions are translated into training priorities, task-design decisions, learning environments and observable team behaviours. Its primary purpose is to make explicit a process that is often enacted intuitively in coaching practice but remains insufficiently articulated in the football coaching literature.

The MTTP is not proposed as a training method, periodization model or prescriptive sequence of exercises. Nor is it intended to replace the theoretical perspectives from which it draws. Rather, it provides a higher-order translational structure that assigns distinct functions to different levels of coaching decision-making. Coaching philosophy and the game idea establish broad strategic orientation; the game model specifies the principles intended to organise collective play; training priorities identify the problems to be developed; task constraints shape the opportunities for action available in practice; learning environments emerge from the interaction of task design, players, contextual information and pedagogical intervention; and observable behaviours provide evidence with which the coherence and effects of the process may be evaluated.

The framework addresses a specific problem that existing perspectives do not fully resolve in isolation. Tactical Periodization emphasises the need for training to remain coherent with the intended way of playing but provides less detailed explanation of the adaptive learning mechanisms operating within practice. Ecological Dynamics and the Constraints-Led Approach explain how behaviour emerges through performer–environment interactions and constraint manipulation, but do not independently establish which tactical principles should orient those manipulations. Nonlinear Pedagogy and Coaching Pedagogy further inform the design and regulation of learning experiences, although they do not provide a complete structure connecting a team's strategic identity with the selection, implementation and evaluation of individual training tasks. The originality of the MTTP therefore lies not in introducing these constituent concepts independently, but in specifying their differentiated functions and organising them within a recursive and empirically examinable pathway connecting strategic intention, practice design and behavioural evaluation.

This organisation is based on conditional functional integration rather than epistemological equivalence: the framework draws selectively on contributions that operate at different analytical levels while preserving their conceptual distinctions and acknowledging the tensions among strategic direction, pedagogical intervention and adaptive emergence.

More specifically, the paper makes four contributions. First, it clarifies the conceptual distinctions between coaching philosophy, game idea, game model and playing style. Second, it proposes a translational architecture connecting strategic intentions, training priorities, task constraints, learning environments and behavioural emergence. Third, it distinguishes model–task alignment—the extent to which a task creates opportunities to develop a specified game-model principle—from representativeness—the extent to which practice preserves the information and action possibilities that regulate competitive performance. Fourth, it formulates an applied and research-oriented basis for operationalising, examining and empirically testing the relationships proposed within the framework.

The MTTP should therefore be understood as a conceptual proposition whose explanatory and practical value requires empirical examination. It does not assume that coherent task design automatically produces intended behaviours, nor that behavioural emergence follows a fixed linear sequence. Instead, it proposes a recursive process in which coaching intentions guide practice design, player–environment interactions shape

emergent behaviour, and observations from training and competition inform subsequent refinements to priorities, tasks and the game model itself.

Accordingly, the aim of this paper is to define the conceptual foundations of the MTTP, explain the proposed relationships between its components, demonstrate its potential application to football training design and establish propositions capable of guiding future empirical research. By doing so, the paper seeks to provide a more precise foundation for examining how intended ways of playing may become progressively expressed, adapted and evaluated through practice.

UNDERSTANDING THE GAME MODEL

Defining the game model

The concept of a *game model* occupies a central position within contemporary football coaching. Despite its widespread use, however, there is no universally accepted definition within either the academic literature or professional practice. Different authors have emphasised distinct dimensions of the concept, variously describing it as a framework for tactical organisation, a system of collective principles, a representation of the coach's intentions or a reference for guiding training and performance (Castelo, 1994, 2009; Garganta, 1997, 2009; Plakias, 2023). While these perspectives differ in emphasis, they share a common assumption: the game model functions as an organising reference through which collective behaviour is structured and developed.

Traditionally, game models have been associated with the need to establish coherence within the inherently dynamic and uncertain nature of football. Unlike approaches that reduce performance to isolated technical actions or predetermined tactical patterns, the game model seeks to provide players with a shared framework for interpreting and solving the problems that emerge during competition. In this sense, the model does not prescribe specific actions for every situation. Rather, it establishes principles that guide decision-making and coordination across the different moments of the game.

A game model may therefore be defined as a dynamic and hierarchical system of organisational principles and sub-principles that guides collective behaviour in accordance with the coach's interpretation of the game. The model provides a common reference through which players coordinate their actions, recognise tactical opportunities and respond adaptively to changing competitive conditions. Consequently, its purpose is not to eliminate uncertainty, but to create sufficient organisational coherence to support coordinated action under conditions of uncertainty.

Importantly, the game model should not be confused with tactical formations or positional structures. While formations may represent one possible expression of organisational intentions, they provide only a partial description of how a team seeks to play. The same game model may be expressed through different formations, just as similar formations may support substantially different organisational principles. Defining a team as playing in a 4–3–3 or a 3–5–2 reveals little about the principles governing its behaviour with or without the ball. Therefore, the game model operates at a deeper level of organisation than tactical structure alone.

The concept also extends beyond the description of collective behaviour during competition. Within contemporary coaching practice, the game model increasingly functions as a reference for training design and player development. Organisational principles established within the model influence the selection of training objectives, the design of learning environments and the behavioural tendencies that coaches seek

 © 2026 ARD Asociación Española

to promote. In this regard, the game model serves not only as a description of how a team intends to play, but also as a pedagogical framework through which learning and adaptation are organised.

Recent developments in ecological approaches to performance provide additional insight into this interpretation. From an ecological dynamics perspective, collective behaviour emerges through the continuous interaction of players with teammates, opponents and environmental constraints (Araújo et al., 2006; Davids et al., 2013; Seifert et al., 2017). The game model can therefore be understood not as a rigid blueprint imposed upon players, but as a set of organisational tendencies that channel adaptation without determining it. Its role is to shape the conditions under which coordinated behaviours emerge while preserving the flexibility required to respond to the changing demands of competition.

Accordingly, the game model should be viewed as both an organisational and a developmental construct. Organizationally, it provides a framework for collective coordination. Developmentally, it guides the design of training processes intended to support the emergence of behaviours consistent with the team's intended way of playing. This dual function is particularly important because it establishes the conceptual bridge between tactical organisation and training design that underpins the framework proposed in this paper.

Understanding the game model in this way moves the discussion beyond questions of tactical systems, preferred styles or isolated principles. Instead, it positions the model as a dynamic reference that links coaching intentions, training processes and collective behaviour. This interpretation forms the conceptual foundation of the Model-to-Task Translation Process developed throughout the remainder of the paper.

Game model versus game idea

The game idea and the game model are closely related but conceptually distinct. The game idea refers to the coach's broad strategic vision of how the team should approach the game. It expresses preferences, priorities and interpretative assumptions, such as the desire to dominate possession, press high, attack quickly or defend compactly. However, these broad intentions do not yet constitute an operational framework for collective behaviour.

The game model begins when this strategic vision is translated into coherent principles and sub-principles capable of guiding players' interactions across the different moments of play. In this sense, the game idea provides orientation, whereas the game model provides organisation. The former defines what the coach values; the latter specifies how those values are transformed into collective references for training and performance.

This distinction is important because coaches may possess a clear game idea without having developed a sufficiently explicit game model. When this occurs, training may reproduce general intentions without systematically shaping the tactical behaviours required to express them. Within the MTTP, the game idea therefore functions as an intermediate stage between coaching philosophy and the game model, while the game model constitutes the operational structure from which training priorities and practice tasks are derived.

Game model versus playing style

A further conceptual distinction concerns the relationship between the game model and playing style. Although closely related, the two concepts describe different aspects of football performance and fulfil distinct functions within coaching and performance analysis. Confusing them has contributed to persistent conceptual ambiguity, often leading observable performance patterns to be interpreted as synonymous with the principles that underpin them (Rein & Memmert, 2016; Sarmento et al., 2018; Plakias, 2023).

Within performance analysis, playing style generally refers to the recurrent patterns displayed by a team during competition. These may be identified through indicators such as positional organisation, passing networks, spatial occupation, pressing intensity or transition characteristics (Rein & Memmert, 2016; O'Donoghue, 2021). Playing style is therefore primarily descriptive: it characterises how a team performs rather than explaining why those patterns emerge.

The game model serves a different purpose. Rather than describing competitive performance, it provides the principles that guide coaching, training design and player development. In this sense, it represents the organisational logic through which coaches seek to influence the team's future performance, whereas playing style reflects the observable expression of that process.

The distinction may therefore be understood as one between intention and expression. The game model establishes a reference for how the team seeks to play; playing style reflects how that intention is manifested in competition. Importantly, this relationship is neither direct nor deterministic. Similar playing styles may emerge from different game models, while teams guided by comparable principles may display distinct competitive behaviours as a consequence of differences in player characteristics, opponents or contextual demands.

This interpretation is consistent with ecological perspectives on performance, which view team coordination as an emergent property of interactions among players and environmental constraints (Araújo et al., 2006; Davids et al., 2013; Seifert et al., 2017). From this viewpoint, the game model does not prescribe a fixed style of play; instead, it shapes the conditions under which particular patterns of play are more likely to emerge.

Recognising this distinction has important implications for both research and coaching. Analysing playing style provides valuable information about competitive performance, but it offers only a partial understanding of the processes that produced it. Explaining performance also requires consideration of the principles, training processes and contextual factors that shape those observable patterns.

Within the MTTP, this distinction is fundamental. The game model functions as the conceptual reference that guides practice design, whereas playing style represents one of its possible competitive expressions. Distinguishing the two provides the conceptual precision necessary for understanding how coaching intentions are progressively translated into team performance.

Dynamic and adaptive nature

A common misconception is to view the game model as a fixed tactical blueprint that should be reproduced consistently across all situations. Such an interpretation is difficult to reconcile with the dynamic and uncertain nature of football, where performance emerges from continuous interactions among players, opponents and contextual constraints. Any framework intended to guide team performance must therefore accommodate adaptation rather than suppress it.

The defining characteristic of the game model is precisely its capacity to balance stability and flexibility. Rather than prescribing specific solutions, it establishes principles that guide how players interpret and respond to evolving tactical problems. In this sense, the game model functions less as a script to be executed than as a reference that supports coordinated decision-making under changing conditions.

This distinction is fundamental because effective performance depends on both consistency and adaptability. Teams require shared principles that promote coordinated action, yet they must also remain capable of

 © 2026 ARD Asociación Española

responding to the variability inherent in competition. The game model provides this adaptive coherence by preserving a stable organisational logic while allowing different behavioural solutions to emerge according to situational demands.

This interpretation is consistent with ecological perspectives on performance, which conceptualise coordinated action as an emergent property of interactions among performers, tasks and environmental constraints (Araújo et al., 2006; Davids et al., 2013; Seifert et al., 2017). From this perspective, successful performance does not result from reproducing predetermined actions but from adapting effectively to continuously evolving situations. The role of the game model is therefore not to prescribe behaviour directly, but to shape the conditions under which functional patterns of play are more likely to emerge.

This perspective also explains why the same game model may generate different competitive expressions across teams, matches and contexts. A team committed to maintaining possession, for example, may rely on different passing structures, spatial relationships or movement solutions depending on the characteristics of the opposition and the evolving demands of the game. What remains stable is not the specific action, but the principles that guide it.

The same reasoning applies to training design. If successful performance depends on adaptation, practice should expose players to representative tactical problems rather than rehearsed solutions. Learning environments should therefore encourage exploration and adjustment while maintaining coherence with the team's intended way of playing. The objective is not to reproduce identical behaviours, but to develop players capable of adapting while remaining aligned with shared principles.

The game model should therefore be understood as a dynamic construct. Its strength lies not in eliminating variability but in channelling it towards coherent forms of team performance. This interpretation provides an essential conceptual foundation for the MTTP, in which learning and performance are viewed as products of continuous interaction between coaching intentions, practice design and player adaptation.

Team coordination and shared affordances

The effectiveness of a game model ultimately depends on its capacity to support team coordination. Regardless of how clearly its principles are defined, they acquire practical value only when players are able to coordinate their actions in ways that reflect the team's intended mode of play. Understanding the game model therefore requires moving beyond the description of tactical principles towards explaining the mechanisms through which coordinated performance emerges.

Contemporary ecological perspectives suggest that coordination does not result primarily from the execution of predefined tactical instructions but from the continuous interactions among players operating within dynamic performance environments (Duarte et al., 2012; Travassos et al., 2012; Davids et al., 2013; Silva et al., 2013). From this perspective, successful coordination depends on players adapting to evolving informational conditions while regulating their actions in relation to teammates and opponents.

The concept of shared affordances provides an important explanation for this process. Building on Gibson's (1979) notion of affordances as opportunities for action, ecological approaches recognise that many opportunities in team sports are inherently collective. Players must not only perceive possibilities for individual action but also recognise opportunities that depend upon coordinated responses among multiple teammates.

Within this framework, the game model shapes the informational landscape to which players progressively become attuned through training and competition. Repeated exposure to representative practice encourages the development of shared perceptions regarding when to press, provide support, create width, exploit space or accelerate attacking play. Rather than prescribing specific behaviours, the game model influences the conditions under which coordinated action is most likely to emerge.

This perspective offers an alternative to mechanistic interpretations of tactical organisation. Team coordination is understood not as the reproduction of predetermined patterns but as the adaptive regulation of collective action around shared informational opportunities. The game model therefore functions less as a set of instructions than as a framework that channels coordination towards the team's intended way of playing.

The development of shared affordances also highlights the importance of training design. Shared understanding cannot be established through verbal instruction alone; it develops through repeated engagement with representative tactical problems that require players to coordinate their actions under varying conditions. Training therefore plays a central role in shaping the perceptual and informational experiences that underpin coordinated performance.

This relationship is fundamental to the Model-to-Task Translation Process. The game model provides strategic direction, representative practice develops shared atonement to relevant affordances, and coordinated team performance emerges through continuous interaction with the learning environment. In this way, shared affordances provide the theoretical mechanism linking tactical organisation, practice design and collective adaptation within the framework proposed in this paper.

THEORETICAL AND METHODOLOGICAL FOUNDATIONS OF TRAINING DESIGN

Tactical periodization

Among contemporary approaches to football training, Tactical Periodization has been one of the most influential frameworks for linking tactical organisation with practice design. Originally developed by Vítor Frade and subsequently expanded by several coaches and scholars, it emerged as an alternative to reductionist models that treated physical, technical, tactical and psychological preparation as separate components of performance (Oliveira et al., 2006; Tamarit, 2013).

A central premise of Tactical Periodization is that the game should constitute the primary reference for all training decisions. Rather than organising practice around isolated physical or technical objectives, training is structured according to the principles that define the team's intended way of playing. Consequently, the game model provides the organising logic for session design, content selection and the sequencing of training throughout the competitive cycle.

This emphasis on the game model represents one of the framework's most important contributions. Tactical Periodization positions coherence between coaching intentions and practice design at the centre of the training process, viewing practice not as a collection of isolated exercises but as a systematic process through which players are repeatedly exposed to situations that reinforce the intended mode of play. Equally important is its interpretation of specificity, understood not simply as resemblance to competition but as the extent to which training tasks express the principles underpinning the game model.

 © 2026 ARD Asociación Española

Despite these strengths, Tactical Periodization provides comparatively limited explanation of the mechanisms through which players adapt within practice. Although it highlights the importance of task specificity and tactical coherence, it pays less attention to the informational processes through which players perceive opportunities, regulate their actions and coordinate with teammates under changing constraints. Consequently, the framework explains what should guide training more explicitly than how adaptive learning emerges.

This limitation does not diminish the value of Tactical Periodization. Rather, it highlights the opportunity for integration with ecological perspectives that offer more detailed accounts of learning, adaptation and constraint interaction. In the present paper, Tactical Periodization provides the foundation upon which the MTTP is built.

For the MTTP, Tactical Periodization therefore provides the strategic and methodological premise that training should be organised around the principles of the intended way of playing. The mechanisms through which players adapt to the resulting practice conditions require complementary explanatory perspectives.

Ecological dynamics

Over the past two decades, Ecological Dynamics has become one of the most influential theoretical perspectives for understanding learning, adaptation and performance in sport. Drawing on ecological psychology and dynamical systems theory, it conceptualises performance as an emergent product of continuous interactions between performers and their environment rather than the execution of internally stored motor programmes (Araújo et al., 2006; Davids et al., 2008, 2013).

A central assumption of the approach is that effective performance depends on athletes becoming increasingly attuned to the informational constraints that shape opportunities for action. Learning is therefore understood as a process of adaptation in which performers continuously perceive, interpret and respond to changing environmental conditions rather than reproducing predefined solutions (Araújo et al., 2006; Seifert et al., 2017).

This perspective has important implications for football. Team performance emerges through ongoing interactions among teammates, opponents and the surrounding performance environment, making coordination an adaptive process rather than the execution of fixed tactical scripts (Duarte et al., 2012; Travassos et al., 2012). From this viewpoint, successful play depends on players regulating their actions in response to shared informational conditions.

The concept of affordances provides the theoretical basis for this interpretation. Affordances represent opportunities for action that arise from the relationship between performers and their environment (Gibson, 1979). In football, these opportunities include passing lanes, pressing triggers, support options and exploitable spaces that continuously evolve during play. Learning therefore involves developing greater sensitivity to these opportunities and improving the capacity to act upon them under dynamic competitive conditions.

A further contribution of Ecological Dynamics lies in its interpretation of variability. Rather than treating variation as error, the approach views it as a functional property of adaptive performance. Practice should therefore encourage exploration, problem-solving and flexible responses instead of reinforcing invariant behavioural solutions.

Despite its explanatory power, Ecological Dynamics provides comparatively less guidance regarding the organisational principles that should orient learning. It offers a sophisticated account of how adaptation occurs but is less explicit about what should guide the design of training when coaches seek to develop a specific tactical identity.

For the MTTP, Ecological Dynamics provides an explanatory account of how adaptive and coordinated behaviours may emerge within practice. It does not, independently, determine the team-specific tactical principles towards which those adaptive processes should be oriented.

Constraints-led approach

The Constraints-Led Approach (CLA) has become one of the leading frameworks for understanding skill acquisition and practice design in sport. Grounded in ecological psychology and dynamical systems theory, it proposes that performance emerges through the interaction of performer, environmental and task constraints rather than through the reproduction of predefined movement solutions (Newell, 1986; Davids et al., 2008; Renshaw et al., 2019).

A central contribution of the CLA is its interpretation of constraints as functional influences on action. Rather than prescribing behaviour directly, constraints shape the opportunities available to performers, encouraging exploration and adaptation within specific performance contexts. Learning is therefore viewed as the progressive adjustment of perception and action to the demands created by these interacting constraints.

Within football, this perspective has important methodological implications. By manipulating variables such as player numbers, pitch dimensions, rules, scoring systems or spatial configurations, coaches modify the informational conditions experienced during practice. Training design thus becomes less concerned with prescribing solutions and more focused on creating situations in which functional solutions are likely to emerge.

The CLA also provides a compelling account of variability. Instead of treating variation as inconsistency or error, it regards it as a necessary characteristic of adaptive performance. Exposure to diverse task configurations encourages players to explore multiple solutions and develop greater flexibility in responding to changing competitive demands. From this perspective, learning is not the stabilisation of a single optimal response but the development of adaptable and context-sensitive performance capabilities.

Despite these strengths, the CLA is primarily concerned with explaining how practice conditions shape learning rather than how coaches should determine the tactical priorities that guide those conditions. It offers powerful methodological tools for manipulating practice but provides comparatively less guidance regarding the organisational principles that should inform those methodological decisions.

This distinction is particularly important in football, where practice is expected to support the development of a specific tactical identity. While the CLA explains how task manipulation influences learning, it does not specify how coaching intentions should be translated into the selection of appropriate constraints.

For the MTTP, the CLA provides the operational logic through which coaches may manipulate practice conditions. The selection of functionally appropriate constraints nevertheless requires a prior specification of the tactical problem and the game-model principle that the task is intended to develop.

 © 2026 ARD Asociación Española

Nonlinear pedagogy

Nonlinear Pedagogy (NLP) emerged as a pedagogical application of Ecological Dynamics and the CLA, providing a framework for designing practice that promotes exploration, adaptation and skill development (Chow et al., 2007; Chow et al., 2016; Chow et al., 2022). Rather than viewing learning as the linear transmission of knowledge or the reproduction of idealised movement patterns, NLP conceptualises it as a dynamic process through which performers adapt to the challenges and opportunities presented by their environment.

A central premise of NLP is that learning develops through engagement with representative performance problems rather than through the accumulation of technical knowledge or repetitive execution of prescribed solutions. Effective coaching therefore involves creating practice conditions that encourage players to perceive, decide and act while exploring functional solutions to evolving tactical problems.

This perspective is particularly relevant to football, where uncertainty, variability and continuous interaction define performance. Practice should therefore expose players to meaningful tactical challenges instead of merely rehearsing predetermined responses. Learning is enhanced not by oversimplifying performance demands but by designing tasks that preserve the informational characteristics of competition while remaining appropriate to players' developmental level.

One of the defining principles of NLP is Representative Learning Design (Pinder et al., 2011; Chow et al., 2016). Practice tasks should preserve the informational variables that specify opportunities for action during competition, allowing players to strengthen perception–action couplings that transfer effectively to match play. Representative practice therefore supports learning by maintaining the essential informational properties of the competitive environment.

Another key contribution concerns the educational role of exploration. Rather than directing performers towards a single optimal solution, NLP recognises that effective performance may emerge through multiple adaptive responses. Variability is therefore treated as a resource for learning rather than a source of error, encouraging players to discover solutions that remain functional under changing competitive conditions.

The framework also emphasises the importance of calibrating task difficulty. Practice should be sufficiently demanding to stimulate adaptation while remaining accessible enough to sustain engagement and exploration. In football, this balance is particularly important because excessive complexity may overwhelm performers, whereas oversimplified tasks may fail to preserve the informational demands that underpin meaningful learning.

Despite its considerable pedagogical value, NLP is primarily concerned with how practice should be designed rather than with the tactical priorities that should guide that design. Although it provides sophisticated principles for representative learning, exploration and skill adaptation, it offers comparatively limited guidance regarding how coaches determine the organisational priorities that shape practice.

For the MTTP, Nonlinear Pedagogy informs how learning opportunities may be designed, simplified and progressively adapted while preserving functional information. The tactical direction of this design must nevertheless be established through the team’s intended way of playing and the priorities derived from it.

Coaching pedagogy

Although contemporary approaches have substantially advanced the design of practice tasks and learning environments, effective coaching extends beyond task manipulation alone. Learning occurs within a social and pedagogical context in which coaches shape experiences, guide attention and influence how players engage with performance problems. Understanding training design therefore requires consideration not only of the practice environment but also of the pedagogical processes through which learning is facilitated.

Coaching Pedagogy provides an important framework for understanding this dimension of practice. Broadly defined, it concerns the processes through which coaches support learning, development and performance through their interactions with athletes (Jones, 2006; Cushion et al., 2003; Lyle & Cushion, 2017). Rather than treating coaching as the transmission of knowledge, contemporary perspectives emphasise learning as a relational process in which players actively construct understanding through engagement with tasks, teammates and coaches.

This perspective is particularly relevant in football, where performance depends on interpreting complex tactical situations rather than reproducing predetermined solutions. Coaches therefore influence learning not only through the design of practice but also through the way they intervene. Feedback, questioning, demonstrations and other pedagogical strategies shape players' attention, encourage reflection and support increasingly sophisticated tactical understanding.

Feedback illustrates this role particularly well. While direct instruction remains appropriate in specific situations, excessive prescription may reduce opportunities for exploration, decision-making and adaptation (Nelson et al., 2006; Cushion et al., 2003). Effective coaching therefore requires balancing guidance with opportunities for players to solve problems independently within representative practice contexts.

Questioning represents a complementary pedagogical strategy. By prompting players to reflect on their decisions and interactions, coaches encourage deeper tactical understanding and greater sensitivity to the informational cues embedded in performance. Learning thus becomes a process of guided discovery rather than passive instruction.

Coaching Pedagogy also extends beyond individual interventions. It encompasses the broader learning culture established by the coach, including the values, expectations and communication processes that shape how players engage with development. The effectiveness of practice therefore depends not only on the quality of task design but also on the pedagogical climate in which those tasks are experienced.

Despite the diversity of pedagogical approaches described in the coaching literature, a consistent principle is the alignment between instructional strategies and learning objectives. Feedback, questioning, demonstration and other interventions are most effective when they reinforce the tactical principles and developmental priorities that underpin practice. Pedagogical intervention should therefore be understood as an integral component of practice design rather than as a separate instructional layer.

For the MTTP, Coaching Pedagogy explains how coaches regulate attention, reflection and engagement within the learning environment. These interventions acquire methodological coherence when they are connected to the tactical problem embedded in the task rather than applied independently of its intended purpose.

 © 2026 ARD Asociación Española

Table 1. Comparative positioning of the MTTP and its theoretical and methodological foundations.

Perspective	Primary question	Principal contribution	Boundary regarding model-to-task translation	Function within the MTTP
Tactical Periodization	What should organise the training process?	Establishes the game model and its principles as the central reference for training specificity and weekly organisation.	Does not primarily explicate the perception–action mechanisms through which players adapt, nor provide explicit criteria for evaluating the alignment of individual tasks.	Provides strategic and methodological orientation.
Ecological Dynamics	How do skilled behaviours and collective coordination emerge?	Explains adaptation through performer–environment interactions, affordances, informational constraints and perception–action coupling.	Does not independently determine which team-specific tactical principles should guide the selection of practice problems.	Provides the explanatory account of adaptation and behavioural emergence.
Constraints-Led Approach	How can practice conditions be manipulated to support functional adaptation?	Provides a methodology for manipulating performer, task and environmental constraints without prescribing a single movement solution.	Does not, by itself, specify how constraints should be derived from a particular game model or tactical priority.	Provides the operational logic for task-constraint manipulation.
Nonlinear Pedagogy	How can representative and adaptive learning experiences be designed?	Provides pedagogical principles concerning representativeness, variability, exploration, task simplification and the calibration of task difficulty.	Does not primarily organise the preceding translation from coaching philosophy and game idea to team-specific training priorities.	Informs the design and progression of representative learning opportunities.
Coaching Pedagogy	How does the coach mediate learning through interaction?	Explains how feedback, questioning, observation, communication and the wider learning climate influence players' engagement and understanding.	Does not provide a complete architecture connecting strategic intentions, task design and the evaluation of emergent team behaviour.	Provides the pedagogical and relational regulation of the learning environment.
MTTP	How are coaching intentions translated into training tasks and evaluated through observable behaviour?	Organises the translation from coaching philosophy and game idea to game-model principles, training priorities, task constraints, learning environments and behavioural emergence.	Its proposed constructs, relationships and decision criteria require operationalisation and empirical validation.	Provides the integrative and recursive architecture connecting strategic orientation, practice design and performance evaluation.

Note. The perspectives are compared according to their primary analytical contribution, not as interchangeable or competing theories. The boundaries identified refer specifically to the model-to-task translation problem and should not be interpreted as general limitations of the respective perspectives. CLA = Constraints-Led Approach; MTTP = Model-to-Task Translation Process.

Comparative positioning and distinctive contribution of the MTTP

The perspectives reviewed above have made substantial but analytically distinct contributions to contemporary football coaching. Tactical Periodization establishes the intended way of playing as the principal reference for organising training. Ecological Dynamics explains how adaptive behaviour emerges through continuous interactions between players and their performance environment. The Constraints-Led Approach provides a methodological basis for manipulating practice conditions, Nonlinear Pedagogy informs the design of representative and adaptive learning experiences, and Coaching Pedagogy explains how

coaches mediate learning through interaction, observation and communication. These contributions are summarised in Table 1.

The perspectives should not be interpreted as directly equivalent or as competing explanations of the same phenomenon. They operate at different analytical levels and address different primary questions. Tactical Periodization is principally concerned with the strategic and methodological organisation of training; Ecological Dynamics provides a theoretical account of adaptation and coordination; the Constraints-Led Approach and Nonlinear Pedagogy inform practice design; and Coaching Pedagogy addresses the relational and educational processes through which coaches facilitate learning. Their relevance to the MTTP therefore lies in their differentiated functions rather than in their conceptual interchangeability.

Despite their respective contributions, a specific problem remains only partially articulated: how a coach moves systematically from an intended way of playing to the design and evaluation of an individual training task. Coaches may establish game-model principles, manipulate constraints, create representative activities and employ appropriate pedagogical interventions without possessing an explicit structure for determining how these decisions should be connected. Consequently, a task may be theoretically informed and game-like while remaining weakly connected to the tactical principle it is intended to develop.

The MTTP addresses this translational problem. Its proposed novelty does not reside in claiming ownership of the concepts of game model, affordances, constraints, representativeness or pedagogical intervention. Instead, it lies in assigning these concepts distinct functions within a common decision architecture. The framework identifies how strategic orientation is progressively specified as a game idea, formalised through game-model principles, filtered into training priorities, embedded in task constraints, experienced within learning environments and examined through observable behavioural emergence.

This architecture introduces a vertical dimension of coherence that extends beyond either tactical specificity or representative learning considered separately. Vertical coherence refers to the traceable correspondence between a coaching intention, the game-model principle derived from it, the tactical problem selected for development, the constraints used to shape that problem and the behaviours available for observation. A task is therefore not considered methodologically coherent solely because it resembles competition or elicits intensive player involvement. Its value depends on whether its design creates meaningful opportunities to perceive and act upon the tactical problem associated with the intended principle.

A second distinctive contribution is the separation of model–task alignment from representativeness. Model–task alignment concerns the extent to which a practice task creates opportunities to develop a specified game-model principle. Representativeness concerns the extent to which the task preserves the informational variables, action possibilities and perception–action relationships that regulate behaviour in competition. The dimensions are complementary but not interchangeable. A task may closely resemble match play while generating few opportunities to develop the intended principle; conversely, a simplified activity may be strongly aligned with a tactical priority while preserving only part of the information available in competition. Distinguishing these dimensions enables a more precise evaluation of task functionality.

A third contribution concerns the recursive nature of the proposed process. The MTTP does not end with task implementation. Behaviour observed during training and competition provides evidence regarding whether the intended tactical problems were encountered, whether functional solutions emerged and whether the relationships among game-model principles, training priorities and task constraints require adjustment.

 © 2026 ARD Asociación Española

Translation is therefore conceptualised as a continuing cycle of specification, design, observation and recalibration rather than as the linear implementation of a predetermined tactical plan.

Accordingly, the MTTP occupies a translational level that is not fully addressed by any of its contributing perspectives in isolation. It does not replace their explanatory or methodological functions and should not be interpreted as theoretically superior to them. Its contribution is to connect those functions around a specific coaching problem: establishing a traceable and examinable relationship between the way a team intends to play, the learning opportunities designed in training and the behaviours that emerge in practice and competition.

This positioning also defines the limits of the framework's claims. The MTTP currently proposes a conceptual architecture rather than an empirically validated account of causal relationships. Whether greater vertical coherence or stronger model–task alignment contributes to behavioural development and transfer remains an empirical question. By defining the relevant constructs and their proposed relationships, however, the framework makes this question more explicit and provides a basis for systematic investigation.

Theoretical compatibility, tensions and limits of integration

The integration proposed within the MTTP does not imply that Tactical Periodization, Ecological Dynamics, the Constraints-Led Approach, Nonlinear Pedagogy and Coaching Pedagogy share identical epistemological assumptions. These perspectives emerged from different theoretical and methodological traditions, operate at different levels of analysis and assign different roles to coaching intention, environmental information, prescription and behavioural emergence. Their inclusion within a common framework therefore requires explicit recognition of both their functional complementarity and their conceptual tensions.

A central tension concerns the relationship between strategic direction and behavioural emergence. Game-model approaches begin with an intended way of playing and organise training around principles selected by the coach. Ecological Dynamics, by contrast, explains behaviour as emerging through continuous performer–environment interactions rather than through the execution of internally prescribed solutions. If the game model is interpreted as a detailed representation of predetermined actions, its prescriptive logic would conflict with an ecological account of adaptive behaviour. Within the MTTP, this tension is addressed by conceptualising the game model as a set of functional principles and shared orientation criteria rather than as a fixed behavioural script. The game model specifies the problems to be addressed and the functions to be fulfilled, but it does not determine the exact solutions through which players must satisfy them.

A related tension concerns the coach's manipulation of task constraints. Constraints are deliberately selected to increase the likelihood that players encounter particular tactical problems, yet the behaviours that emerge from those conditions cannot be fully predicted or controlled. The MTTP therefore distinguishes between designing for an intended behaviour and prescribing its precise form. Coaches may manipulate space, player numbers, rules, scoring conditions or starting positions to privilege relevant information and action possibilities, but players must retain meaningful opportunities to perceive, decide and adapt. Task constraints should channel exploration towards a tactical purpose without reducing the activity to the reproduction of a predetermined response.

Specificity and representativeness create a further conceptual trade-off. Within game-model approaches, specificity primarily concerns coherence with the team's intended way of playing. Within ecological approaches, representativeness concerns the preservation of information and perception–action relations that regulate competitive behaviour. These criteria may converge, but they are not equivalent. A task may be

closely aligned with a game-model principle while simplifying important sources of competitive information. Conversely, a task may preserve many features of match play while providing insufficient opportunities to develop the selected tactical priority. The MTTP does not resolve this tension by assuming that every task should maximise both dimensions. Instead, it treats alignment and representativeness as separate design criteria whose relative weighting depends on the learning objective, player characteristics and stage of development.

The role of pedagogical intervention also requires qualification. Coaching Pedagogy recognises the importance of explanation, feedback, questioning and guided reflection, whereas ecological approaches caution that excessive verbal prescription may disrupt exploration or direct attention towards information that is not functionally relevant. Within the MTTP, pedagogical intervention is therefore neither eliminated nor treated as the primary cause of learning. Its function is to support players 'engagement with the tactical problem, guide attention when necessary and facilitate reflection on emerging solutions. The form, timing and frequency of intervention should be adapted to the task, the players 'needs and the information already available within the learning environment.

These tensions establish clear boundaries for theoretical integration. Compatibility is strengthened when the game model provides functional direction without prescribing invariant actions; when constraints create opportunities without predetermining solutions; when pedagogical intervention guides attention without replacing perception and decision-making; and when behavioural variability is evaluated according to its functionality rather than its conformity to an idealised movement pattern. Compatibility becomes weaker when the game model is treated as a rigid script, task constraints are used to compel a single response, or coaching intervention suppresses the adaptive exploration required by changing performance conditions.

The MTTP therefore adopts a position of conditional functional integration. Tactical Periodization contributes strategic direction; Ecological Dynamics provides an account of adaptive emergence; the Constraints-Led Approach and Nonlinear Pedagogy inform the design of practice conditions; and Coaching Pedagogy addresses the mediation of learning through coach–player interaction. These contributions can be articulated because they address different functions within the model-to-task translation process, but their theoretical differences should not be erased. The coherence of the MTTP depends precisely on preserving those differences while specifying the conditions under which their contributions can operate together.

This position also limits the claims that can be made for the framework. The MTTP does not propose a unified theory derived from the complete epistemological reconciliation of its contributing perspectives. It proposes a translational framework in which selected and explicitly delimited contributions are organised around a shared practical problem. The adequacy of this integration, including the conditions under which strategic direction supports or constrains adaptive learning, remains open to conceptual refinement and empirical investigation.

THE MODEL-TO-TASK TRANSLATION PROCESS

The Model-to-Task Translation Process is proposed as an integrative conceptual and decision-guiding framework for organising the translation of coaching intentions into practice. Its purpose is not to prescribe a universal training method, but to clarify the distinct decisions and relationships through which an intended way of playing may inform training priorities, task design, learning environments and the observation of team behaviour.

 © 2026 ARD Asociación Española

The MTTP comprises a sequence of analytically distinguishable but dynamically interdependent components: coaching philosophy, game idea, game model, training priorities, task constraints, learning environments and behavioural emergence. These components should not be interpreted as a rigid linear chain. The framework represents a recursive process in which decisions made at one level constrain—but do not determine—the possibilities available at subsequent levels, while evidence emerging from training and competition may lead to the reconsideration of earlier decisions.

The framework therefore combines strategic direction with adaptive emergence. Coaching philosophy, game idea and game-model principles specify the intended direction of development; training priorities and task constraints translate that direction into practice conditions; learning environments provide opportunities for perception, action and interaction; and behavioural emergence constitutes the observable, context-dependent expression of players 'adaptations. The quality of the translation process depends on the coherence among these components rather than on the isolated methodological value of any single exercise.

As established in Section 3.7, this integration is conditional rather than absolute. Strategic direction, constraint manipulation, pedagogical intervention and behavioural emergence remain conceptually distinct within the MTTP. Their articulation depends on preserving adaptive degrees of freedom: the coach may specify the intended tactical function and design conditions that privilege relevant opportunities for action, but the precise behavioural solution remains contingent on player–environment interaction.

Table 2. Constructs, functions and outputs within the Model-to-Task Translation Process.

MTTP component	Definition	Specific function	Primary output	Football example
Coaching philosophy	The relatively enduring beliefs and values through which the coach interprets football, learning, leadership and player development.	Establishes the normative and pedagogical foundations of the coaching process.	Broad criteria for deciding what is valued and how players should be developed.	Valuing proactive play, collective responsibility and adaptive decision-making.
Game idea	The coach's context-sensitive strategic conception of how the team should approach the game.	Converts general beliefs into an intended football identity and broad strategic orientation.	An overarching conception of the intended way of playing.	Seeking to control the game through territorial initiative, rapid ball recovery and purposeful possession.
Game model	A dynamic and hierarchically organised system of principles and subprinciples intended to guide collective behaviour.	Specifies the functional principles through which the game idea can be expressed across moments of play.	Game-model principles and subprinciples.	Directing the opponent's build-up towards the touchline before initiating coordinated pressure.
Training priorities	The contextually selected tactical problems or developmental emphases derived from the game model for a defined period or session.	Filters the breadth of the game model into a manageable focus for learning and practice design.	A clearly delimited tactical problem and associated learning intention.	Coordinating the winger's pressing trigger with the striker's cover of the inside passing lane.
Task constraints	The practice conditions deliberately manipulated to shape available information, action possibilities and player interactions.	Operationalises the training priority by increasing the likelihood that players encounter and explore the intended tactical problem.	A task configuration specifying space, numbers, rules, objectives, restarts and scoring conditions.	Requiring build-up to begin through the opposing centre-backs and awarding additional points for regaining possession in a wide pressing zone.

Learning environment	The dynamic experiential context emerging from the interaction among players, task constraints, available information, pedagogical intervention and wider contextual conditions.	Provides the situated opportunities through which players perceive, decide, coordinate and adapt.	Experienced tactical problems, information–action relationships and opportunities for exploration.	Repeated exposure to variable opposition build-up patterns requiring coordinated pressing decisions under active resistance.
Behavioural emergence	The context-dependent appearance and development of individual and collective behavioural tendencies during training and competition.	Provides observable evidence for evaluating the effects and coherence of the translation process.	Behavioural patterns and performance indicators that may confirm, qualify or challenge the initial design assumptions.	Increasing synchronisation among winger, striker and full-back while preserving adaptation to different opposition movements.

Note. The components are analytically distinguishable but dynamically interdependent. Output" refers to the principal product of each stage for the subsequent translation process and does not imply a fixed or deterministic causal sequence. MTTP = Model-to-Task Translation Process.

Coaching philosophy

Within the MTTP, coaching philosophy constitutes the foundational level of the translation process. It refers to the beliefs, values and assumptions through which coaches interpret football, player development and their own professional role (Jones, 2006; Cushion et al., 2003; Lyle & Cushion, 2017). These commitments influence how performance problems are understood, which developmental outcomes are valued and how authority, feedback and player autonomy are negotiated.

Its function within the framework is generative rather than operational. Coaching philosophy does not directly specify tactical behaviours or task conditions; instead, it provides the criteria from which strategic preferences and pedagogical orientations are formed. Philosophical commitments concerning collective organisation, adaptability or player agency may therefore shape both the intended way of playing and the manner in which players are supported in developing it.

This position establishes the first requirement of vertical coherence within the MTTP: subsequent strategic, methodological and pedagogical decisions should remain interpretable in relation to the beliefs that initially give them direction, without assuming that philosophy determines those decisions in a fixed or linear manner. Inconsistency may arise, for example, when a coach endorses player autonomy but systematically uses highly prescriptive tasks and interventions that restrict opportunities for perception, decision-making and exploration.

Although relatively enduring, coaching philosophy may be revised through experience, reflection and contextual change. This capacity for development does not diminish its foundational role; rather, it indicates that the starting point of the MTTP is itself open to professional learning. Its principal output for the subsequent stage is a sufficiently explicit set of beliefs from which a context-sensitive game idea can be constructed.

Game idea

The game idea represents the first context-sensitive strategic expression of coaching philosophy. It articulates an overarching conception of how the team should approach the game, including broad intentions such as controlling territory, recovering possession rapidly, exploiting transitions or sustaining purposeful possession. These intentions provide direction but do not yet specify the principles through which players should coordinate their actions in particular tactical situations.

 © 2026 ARD Asociación Española

Its function within the MTTP is therefore orientational. The game idea converts general beliefs into a recognisable football identity while preserving the distinction between strategic intention and operational organisation. This distinction is important because statements such as "*press aggressively*" or "*control possession*" communicate a preferred direction but remain insufficient for designing practice until the tactical problems and functional relationships contained within them are made explicit.

The game idea is shaped not only by coaching philosophy but also by player characteristics, competitive demands, club culture and available resources. Similar philosophical positions may consequently produce different strategic orientations in different contexts, while a coach may adapt the expression of a game idea without abandoning the beliefs on which it is founded. The construct should therefore be regarded as context sensitive and revisable rather than as a fixed declaration of tactical identity.

Its principal output is an overarching and contextually feasible conception of the intended way of playing. To inform collective behaviour and practice design, however, this strategic conception must be translated into more explicit functional principles and subprinciples. That translation defines the organisational role of the game model within the MTTP.

Game model

Within the MTTP, the game model occupies the principal organisational position between strategic intention and practice design. It is understood as a dynamic and hierarchically organised system of principles and subprinciples intended to guide collective behaviour across the different moments of play (Castelo, 1994, 2009; Garganta, 1997, 2009; Plakias, 2023). Its specific function is to translate the game idea into functional references from which contextually relevant training priorities can be selected.

Game-model principles specify the tactical problems the team is intended to solve and the functional relationships through which collective coordination may be achieved. They may define, for example, how space should be managed, how pressure should be coordinated or how numerical and positional advantages should be created. These principles provide direction without prescribing invariant actions: their purpose is to channel perception and coordination while preserving players' capacity to adapt to opponents, teammates and changing competitive conditions.

The game model should therefore neither be reduced to a description of observed playing style nor treated as a predetermined tactical script. It establishes an intended organisational logic, whereas its behavioural expression remains context dependent and may include multiple functional solutions (Araújo et al., 2006; Davids et al., 2013; Seifert et al., 2017). This distinction reconciles strategic direction with adaptive performance: the game model identifies what collective functions should be developed without predetermining the precise actions through which players must express them.

The principal output of this stage is an explicit and hierarchically organised set of game-model principles. These principles are not themselves training priorities or task constraints. They express relatively enduring functional intentions concerning collective play; training priorities identify which tactical problem requires particular attention within a defined period; and task constraints subsequently configure the practice conditions through which players may engage with that problem. Because the entire game model cannot be addressed simultaneously, its principles must be filtered according to observed performance, developmental needs and contextual demands. This selection produces the training priorities examined in the following subsection.

Training priorities

The game model may contain multiple principles and subprinciples across different moments of play, but these cannot all receive equal emphasis within every session or training period. Within the MTTP, training priorities are the contextually selected tactical problems or developmental emphases derived from the game model for a defined period of practice. Their function is to filter the breadth and complexity of the game model into a manageable focus capable of guiding task design.

The distinction between game-model principles and training priorities concerns both stability and function. Game-model principles express relatively enduring intentions regarding how the team seeks to organise collective play. Training priorities identify which aspect of those intentions requires particular developmental attention at a given moment. A principle may therefore remain stable while its priority changes according to observed performance, player development, the stage of the season, forthcoming competitive demands or evidence of learning.

Training priorities should be formulated as tactical problems rather than as decontextualised technical actions or predetermined behavioural solutions. For example, a game-model principle may seek to direct the opponent's build-up towards the touchline before initiating collective pressure. A corresponding training priority might focus on coordinating the winger's pressing trigger with the striker's protection of the inside passing lane and the full-back's control of the wide receiving option. This formulation specifies the functional problem that practice should repeatedly make available without prescribing the precise movements through which players must solve it.

A training priority should therefore identify the game-model principle being developed, the tactical problem that players are expected to recognise and solve, and the functional relationships that should become available for observation. General objectives such as improving passing, increasing intensity or developing communication are insufficient unless their intended tactical function is made explicit. Within the MTTP, the priority defines why a particular focus is relevant to the intended way of playing.

Priority selection also connects performance analysis with intervention. Evidence from training and competition may indicate that a game-model principle is absent, unstable, poorly coordinated or insufficiently adaptable. The coach must then determine which aspect of that principle requires focused attention and the level of complexity at which it should be addressed. Selection is therefore not a mechanical deduction from the game model, but a contextual judgement informed by observation, developmental needs and the wider training process.

A training priority does not yet constitute a practice task. It defines the intended learning focus but not the conditions through which players will experience it. Different tasks may address the same priority, and the same task format may serve different priorities depending on how its constraints are configured. Once the priority has been established, it must therefore be operationalised through practice conditions that create meaningful opportunities for players to engage with the relevant tactical problem. Within the MTTP, these deliberately manipulated conditions are defined as task constraints.

Task constraints

Once a training priority has been established, the next decision concerns how the corresponding tactical problem will be made available to players in practice. Within the MTTP, task constraints refer specifically to the practice conditions deliberately configured by the coach to shape available information, action possibilities

 © 2026 ARD Asociación Española

and player interactions. They constitute the operational means through which a training priority is embedded in task design; they are not themselves the intended learning content.

The concept of constraints occupies a central position in contemporary theories of learning and performance. From the perspective of the CLA, behaviour emerges through the interaction of performer, environmental and task constraints (Newell, 1986; Davids et al., 2008; Renshaw et al., 2019). The MTTP focuses at this stage on task constraints because these are especially amenable to deliberate coaching intervention. Their manipulation may influence the opportunities encountered by players, but it does not determine the responses that will emerge.

In football, task constraints include pitch dimensions, numerical configurations, playing rules, scoring conditions, target areas, restart locations, temporal demands and task objectives. These variables function as an interacting configuration rather than as isolated design elements. Altering playing space, for example, may change interpersonal distances, pressure time, available passing lanes and the functional effects of numerical relations. Task design therefore requires consideration of how multiple constraints combine to amplify, reduce or transform the tactical problem experienced by players.

The distinction between a training priority and a task constraint concerns function rather than surface content. "*Protecting the central corridor while directing the opponent towards the touchline*" describes the tactical problem to be developed and therefore constitutes a training priority. A rule requiring the attacking team to initiate build-up through a defined central area or awarding additional points for regaining possession in a wide pressing zone, constitutes a task constraint because it configures the conditions through which that problem becomes available. Confusing these levels obscures the difference between the purpose of practice and the means used to pursue it.

The functionality of task constraints depends on both model–task alignment and representativeness. Constraints should create recurring opportunities to engage with the selected tactical problem while preserving, to an appropriate degree, the information and perception–action relationships that regulate performance in competition. Simplification may be useful when it foregrounds a problem that players are not yet able to manage under full complexity, but its developmental value depends on subsequent progression towards more representative conditions. Conversely, an activity may closely resemble competition while remaining poorly aligned if its constraints predominantly invite behaviours unrelated to the selected priority.

Task constraints consequently describe what the coach deliberately designs, but not the totality of what players experience. The resulting learning environment emerges only when these conditions interact with players 'capabilities, intentions and previous experiences, the behaviour of teammates and opponents, the information available during activity and the coach's pedagogical intervention. This distinction establishes the transition from configured task conditions to the experiential context examined in the following subsection.

Learning environments

Within the MTTP, the learning environment is the dynamic experiential context that emerges from the interaction among players, task constraints, available information, pedagogical intervention and wider contextual conditions. Whereas task constraints refer to the conditions deliberately configured by the coach, the learning environment concerns the opportunities and interactions that become available as players engage with those conditions. It therefore cannot be reduced to the formal structure of the task or fully specified in advance.

This distinction is essential because task design alone does not determine what players perceive, explore or learn. Two activities with identical formal constraints may generate different learning environments because player expertise, fatigue, motivation, interpersonal relationships, opposition behaviour, previous experience and coaching intervention alter the information available and the possibilities for action. Conversely, different task configurations may create functionally comparable opportunities when they preserve the same tactical problem and relevant information–action relationships.

From an ecological perspective, learning environments are dynamic systems in which informational, social and tactical influences continuously interact (Araújo et al., 2006; Davids et al., 2013; Chow et al., 2016). Players adapt their actions through their ongoing relationships with teammates, opponents, space, time and task objectives. Effective environments should therefore preserve, to a degree appropriate to the developmental purpose, the information that regulates performance in competition. Representative Learning Design emphasises the importance of maintaining relevant perception–action relationships so that practice supports atonement to competition-relevant opportunities for action (Pinder et al., 2011; Woods et al., 2020).

Representativeness does not, however, establish whether an environment serves the selected game-model principle. A practice activity may preserve substantial competition-relevant information while predominantly inviting behaviours unrelated to the training priority. Conversely, a highly aligned but extensively simplified activity may foreground the intended tactical problem while temporarily removing information required for transfer. The functionality of the learning environment therefore depends on the relationship between alignment, representativeness, player readiness and the position of the activity within a broader task progression.

Pedagogical intervention forms part of this environment rather than operating outside it. Feedback, questioning, attentional guidance and task adjustment may support players' engagement with the tactical problem, but their effects depend on timing, content and compatibility with the information available in the activity. Intervention should clarify purpose or redirect attention when necessary without replacing players' perception and decision-making or prescribing an invariant solution.

The quality of a learning environment should not be inferred solely from immediate task performance. Successful execution may reflect familiarity, repeated instruction or temporary adaptation to a particular activity, whereas exploration and short-term inconsistency may accompany productive engagement with a demanding tactical problem. Evaluation should therefore consider the opportunities made available, the behaviours observed across repeated exposures and their subsequent stability, adaptability and transfer. Within the MTTP, the learning environment provides the situated conditions from which behavioural tendencies may emerge; those tendencies constitute evidence for evaluating, rather than proof of, the effectiveness of the preceding translation decisions.

Behavioural emergence

The observable component of the MTTP concerns behavioural emergence: the context-dependent appearance and development of individual and collective behavioural tendencies during training and competition. These tendencies may become functionally consistent with the selected game-model principle, but they should not be interpreted as its direct or predetermined expression. They emerge through the interaction of players, task conditions, available information, pedagogical influences and the wider performance context (Araújo et al., 2006; Davids et al., 2013; Seifert et al., 2017).

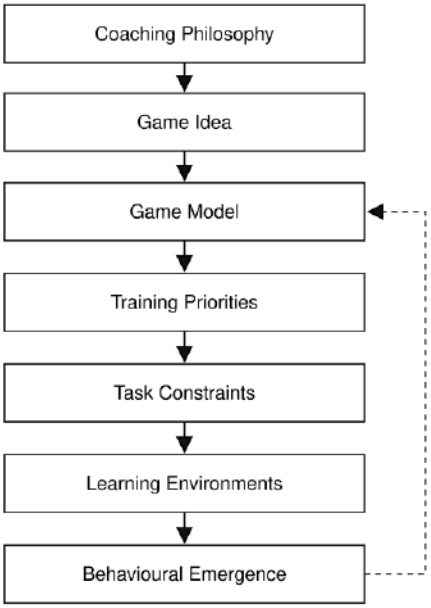
 © 2026 ARD Asociación Española

Behavioural emergence may be examined through patterns such as team compactness, pressing coordination, positional rotations, support relationships, spatial occupation and responses to transitions. The relevant indicators should be derived from the game-model principle and training priority established earlier in the process. For a priority concerning coordinated wide pressing, for example, observation might focus on the synchronisation of the winger's approach, the striker's protection of the inside passing lane, the full-back's control of the wide receiver and the collective response when the opponent changes the direction of play.

Observed behaviour must nevertheless be interpreted in relation to the opportunities generated by the task. The absence of an intended response is informative only when the corresponding tactical problem was available, while the occurrence of an apparently appropriate action provides limited evidence if it resulted from an atypical event, an opponent's unforced error or a task condition that removed the need for perception and decision-making. Evaluation should therefore consider not only whether a behaviour occurred, but also the informational and interactional conditions under which it emerged.

Nor should the appearance of an intended behaviour during a single activity be treated as evidence of learning or transfer. Stronger evidence requires repeated observation across varying task conditions and, ultimately, examination of whether the behavioural tendency remains stable, adaptable and functionally effective in competition. Within the MTTP, behavioural emergence provides evidence with which the coherence and effects of previous decisions may be evaluated; it does not, by itself, validate those decisions or establish a causal relationship between task design and learning.

This evidence also supports the recursive regulation of the translation process. Behavioural observations may indicate that task constraints require adjustment, that a training priority should be maintained or progressed, or that the underlying game-model principle requires reconsideration. Feedback therefore operates across different timescales: immediate observations may inform task modification, recurring tendencies may influence subsequent training priorities, and evidence accumulated across training and competition may contribute to the longer-term refinement of the game model.



Note. Solid arrows represent the translation process; the dashed arrow represents feedback from behavioural emergence to the game model.

Figure 1. The Model-to-Task Translation Process (MTTP).

Figure 1 summarises the MTTP and illustrates the recursive relationships linking coaching philosophy, game idea, game model, training priorities, task constraints, learning environments and behavioural emergence.

PRACTICAL APPLICATIONS FOR FOOTBALL TRAINING DESIGN

From training priority to coherent task design

The practical application of the MTTP begins with the definition of a training priority rather than the selection of an exercise. Coaches must first identify the game-model principle to be developed, determine the tactical problem requiring attention and specify the functional relationships that practice should make available. Task selection and design follow from these decisions.

A training task has no inherent methodological value. Its relevance depends on whether its constraints repeatedly create opportunities for players to engage with the intended tactical problem. Activities with similar formats may serve different purposes, whereas structurally different tasks may address the same priority. Task quality should therefore be evaluated through the functional relationship between the selected priority, the information available to players and the interactions that the activity generates.

Constraints such as playing space, numerical relations, rules, scoring conditions, restart locations and temporal demands provide the principal means of embedding a training priority in practice. Their manipulation should privilege relevant opportunities for action without predetermining the solutions players must adopt. Coherence with the game model concerns the function of the behaviour being developed, not the reproduction of fixed movements or tactical scripts.

Session design also requires purposeful sequencing. Practice may initially reduce complexity to increase engagement with a tactical problem and then progressively restore information, variability and opposition pressure. Activities need not share the same format, but they should maintain a traceable relationship with the session priority. Variation is methodologically coherent when it exposes players to complementary expressions of the same problem rather than introducing unrelated content.

Pedagogical intervention should preserve this direction. Feedback, questioning and task adjustments are most useful when they guide attention towards information relevant to the tactical problem while retaining opportunities for perception, decision-making and exploration. Intervention should clarify the intended function without imposing an invariant behavioural form.

Coherent task design is therefore not achieved by selecting exercises that merely resemble competition. It depends on whether the intended tactical problem is available, whether players engage with competition-relevant information and whether the behaviours observed provide evidence for maintaining, progressing or recalibrating the activity. The following applied case illustrates this translation from strategic intention to task design and evaluation.

Applied case: Translating coordinated high pressing into practice

The MTTP described above can be illustrated through a team seeking to develop coordinated high pressing against an opponent's build-up from the goalkeeper. The example does not prescribe a universal pressing strategy or training activity; it demonstrates how successive decisions may remain traceable while preserving players 'opportunities to perceive, decide and adapt.

 © 2026 ARD Asociación Española

Consider a senior team organised predominantly in a 1–4–3–3 formation. The coach's philosophy values proactive play, collective responsibility and the capacity to influence the opponent rather than respond passively. This orientation informs a game idea based on recovering possession early, restricting central progression and using collective pressure to maintain territorial initiative. These intentions remain too broad to guide an individual training task and must therefore be specified through the game model.

Within the game model, one principle establishes that the team should protect central progression while directing the opponent's build-up towards the touchline. A related subprinciple specifies that a pass from an opposing centre-back to the full-back functions as a potential pressing trigger. The intended collective response involves the ball-side winger pressing from an inside-to-outside trajectory, the striker restricting the return pass and access to the nearest pivot, the ball-side midfielder protecting the inside progression route, and the full-back advancing to control the wide receiving option. The remaining players adjust their positions to preserve compactness, defensive cover and protection against direct progression.

The game-model principle does not automatically determine the immediate content of training. Analysis of recent training and match performance may reveal, for example, that the winger initiates pressure but the supporting movements occur too late, allowing opponents to escape through the inside passing lane. The training priority is therefore formulated more specifically: to improve the temporal coordination of the winger, striker, ball-side midfielder and full-back when the opponent circulates the ball from a centre-back towards the touchline. Table 3 summarises the complete translation pathway.

Table 3. Applied translation of coordinated high pressing through the MTTP.

MTTP component	Application to the case
Coaching philosophy	Promote proactive, collectively responsible and adaptable play.
Game idea	Recover possession early, restrict central progression and sustain territorial initiative.
Game-model principle	Protect the centre and direct the opponent's build-up towards the touchline before applying coordinated pressure.
Game-model subprinciple	Treat the pass from centre-back to full-back as a potential pressing trigger, provided that supporting positions enable collective pressure.
Training priority	Improve the temporal and spatial coordination of the winger, striker, ball-side midfielder and full-back during wide pressing.
Task constraints	Recurrent build-up from the goalkeeper; active opposition; directional play; pitch dimensions preserving central and wide progression; scoring incentives for successful progression and high regains; variable build-up solutions.
Learning environment	Repeated but non-identical opportunities to detect pressing triggers, coordinate supporting actions and adapt to different opponent responses under representative informational conditions.
Pedagogical intervention	Brief questioning, guided attention and task adjustment focused on the relationships among the pressing players rather than prescribing identical movements.
Behavioural indicators	Direction of opposition progression, response to the pressing trigger, protection of central access, synchronisation of supporting movements, collective compactness and the outcome of the pressing sequence.
Feedback and recalibration	Observed behaviours inform subsequent adjustments to the priority, task constraints, intervention or relevant game-model subprinciple.

Note. The example illustrates one context-specific application and should not be interpreted as a universal pressing model or standardised training prescription. MTTP = Model-to-Task Translation Process.

A possible practice activity involves two teams of eight outfield players and two goalkeepers on an approximately 65 × 52 m playing area, adjusted according to player level and the physical and informational demands intended by the coach. The team selected to develop high pressing is organised with a front three, two midfielders and three covering players. The opposition is organised to reproduce the principal

relationships of build-up play, including central defenders, full-backs, midfield support and advanced targets. The numerical configuration is not intended to reproduce the full match structure but to preserve the relationships most relevant to the targeted pressing problem.

Each sequence begins with the opposition goalkeeper, ensuring repeated exposure to the build-up phase without predetermining where the ball must be played. The team in possession attempts to progress through controlled possession and score in the opposing goal. The pressing team plays normally after regaining possession, but an additional reward may be attributed to goals scored shortly after a regain in the attacking sector. This incentive gives functional value to high recovery without requiring players to press in every situation irrespective of the conditions available.

The playing area should preserve sufficient width for the opposition to use central and wide progression routes. Marked lateral reference channels may initially help the coach and players identify where pressing situations occur, but they should not oblige the opposition to play wide or require defenders to remain within predetermined zones. If the task guarantees the desired pass or fixes every subsequent movement, players may reproduce the external form of pressing without learning to detect whether the relevant informational conditions are present.

The opposition should therefore be encouraged to vary its build-up. It may circulate between centre-backs, use the goalkeeper to change the point of attack, connect with a supporting midfielder, progress through the full-back or play directly towards an advanced player. This variability is essential because the pressing team must learn to distinguish between situations in which collective pressure is functionally available and situations in which delaying, adjusting or reorganising is more appropriate.

Task constraints are selected according to their function. Recurrent restarts from the goalkeeper increase the availability of the targeted problem. Directional play preserves the relationship between pressure, territorial progression and goal protection. Active opposition maintains representative perception–action demands. The pitch dimensions regulate the time and space available for circulation, pressure and defensive cover. Scoring incentives increase the value of high regains and successful opposition progression without prescribing the precise actions through which either team must achieve them.

These constraints operationalise the training priority, but they do not constitute the learning environment in isolation. The environment emerges as players interact with the task, interpret the movements of teammates and opponents, detect or fail to detect pressing opportunities, and adapt their positioning across successive sequences. Its quality depends on whether the activity repeatedly generates the intended tactical problem while preserving enough variability for players to explore different functional solutions.

Pedagogical intervention should focus on the relationships that support collective pressure rather than on prescribing a fixed movement sequence. During brief pauses, the coach might ask: What information indicated that pressure could be initiated? Which passing option had to be removed before the winger advanced? What allowed the opponent to escape inside? How did the position of the ball-side midfielder affect the full-back's decision? Such questions direct attention towards functionally relevant information while allowing players to reconstruct the solution from their experience.

Direct feedback may be appropriate when the tactical function is unclear or when a recurring coordination problem prevents meaningful engagement with the task. Even in these situations, feedback should distinguish the intended function from its possible behavioural forms. The requirement to restrict central

 © 2026 ARD Asociación Española

progression may remain stable, while the precise distances, angles and timing through which players achieve it vary according to ball speed, opponent positioning and the movements of teammates.

The coach may evaluate the activity through opportunity, process and outcome indicators. Opportunity indicators establish whether the task generated a sufficient number of relevant pressing situations. Process indicators examine whether players recognised the trigger, protected central access and synchronised supporting movements. Outcome indicators record whether the opponent was forced backwards, directed into a less advantageous action, compelled to play long, dispossessed in an advanced area or able to escape pressure. This distinction is necessary because a successful ball recovery may result from an opponent's technical error, while a well-coordinated pressing action may not result in possession being regained.

Evidence from the activity should inform subsequent decisions. If few relevant situations occur, the task constraints may require adjustment. If the winger consistently initiates pressure before central access is protected, the training priority or pedagogical intervention may need greater emphasis on the preparatory relationships. If the opposition can no longer create meaningful variation, the task may have become too predictable and should be progressed. If coordination stabilises only under simplified conditions, representativeness may need to increase gradually before transfer to competition can be reasonably examined.

The recursive feedback represented in Figure 1 becomes operational in this process. Observed behaviour does not merely indicate whether the players complied with the coach's instructions. It provides evidence concerning the adequacy of the original translation: whether the training priority captured the relevant performance problem, whether the task constraints made that problem available, whether the learning environment supported adaptive engagement and whether the game-model subprinciple was defined with sufficient functional clarity.

Across subsequent sessions, the task format may change while the developmental direction remains coherent. The same priority may be explored through larger numerical configurations, different opposition structures or practice closer to full match conditions. Conversely, the same task format may be retained but redesigned to address a different priority. Model coherence therefore resides in the traceable relationship among intention, tactical problem, task design and behavioural evaluation, not in the repeated use of a particular exercise.

This example illustrates the practical function of the MTTP. The framework does not determine which pressing model a coach should adopt or guarantee that the intended behaviour will emerge. It provides a structure for making the reasoning behind practice design explicit, evaluating whether the intended tactical problem was meaningfully represented and using observed behaviour to recalibrate subsequent decisions.

Monitoring and recursive recalibration

Monitoring within the MTTP is intended to determine whether the translation from training priority to task design is functioning as proposed and what subsequent adjustment, if any, is warranted. Before implementation, coaches should specify the tactical problem to be observed, the conditions under which opportunities to address it are expected to occur and the behavioural relationships that would provide relevant evidence. This prospective definition reduces the risk of evaluating an activity only through its most visible or successful outcomes.

Observation should distinguish among opportunity, process and outcome indicators. Opportunity indicators establish whether the task generated the situations required for the selected tactical problem to become available. Process indicators examine how players perceived and coordinated their responses within those situations. Outcome indicators record the consequences of those responses, such as progression, disruption, territorial gain, chance creation or ball recovery. These levels should not be conflated: a favourable outcome may result from an opponent's error, whereas a functionally coordinated response may not produce immediate success.

Interpretation should also account for exposure and context. An intended behaviour cannot reasonably be expected when the relevant opportunity rarely occurs, and its appearance in a single sequence provides weak evidence of development. Monitoring should therefore examine the frequency, coordination and adaptability of behavioural tendencies across repeated task exposures, changing opposition responses and progressively more representative conditions. When feasible, observations from training should be compared with corresponding situations in competition.

Complementary evidence may strengthen this evaluation. Systematic observation and video analysis can document tactical opportunities and collective coordination; positional or event data may quantify spatial, temporal and interactional tendencies; and brief player or coach reflections may clarify how relevant information and task intentions were perceived. The choice of evidence should remain proportional to the question being examined and should not imply that every application of the MTTP requires advanced technology.

Monitoring becomes functionally useful when observations are connected to explicit decisions. If the intended tactical problem rarely becomes available, task constraints should be reconsidered. If opportunities occur but coordination remains consistently inappropriate, the coach should examine player readiness, task difficulty and pedagogical intervention. If the intended behaviour appears only under simplified conditions, representativeness should be progressively increased. If it remains stable and adaptable across varied practice and competition contexts, the priority may be progressed, integrated with another problem or temporarily reduced in emphasis. Recurring evidence that the selected priority does not address the underlying performance problem may require reconsideration of the corresponding game-model principle.

Recursive recalibration should therefore operate at different levels and timescales. Immediate evidence may justify modifying a rule, space or numerical relation within the activity; patterns observed across sessions may lead to the continuation or reformulation of a training priority; and evidence accumulated across training and competition may contribute to longer-term refinement of the game model. Monitoring does not close the translation process by confirming whether coaching intentions were reproduced. It reopens that process by testing the adequacy of the decisions through which those intentions were translated into practice.

Operationalising the Model–Task Alignment Matrix

The Model–Task Alignment Matrix evaluates training activities according to two complementary but analytically distinct dimensions: alignment with the selected game-model principle and representativeness of the relevant competitive demands. Alignment concerns whether the task creates meaningful opportunities to engage with the tactical problem that the coach intends to develop. Representativeness concerns whether the activity preserves the information, interactions and perception–action relationships required to regulate behaviour in the corresponding competitive situation.

 © 2026 ARD Asociación Española

Neither dimension should be inferred from task format alone. Player numbers, pitch dimensions, rules and spatial configurations describe how an activity is organised, but do not establish its functional value. A task is aligned only when its constraints repeatedly make the selected tactical problem available and enable the relevant behaviours to be observed. It is representative only when players perceive and act upon information functionally related to that which regulates performance in competition.

Table 4 presents a preliminary set of criteria for examining both dimensions. The criteria are intended to support systematic reflection and transparent decision-making rather than to constitute a validated measurement instrument. Each criterion may be rated on a three-point ordinal scale: 0 = absent, contradicted or functionally irrelevant; 1 = partially or inconsistently present; and 2 = clearly and consistently present. Ratings should be supported by task-design information and observation of the activity rather than by the coach's intention alone.

Table 4. Preliminary criteria for assessing model–task alignment and training representativeness.

Dimension	Criterion	Operational question
Model–task alignment	Explicit derivation	Is the task explicitly derived from a defined training priority and corresponding game-model principle?
Model–task alignment	Tactical-problem availability	Does the activity repeatedly create functional opportunities for players to encounter the intended tactical problem?
Model–task alignment	Constraint–priority coherence	Do the manipulated constraints privilege the relevant interactions without distorting the intended tactical function?
Model–task alignment	Behavioural opportunity	Are players able to perceive, select and perform behaviours functionally consistent with the targeted principle?
Model–task alignment	Observability	Can the relevant behaviours and their coordination be evaluated relative to the opportunities created by the task?
Representativeness	Performer–environment coupling	Does performance depend on active interaction with relevant teammates, opponents, the ball and space?
Representativeness	Informational fidelity	Are the principal informational variables that regulate the corresponding competitive behaviour available?
Representativeness	Perception–action coupling	Are players required to perceive, decide and act within the same unfolding sequence rather than perform these processes separately?
Representativeness	Spatiotemporal and consequential fidelity	Does the task preserve functionally relevant spatial, temporal, pressure and action–outcome relationships?
Representativeness	Functional variability	Does the activity include sufficient variation for players to adapt their responses to changing but relevant performance conditions?

Note. The criteria constitute a preliminary heuristic framework and have not been empirically validated. Ratings should be interpreted as ordinal criterion profiles rather than as interval measurements. Model–task alignment must be assessed relative to a previously specified game-model principle and training priority; representativeness must be assessed relative to the competitive situation for which the activity is intended to prepare players.

Assessment should begin before the activity is implemented. The coach should specify the game-model principle, the training priority, the tactical problem to be made available and the corresponding competitive situation. The information that regulates successful performance in that situation should also be identified. Without these prior references, both alignment and representativeness risk being judged retrospectively according to whether the activity appeared successful.

The task should then be observed across a sufficient number of sequences to determine what opportunities it actually generates. A well-intended design may produce few occurrences of the targeted problem, while an apparently simple activity may preserve its essential informational relationships. Whenever possible, ratings

should combine the contextual knowledge of the coach with systematic observation, video review or assessment by a second informed observer. Disagreement should lead to examination of the evidence supporting each rating rather than automatic averaging of subjective scores.

The five ratings within each dimension form an ordinal criterion profile. For preliminary heuristic use, they may also be summed to produce a total ranging from 0 to 10, but this total should not be treated as an interval score or a validated measurement scale. Scores from 0 to 4 indicate predominantly low fulfilment of the dimension, whereas scores from 6 to 10 indicate predominantly high fulfilment. A score of 5 represents a boundary or indeterminate profile and should not be assigned automatically to either category. In all cases, quadrant positioning should be supported by examination of the individual criteria and the contextual evidence on which the ratings are based. These provisional decision rules are intended to improve transparency and require empirical validation.

Importantly, the total score should not replace examination of the criterion profile. Two tasks may obtain the same total through different combinations of strengths and weaknesses. In representativeness, for example, active opposition cannot necessarily compensate for the absence of information that specifies the targeted decision. Similarly, frequent occurrence of a tactical problem does not ensure alignment if the task constraints systematically encourage solutions that conflict with the intended game-model principle.

The resulting profiles allow activities to be positioned within the four quadrants represented in Figure 2. These quadrants should not be interpreted as fixed categories of exercise quality. They describe the relationship between a task and a specified purpose at a particular moment. The same activity may occupy a different position when applied to another training priority, age group, expertise level or stage of learning.

Quadrant I: high alignment and high representativeness
Tasks in this quadrant create repeated opportunities to engage with the intended tactical problem while preserving the principal information–action relationships of competition. They are particularly valuable when the objective is to consolidate, adapt or examine transfer of a game-model principle under functionally realistic conditions. Their classification as high in both dimensions does not guarantee learning, and does it make them universally preferable. Excessive complexity may still exceed players ' current capabilities or reduce the frequency with which the targeted problem occurs.

Quadrant II: high alignment and low representativeness
These activities emphasise the intended tactical problem under selectively simplified conditions. They may be useful when introducing a principle, increasing the frequency of a particular interaction or temporarily reducing complexity. Their developmental value depends on whether simplification preserves the functional core of the problem and whether subsequent practice progressively restores relevant information and variability. Remaining indefinitely in this quadrant may limit transfer.

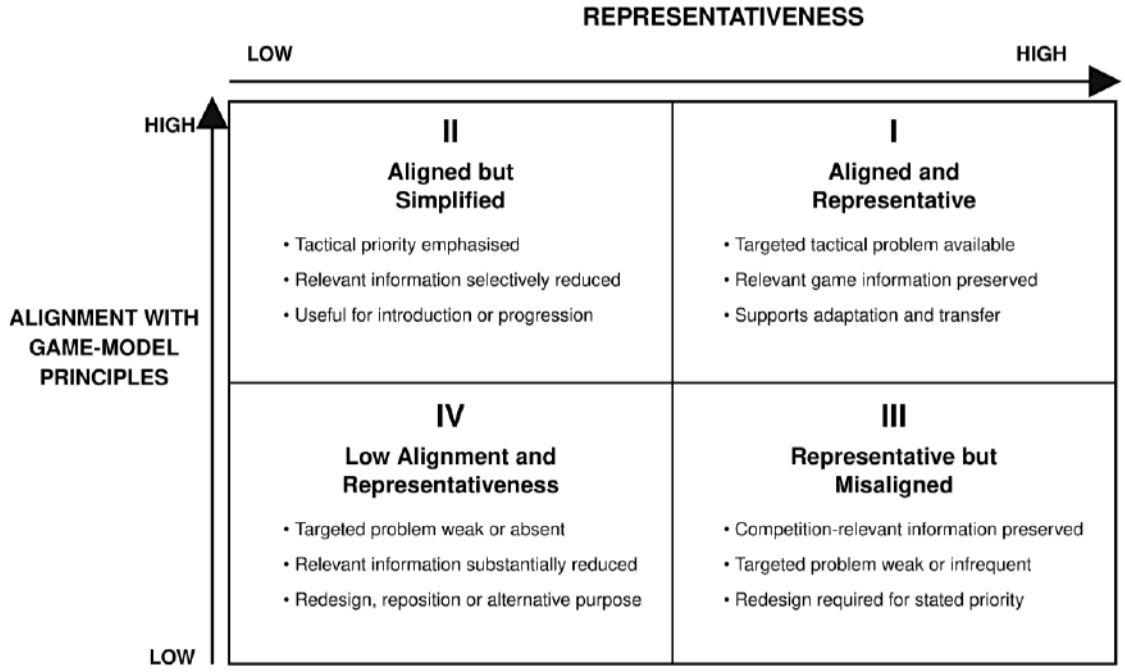
Quadrant III: low alignment and high representativeness
These activities preserve many characteristics of competitive play but provide limited or inconsistent opportunities to develop the selected game-model principle. They may remain useful for general adaptation, assessment, physical conditioning or other explicitly stated purposes. However, when presented as a task for developing a specific tactical priority, they risk creating methodological incoherence. The appropriate response is not necessarily to reduce representativeness, but to reconsider the task constraints or redefine the intended priority.

 © 2026 ARD Asociación Española

Quadrant IV: low alignment and low representativeness
Tasks in this quadrant neither make the selected tactical problem meaningfully available nor preserve the principal information–action relationships of competition. Their contribution to the stated tactical priority is therefore limited and the activity should normally be redesigned, repositioned within the session or justified by an objective outside the MTTP, such as rehabilitation or isolated familiarisation. Classification in this quadrant does not imply that the exercise has no possible value; it indicates that its value is poorly supported relative to the specified game-model principle.

When the two dimensions conflict, the appropriate decision depends on the purpose and timing of practice. Alignment may be prioritised temporarily when players require a simplified introduction to a tactical problem, whereas representativeness should progressively increase when adaptation and transfer become central objectives. Conversely, a highly representative activity should not be retained solely because it resembles competition if it repeatedly fails to generate the problem selected for development. The matrix therefore supports progression and task redesign rather than prescribing a single optimal quadrant for every stage of learning.

Figure 2 summarises the interaction between model–task alignment and representativeness. Its principal function is diagnostic: it helps coaches identify why an activity may or may not serve a specified tactical purpose and what form of adjustment may be required.



Note. Alignment refers to coherence with the selected game-model principle; representativeness refers to the preservation of competition-relevant information and perception–action relationships. Quadrant positions are heuristic and context dependent.

Figure 2. Model–Task Alignment Matrix.

Used in this way, the matrix does not prescribe particular training methods or reduce task quality to a numerical score. It provides a structured basis for examining whether task design, experienced information and the selected tactical purpose remain functionally connected. Repeated assessment may also reveal how activities should be simplified, progressed or recalibrated as players and performance demands evolve.

FUTURE RESEARCH DIRECTIONS

Testable propositions derived from the MTTP

The scientific value of the MTTP depends on whether its proposed relationships can be operationalised, examined and revised through empirical evidence. The framework should therefore generate propositions that extend beyond descriptive classification and specify expected relationships among model–task alignment, training representativeness, pedagogical intervention, behavioural emergence and transfer to competition.

At this stage, these relationships are formulated as directional propositions rather than confirmed hypotheses. Their empirical examination depends on the prior validation of the constructs and preliminary assessment criteria introduced in Table 4. The propositions are not intended to exhaust all possible applications of the MTTP; they identify the relationships most central to determining whether the framework possesses explanatory and practical value.

Table 5. Testable propositions derived from the Model-to-Task Translation Process.

Proposition	Predicted relationship	Illustrative operationalisation	Appropriate research design
P1. Alignment–behaviour proposition	Greater model–task alignment will be associated with more frequent and coordinated expression of the targeted tactical behaviours during training.	Alignment profile; number of functional opportunities; proportion of opportunities producing the targeted individual and collective responses; coordination quality.	Repeated-measures observational studies comparing tasks designed to differ in alignment.
P2. Representativeness–transfer proposition	Representativeness will moderate the relationship between model–task alignment and transfer: the association between alignment and expression of targeted behaviours in competition will be stronger when practice preserves relevant information–action relationships.	Alignment and representativeness profiles; behavioural correspondence between training and competition; stability and adaptability across opponents.	Longitudinal designs linking training-task exposure with subsequent competitive behaviour; multilevel moderation models.
P3. Progression proposition	Progression from highly aligned but simplified practice towards highly aligned and representative practice will produce stronger transfer than prolonged exposure to simplified conditions alone.	Planned movement from Quadrant II towards Quadrant I; behavioural performance during simplified practice, representative practice and competition.	Controlled interventions comparing progressive and non-progressive task sequences.
P4. Cumulative coherence proposition	More consistent model–task alignment across successive sessions will be associated with greater stability and adaptability of targeted collective behaviours than isolated exposure to highly aligned tasks.	Session-level alignment profiles; cumulative exposure; longitudinal change in tactical coordination, variability and opponent-specific adaptation.	Prospective longitudinal studies using session-level observations nested within players and teams.
P5. Pedagogical congruence proposition	Pedagogical interventions that direct attention towards information relevant to the training priority, without prescribing invariant solutions, will strengthen the relationship between task design and adaptive behavioural emergence.	Congruence between intervention content and training priority; timing and frequency of feedback or questioning; functional variability and behavioural coordination.	Comparative interventions, systematic observation of coaching behaviour and mixed-method studies.

 © 2026 ARD Asociación Española

P6. Recursive recalibration proposition	Systematic use of behavioural evidence to recalibrate training priorities and task constraints will improve subsequent model–task coherence more than planning that does not incorporate structured feedback.	Documentation of observation-informed task adjustments; changes in alignment profiles; subsequent availability and expression of targeted behaviours.	Longitudinal case studies, interrupted time-series designs or team-level comparative interventions.

Note. The propositions express theoretically expected relationships rather than established causal effects. MTTP = Model-to-Task Translation Process.

The propositions operate at different levels of analysis and should not be interpreted solely through task outcomes. For P1, alignment must be evaluated in relation to the opportunities generated: the absence of a targeted response is informative only when the relevant tactical problem was available, while an apparently successful action provides weak evidence when it results from an atypical event or an opponent's unforced error.

P2 and P3 distinguish the expression of behaviour during practice from transfer beyond it. Alignment may increase engagement with the selected tactical problem, but transfer is expected to depend on whether practice preserves the information–action relationships that regulate performance in competition. P4 extends this reasoning from the individual task to cumulative exposure, proposing that coherence across successive sessions matters more than isolated use of a highly aligned activity.

P5 and P6 address the regulation of the translation process. Pedagogical intervention may strengthen task functionality when it directs attention towards relevant information without prescribing invariant solutions. Systematic monitoring may, in turn, improve subsequent decisions by revealing whether priorities, constraints and task progressions require adjustment. Together, the six propositions establish an empirical programme spanning task sequences, training sessions, intervention periods and competitive seasons. Evidence should be used not only to examine the predicted relationships but also to refine the constructs and boundary conditions of the MTTP.

Measuring model–task alignment

The empirical examination of Propositions 1, 3, 4 and 6 requires valid and reliable methods for assessing model–task alignment. The preliminary criteria proposed in Table 4 translate the construct into observable questions, but they should not yet be interpreted as a psychometrically established measurement instrument.

Research must determine whether these criteria adequately represent the construct, can be applied consistently across observers and coaching contexts, and meaningfully discriminate between tasks with different relationships to the intended game model.

Addressing this gap requires moving beyond descriptive features such as pitch dimensions, player numbers or exercise format. Instead, research should examine whether practice tasks consistently expose players to the tactical problems, informational demands and decision-making opportunities associated with the principles they are intended to develop. Alignment should therefore be evaluated according to function rather than appearance.

One promising direction is the development of observational instruments capable of linking game-model principles, task characteristics and performance outcomes. For example, a practice designed to develop coordinated high pressing could be assessed according to the frequency and quality of pressing triggers,

collective synchronisation, defensive cover and ball recovery opportunities it generates. Similarly, tasks targeting positional play could be examined through indicators related to spatial occupation, support structures, ball circulation and the creation or exploitation of numerical superiority.

Future research may also benefit from combining systematic observation with expert judgement. Coaches possess detailed contextual knowledge of their intended playing model, but this expertise must be translated into explicit and reliable evaluation criteria if alignment is to be examined rigorously. Integrating coach interviews, expert panels, video analysis and performance indicators could therefore provide a more comprehensive approach while preserving the contextual nature of coaching practice. Validation should proceed in stages. Content validity may initially be examined through expert consultation and structured consensus procedures. Interobserver reliability should then be tested using standardised video samples and independently applied rating criteria. Construct validity may be explored by comparing tasks intentionally designed to differ in alignment, while predictive and ecological validity require examining whether higher alignment is associated with more frequent, coordinated or adaptable expression of the targeted behaviours during subsequent training and competition.

Another important question concerns the degree of alignment. Rather than treating alignment as a simple yes-or-no condition, future studies should examine it as a continuum. Practice tasks are likely to differ in the extent to which they reinforce particular playing principles, and these differences may have important consequences for learning, transfer and long-term player development.

Validating model–task alignment would provide a direct test of the MTTP's central translational claim. Reliable assessment should determine not only whether tasks differ in alignment, but whether those differences are associated with the availability, coordination and subsequent expression of the targeted tactical behaviours.

Assessing training representativeness

The empirical examination of Propositions 2 and 3 requires valid and context-sensitive methods for assessing training representativeness. Table 4 proposes preliminary criteria concerning performer–environment coupling, informational fidelity, perception–action coupling, spatiotemporal and consequential fidelity, and functional variability. These criteria provide a starting point for systematic analysis, but their relevance, reliability and sensitivity across football contexts and developmental levels remain to be established.

Although Representative Learning Design has become a central concept in skill acquisition and coaching, there is still limited agreement on how representativeness should be defined, measured and evaluated in applied football settings. Consequently, coaches often rely on subjective judgement when determining whether practice adequately reflects the informational and tactical demands of competition.

From an ecological perspective, representativeness refers to the extent to which practice preserves the informational variables that regulate action during competition (Pinder et al., 2011; Chow et al., 2016; Woods et al., 2020). Effective practice should therefore provide opportunities for players to perceive, decide and act in response to information that closely resembles that encountered in match play. Preserving these informational relationships is considered essential for developing perception–action couplings that transfer successfully beyond the training context.

Despite broad acceptance of this principle, assessing representativeness remains challenging. Activities may appear highly game-like while failing to preserve the informational features that drive decision-making.

 © 2026 ARD Asociación Española

Conversely, practice tasks that differ substantially from competition in their outward appearance may still retain the critical tactical and perceptual demands required for effective learning. Representativeness should therefore be evaluated according to informational fidelity rather than visual similarity.

Future research should focus on identifying practical indicators capable of operationalising representativeness in football. Variables such as interpersonal interactions, spatial-temporal relationships, perceptual demands, decision-making opportunities and tactical problem structures provide promising starting points. Comparing these characteristics across training and competition could establish more objective criteria for evaluating the extent to which practice reflects the informational realities of the game.

Another promising direction is the examination of representativeness across different stages of player development. Younger or less experienced players may benefit from practice that selectively simplifies informational demands without compromising their functional relevance, whereas advanced performers may require increasingly representative conditions to maximise transfer to competition. Investigating how representativeness should evolve across developmental stages could provide valuable guidance for age-specific and expertise-specific practice design.

Research should ultimately determine which informational relationships must be preserved, which may be temporarily simplified and how these requirements vary with expertise and developmental stage. Such evidence is necessary to distinguish functional simplification from task designs that remove the information required for transfer.

Tracking behavioural emergence over time

A third priority for future research is the longitudinal investigation of behaviour emergence. Although this concept is central to contemporary perspectives on learning and performance, relatively little research has examined how coordinated team play develops over extended periods of football training. Most existing studies focus on short-term interventions, isolated practice tasks or single matches, providing only limited insight into how behaviours functionally related to playing principles become progressively more frequent, coordinated and adaptable within team performance.

This research direction is particularly relevant to Propositions 2 and 4. Testing transfer and cumulative coherence requires repeated observation of both training exposure and competitive behaviour, while accounting for changes in opponents, player availability, task design and competitive context.

Longitudinal research could provide valuable insight into how players progressively attune to the informational variables that regulate performance. Such studies may examine the evolution of tactical awareness, coordination, decision-making and collective adaptation as teams gain sustained exposure to coherent practice. This perspective would advance understanding of learning as a gradual developmental process rather than a sequence of isolated acquisitions.

Future work should also examine the temporal dynamics of development. Different playing principles are unlikely to evolve at the same rate. Some aspects of collective play may stabilise relatively quickly, whereas others may require prolonged exposure before becoming consistently expressed. Identifying these developmental trajectories would improve understanding of the relationship between practice design, learning and performance.

Another important question concerns the stability of emerging performance patterns. Football is characterised by continual adaptation to changing opponents and competitive contexts, making variability an inherent feature of performance. Longitudinal studies could help distinguish adaptive flexibility from inconsistency arising from insufficient development, providing coaches with more meaningful criteria for interpreting change over time.

Training history also deserves greater attention. Players do not enter practice as blank slates but bring experiences accumulated across previous teams, coaches and developmental environments. Examining how these experiences influence responsiveness to different training processes may improve understanding of why teams and individuals evolve differently despite being exposed to similar practice conditions.

Methodologically, this area would benefit from integrating quantitative and qualitative approaches. Positional data, social network analysis, tactical performance indicators and systematic observation can document changes in collective functioning, while interviews, reflective methods and video-based discussions may reveal how players interpret tactical problems and construct shared understanding. Combining these approaches would provide a richer account of long-term development than either could achieve independently.

Longitudinal evidence is required to test whether cumulative coherence is associated with greater stability and adaptability of targeted collective behaviours. Such designs should also clarify the timescales over which different tactical tendencies develop and distinguish functional variability from inconsistency arising from insufficient exposure or poorly aligned practice.

Investigating game-model development

A fourth priority for future research is the longitudinal investigation of game model development. Although game models are commonly described as relatively stable references for organising team play, coaching practice suggests that they evolve continuously in response to experience, player development and changing competitive demands. They should therefore be understood not as fixed structures but as dynamic systems that are progressively refined over time.

Despite their central importance in football coaching, relatively little research has examined how game models are constructed, adapted and transformed across extended periods of practice and competition. Most existing studies provide cross-sectional descriptions of tactical characteristics, offering limited insight into the developmental processes through which playing principles are established, adjusted and consolidated. Consequently, our understanding of how coaches shape and refine their game models throughout their professional careers remains incomplete.

Longitudinal research could help clarify the mechanisms that drive this evolution. Studies may investigate how playing principles change in response to player profiles, competitive experiences, injuries, tactical innovations or shifts in coaching philosophy. Such work would contribute to a more realistic understanding of coaching as an adaptive process rather than the implementation of a predetermined tactical blueprint.

Particular attention should be given to the balance between continuity and change. Successful teams often preserve a recognisable playing identity while adapting to new challenges and competitive contexts. Future research could therefore examine how coaches maintain core principles while modifying specific aspects of the game model in response to evolving circumstances. Understanding this balance would address one of the most persistent questions in football coaching: how to remain consistent without becoming inflexible.

 © 2026 ARD Asociación Española

Proposition 6 concerns the reciprocal relationship between observed performance and game-model development. The MTTP proposes that evidence from training and competition informs subsequent priorities, task constraints and over longer periods, the refinement of the game model itself. Longitudinal studies could examine how recurring tactical tendencies lead to changes in planning and whether those adjustments subsequently alter practice and competitive performance.

Research should also examine how model development differs across coaching contexts. Professional teams, youth academies and long-term development programmes operate under different constraints, objectives and timescales, all of which are likely to influence the pace and nature of tactical evolution. Comparative studies across these settings could provide valuable insight into how contextual factors shape the development of a team's playing identity.

Methodologically, this field would benefit from combining tactical analysis with coach-centred inquiry. Match and training data can document changes in team organisation over time, while interviews, planning documents and observational studies can reveal the reasoning that underpins those changes. Integrating these sources would enable researchers to examine both the evolution of team play and the decision-making processes that drive it.

CONCLUSION

This paper addressed the insufficiently articulated relationship between coaching intentions, game-model principles and everyday training design by proposing the MTTP as an integrative conceptual and decision-guiding framework. The MTTP is not an empirically validated training method or a prescriptive sequence of exercises. Its originality lies in specifying the differentiated functions and relationships through which strategic intentions may inform training priorities, task constraints, learning environments and observable team behaviour.

The framework offers three principal conceptual contributions. First, it establishes a vertically coherent pathway through which coaching decisions can be traced from strategic intention to task design and behavioural evaluation. Second, it distinguishes model–task alignment from training representativeness: the former concerns whether practice makes a selected tactical problem available, whereas the latter concerns whether players engage with that problem through competition-relevant information and perception–action relationships. Third, it conceptualises translation as recursive, because evidence from training and competition may lead to the recalibration of priorities, tasks and the game model itself.

These contributions depend on conditional functional integration rather than epistemological equivalence among Tactical Periodization, Ecological Dynamics, the Constraints-Led Approach, Nonlinear Pedagogy and Coaching Pedagogy. Within the MTTP, the game model provides functional direction without prescribing invariant actions; constraints shape opportunities without determining solutions; and pedagogical intervention may guide attention without replacing players ' perception and decision-making. The game model therefore operates as a dynamic reference that channels adaptation while remaining responsive to players, opponents and context.

For practitioners, the MTTP provides a rationale for moving from exercise selection towards the explicit justification of task purpose, design and evaluation. The applied case and Model–Task Alignment Matrix illustrate how coaches may examine whether a tactical problem is available, whether relevant information is preserved and whether observed responses warrant task progression or redesign. These tools are

preliminary and should support contextual judgement rather than prescribe a universally optimal form of practice.

For research, the six directional propositions specify expected relationships concerning alignment, representativeness, task progression, cumulative coherence, pedagogical congruence and recursive recalibration. Their examination requires validation of the proposed constructs and assessment criteria through observational, longitudinal, intervention-based and mixed-method designs. Evidence may support, qualify or reject these relationships and should be used to refine the framework's assumptions and boundary conditions.

The MTTP thus provides a conceptually explicit and empirically examinable account of how an intended way of playing may acquire practical expression through training. Its contribution will ultimately depend on whether it improves the precision with which researchers and practitioners design, observe and evaluate the translation between game model and training task.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Araújo, D., Davids, K., & Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychology of Sport and Exercise,* 7(6), 653-676. https://doi.org/10.1016/j.psychsport.2006.07.002

Castelo, J. (1994). *Futebol: Modelo técnico-táctico do jogo: Identificação e caracterização das grandes tendências evolutivas das equipas de rendimento superior*. Faculdade de Motricidade Humana.

Castelo, J. (2009). *Futebol: Organização dinâmica do jogo* (3rd ed.). Faculdade de Motricidade Humana.

Chow, J. Y., Davids, K., Button, C., Shuttleworth, R., Renshaw, I., & Araújo, D. (2007). The role of nonlinear pedagogy in physical education. *Review of Educational Research,* 77(3), 251-278. https://doi.org/10.3102/003465430305615

Chow, J. Y., Davids, K., Button, C., & Renshaw, I. (2016). *Nonlinear pedagogy in skill acquisition: An introduction*. Routledge. https://doi.org/10.4324/9781315813042

Chow, J. Y., Davids, K., Button, C., & Renshaw, I. (2022). *Nonlinear pedagogy in skill acquisition: An introduction (2nd ed.)*. Routledge. https://doi.org/10.4324/9781003247456

 © 2026 ARD Asociación Española

Cushion, C. J., Armour, K. M., & Jones, R. L. (2003). Coach education and continuing professional development: Experience and learning to coach. *Quest, 55*(3), 215-230. https://doi.org/10.1080/00336297.2003.10491800

Davids, K., Araújo, D., Vilar, L., Renshaw, I., & Pinder, R. A. (2013). An ecological dynamics approach to skill acquisition: Implications for development of talent in sport. *Talent Development & Excellence, 5*(1), 21-34.

Davids, K., Button, C., & Bennett, S. (2008). *Dynamics of skill acquisition: A constraints-led approach*. Human Kinetics.

Duarte, R., Araújo, D., Correia, V., & Davids, K. (2012). Sports teams as superorganisms: Implications of sociobiological models of behaviour for research and practice in team sports performance analysis. *Sports Medicine, 42*(8), 633-642. https://doi.org/10.2165/11632450-000000000-00000

Garganta, J. (1997). *Modelação táctica do jogo de futebol: Estudo da organização da fase ofensiva em equipas de alto rendimento* [Doctoral dissertation, Universidade do Porto].

Garganta, J. (2009). Trends of tactical performance analysis in team sports: Bridging the gap between research, training and competition. *Revista Portuguesa de Ciências do Desporto, 9*(1), 81-89. https://doi.org/10.5628/rpcd.09.01.81

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin.

Jones, R. L. (Ed.). (2006). *The sports coach as educator: Re-conceptualising sports coaching*. Routledge. https://doi.org/10.4324/9780203020074

Lyle, J., & Cushion, C. (2017). *Sport coaching concepts: A framework for coaching practice (2nd ed.)*. Routledge. https://doi.org/10.4324/9780203126424

Nelson, L. J., Cushion, C. J., & Potrac, P. (2006). Formal, nonformal and informal coach learning: A holistic conceptualisation. *International Journal of Sports Science & Coaching, 1*(3), 247-259. https://doi.org/10.1260/174795406778604627

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341-360). Martinus Nijhoff. https://doi.org/10.1007/978-94-009-4460-2_19

O'Donoghue, P. (2021). *An introduction to performance analysis of sport (3rd ed.)*. Routledge.

Oliveira, B., Amieiro, N., Resende, N., & Barreto, R. (2006). *Mourinho: Porquê tantas vitórias?* Gradiva.

Pinder, R. A., Davids, K., Renshaw, I., & Araújo, D. (2011). Representative learning design and functionality of research and practice in sport. *Journal of Sport and Exercise Psychology, 33*(1), 146-155. https://doi.org/10.1123/jsep.33.1.146

Plakias, S. (2023). An integrative review of the game model in soccer: Definition, misconceptions, and practical significance. *Trends in Sport Sciences, 30*(2), 85-92.

Rein, R., & Memmert, D. (2016). Big data and tactical analysis in elite soccer: Future challenges and opportunities for sports science. *SpringerPlus, 5*, Article 1410. https://doi.org/10.1186/s40064-016-3108-2

Renshaw, I., Davids, K., Newcombe, D., & Roberts, W. (2019). *The constraints-led approach: Principles for sports coaching and practice design*. Routledge. https://doi.org/10.4324/9781315102351

Sarmento, H., Anguera, M. T., Pereira, A., & Araújo, D. (2018). Talent identification and development in male football: A systematic review. *Sports Medicine, 48*(4), 907-931. https://doi.org/10.1007/s40279-017-0851-7

Seifert, L., Araújo, D., Komar, J., & Davids, K. (2017). Understanding constraints on sport performance from the complexity sciences paradigm: An ecological dynamics framework. *Human Movement Science, 56*, 178-180. https://doi.org/10.1016/j.humov.2017.05.001

Silva, P., Garganta, J., Araújo, D., Davids, K., & Aguiar, P. (2013). Shared knowledge or shared affordances? Insights from an ecological dynamics approach to team coordination in sports. *Sports Medicine, 43*(9), 765-772. https://doi.org/10.1007/s40279-013-0070-9

Tamarit, X. (2013). *Periodización táctica: Vivenciar el juego para condicionar el juego*. MC Sports.

Travassos, B., Araújo, D., Duarte, R., & McGarry, T. (2012). Spatiotemporal coordination behaviours in futsal (indoor football) are guided by informational game constraints. *Human Movement Science, 31*(4), 932-945. https://doi.org/10.1016/j.humov.2011.10.004

Woods, C. T., Rudd, J., Robertson, S., & Davids, K. (2020). Wayfinding: How ecological perspectives of navigating dynamic environments can enrich our understanding of the learner and the learning process in sport. *Sports Medicine - Open, 6*, Article 51. https://doi.org/10.1186/s40798-020-00280-9

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Construction and validation of a water polo specific anaerobic swimming test

Toni Propadalo . *Faculty of Kinesiology. University of Split. Split, Croatia.*
Jakov Marasović. *Faculty of Kinesiology. University of Split. Split, Croatia.*
Ognjen Uljevic. *Faculty of Kinesiology. University of Split. Split, Croatia.*

ABSTRACT

Water polo lacks sport-specific anaerobic field tests that adequately reflect the physiological and respiratory demands of competition. The repeated sprint ability (RSA) test is commonly used to assess anaerobic performance; however, it does not account for the dynamic apnoea frequently experienced during match play. This study aimed to evaluate the reliability and validity of a newly developed water polo-specific anaerobic swimming test (TP) that combines repeated sprint swimming with dynamic apnoea. The protocol was designed to provide a more ecologically valid assessment of water polo performance by incorporating respiratory constraints that mimic real-game situations. Ten elite junior male water polo players participated in the study. The TP test consisted of repeated maximal swimming efforts combined with dynamic apnoea. Reliability was assessed using the intraclass correlation coefficient (ICC), coefficient of variation (CV), paired-samples t-test, and minimal detectable change (MDC). Criterion validity was examined through Pearson correlations between TP outcomes and RSA performance. The Kolmogorov-Smirnov test confirmed normal data distribution for all variables ($p > .20$). The TP test demonstrated high relative reliability (ICC = .86), indicating good consistency between testing occasions. The coefficient of variation was 8.6%, suggesting moderate measurement variability, while a significant difference between test and retest scores was observed ($t = 2.50$). The MDC was 1.99. Criterion validity analysis revealed moderate positive correlations with RSA performance (test: $r = .488$; retest: $r = .543$), indicating that both protocols assess related aspects of anaerobic performance while capturing different physiological demands. The TP test showed satisfactory reliability and moderate criterion validity. By integrating dynamic apnoea into repeated sprint assessment, the protocol captures sport-specific respiratory and anaerobic demands not addressed by traditional RSA testing. Although further validation in larger samples is required, the TP test appears to be a practical tool for athlete profiling and performance assessment in water polo.

Keywords: performance analysis; water polo; anaerobic performance; sport-specific test; sprint performance; sports conditioning.

Cite this article as:
Propadalo, T., Marasović, J., & Uljevic, O. (2026). Construction and validation of a water polo specific anaerobic swimming test. *Journal of Human Sport and Exercise, 21*(4), 1557-1567. https://doi.org/10.55860/nr2j1z93

Corresponding author. *Faculty of Kinesiology. University of Split. Teslina 6. 21000 Split, Croatia.*
E-mail: tonipropadalo08@gmail.com
Submitted for publication June 30, 2026.
Accepted for publication August 06, 2026.
Published August 19, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/nr2j1z93

INTRODUCTION

Water polo is a complex team sport characterized by a large number of alternating activities in which short, intense efforts <15 seconds duration and periods of somewhat lower intensity <20 seconds duration alternate (Smith, 1998). The additional difficulty of the game is represented by the fact that water polo takes place in a water medium, which places additional demands on the players in the form of overcoming water resistance with moments of difficulty or impossibility of breathing. From a physiological point of view, water polo belongs to the combined aerobic-anaerobic sports, although such studies are rare due to the limitation of precise sampling of physiological and metabolic variables during competition. However, anaerobic energy systems play a dominant role in actions where speed, strength, and explosive power come to the fore, such as goal kicks, jumping out of water, water wrestling, sprints, etc. Reviewing the literature, repetitive high-intensity intervals dominate in matches, which rely on the phosphagen and glycolytic systems. Such game intensity results in increased metabolic stress and increased lactate production (Smith, 1998; Tan et al., 2009). This has been confirmed in research with blood lactate concentrations often >10 mmol/L in elite water polo players and supports the fact about the anaerobic demands of the game (Platanou, 2004; Botonis et al., 2018). Anaerobic capacity, including strength, speed, and lactate tolerance, is crucial for success in water polo.

However, in addition to all the listed requirements of playing water polo, water polo players also face another phenomenon, which is difficulty breathing. Namely, during fast sprints, wrestling, fighting for position, etc., players arbitrarily or due to collisions with an opponent reduce or completely (when their head is below the surface of the water) stop breathing, which significantly affects recovery from high-intensity actions. These periods of breath holding, known as apnoea, create progressive hypoxia and hypercapnia due to continued metabolic activity in the absence of ventilation (Ferretti, 2001). Dynamic apnoea presents a unique physiological challenge because, despite a temporary cessation of pulmonary ventilation, oxygen consumption continues, leading to progressive hypoxemia and hypercapnia. Hypoxemia and hypercapnia trigger complex cardiovascular, respiratory, and metabolic responses. These physiological responses lead to a reduction of oxygen delivery to active muscles and increase the work of respiratory muscles, which increases reliance on anaerobic energy production during repeated high-intensity exercise. (Elia & Lemaître, 2025).

Oxygen reduction has been associated with impaired recovery between repeated maximal efforts, accelerated neuromuscular fatigue, and reduced repeated-sprint performance (Faiss et al., 2025). Furthermore, acute hypoxia may negatively affect cognitive performance, including response speed, attention, and executive functioning, particularly when the reduction in oxygen availability is low (McMorris et al., 2017; Virués-Ortega et al., 2004).

Water polo is a sport in which these physiological and cognitive responses are particularly important. Maximal swimming efforts in water polo are often combined with underwater duels and wrestling, rapid tactical decisions, diving, and explosive jumps. Testing protocols that do not take into account respiratory stress imposed by dynamic apnoea may underestimate the true physiological and cognitive demands of competitive water polo.

Avoiding apnoea in water sports, including water polo, is practically impossible. By ignoring such a large element of metabolic and respiratory stressors as apnoea, we are not getting the full picture. In previous research, a number of specific tests in water polo were developed which, according to the author's knowledge, measure almost exclusively functional abilities of an aerobic (I Mujika, G McFadden, M Hubbard, K Royal, and A Hahn, 2006) and anaerobic character (Rodriguez, 1994).

 © 2026 ARD Asociación Española

Also, the prolonged and high-intensity nature of the match increases metabolic and cardiovascular disorders and leads to a progressive decrease in game intensity (Galy et al., 2014; Pinnington et al., 1988; Platanou and Geladas, 2006). Therefore, RSA protocols for aquatic sports have been designed and are mainly used to assess sprint reduction, average sprint time, and fatigue development during repeated efforts (Meckel et al., 2013). From these studies, it is clear that this problem is attracting the attention of scientists worldwide. However, to the authors' knowledge, there is no previous research on apnoea in water polo, which represents a major gap in this area of water polo.

These are all valid and important factors for obtaining a complete picture of an athlete's fitness. But do they mimic game situations? The RSA testing protocol that we took as a reference consisted of eight maximal 25 m sprints performed with a 30-second break between sprints (Dalamitros et al., 2021). This type of testing gave us an excellent starting point to include apnoea in the testing.

Namely, you will notice that players in the game have duels, quick changes from attack to defence and have periods in the game in which they perform dynamic apnoea movements. By dynamic apnoea, we mean all underwater wrestling or swimming while holding their breath. This is an element that we believe is missing from the RSA test in order to capture the real demands of water polo.

Therefore, our idea was to include dynamic apnoea in the existing RSA protocol and thus create a new test that provides a better insight into the anaerobic and respiratory capacity of the athlete. Most existing protocols that cover anaerobic capacities neglect apnoea and fail to include the combined metabolic and respiratory demands specific to water polo. As we already know, diagnostic procedures should reflect the real physiological and motor demands of competition as accurately as possible (Young, 2006). Increasing the ecological validity of testing protocols is essential to capture important performance indicators in water polo.

Therefore, the aim of this study was to construct a test, using the gold standard, to assess anaerobic performance in water polo. And to see whether this newly constructed test meets the criteria of validity and reliability in assessing anaerobic performance in water polo. The main hypothesis of the work is that subjects with a lower coefficient on the test will have better anaerobic properties, which will significantly contribute to the quality of performance in water polo.

MATERIALS AND METHODS

Participants

The sample of participants we took was 10 male junior water polo players from the water polo club Jadran Split. Our athletes age was 15.5 ± 1.5 years (range: 14–17 years), with a mean body height of 186.6 ± 5.9 cm (range: 175.3–194.0 cm), a mean body mass of 78.8 ± 11.1 kg (range: 68.7–102.7 kg), and a mean body mass index (BMI) of 22.6 ± 2.8 $kg \cdot m^{-2}$ (range: 20.1–27.2 $kg \cdot m^{-2}$).

We consider them an elite sample because they were national champions a season before testing. Aside from being champions, part of the junior team we tested is involved in the senior team squad. Jadran Split is currently one of the top water polo teams in Croatia. Last three seasons, they won the Croatian championship title and are playing in the LEN Champions League. Also, some of the participants were chosen for the national junior team squad and are competing in European and World championships.

All of the players have been exposed to multiple years of an organized training system in the club. At the moment of testing, they had a volume of about 12 hours of training a week. To ensure optimal performance,

participants completed all tests with a two-day rest period between testing sessions. All participants and their parents provided informed consent prior to participation and received written information about the study procedures. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Faculty of Kinesiology, University of Split (approval number: 2181-205-02-05-26-0014).

Procedures

The tests are described in detail as follows:

Repeated sprint ability test (RSA)

The test included 8 repetitions of a single 25-m all-out sprint set (8 × 25 m), executed with the front-crawl technique. Each 25-m effort was separated by a 30-second rest interval. The players started each sprint with a push-start, while they were instructed to start swimming immediately after their feet left the wall. Two experienced researchers timed each 25-m effort individually with a commercial stopwatch, Seiko S141, Japan (Dalamitros et al., 2021).

Newly constructed anaerobic test

The repeated sprint–dynamic apnoea (TP) test consisted of eight consecutive sets, each comprising a 25-m maximal front-crawl sprint followed by a dynamic apnoea swim performed at maximal (sprint) intensity. During the sprint phase, participants were allowed to breathe freely and were instructed to complete the distance in the shortest possible time. Upon completion of the sprint, a 10-s passive recovery period was provided. Immediately thereafter, participants performed a dynamic apnoea swim without breathing and at maximal swimming intensity, during which the total distance covered was recorded. Distance was measured using visual markers placed at 1-m intervals along the poolside to ensure measurement accuracy. After performing the dynamic apnoea swim, participants had 30-s recovery. If participants finish dynamic apnoea in the middle of the pool, we start a 30-s pause, and they swim at a low tempo till they reach the nearest edge of the pool.

Athletes performed this procedure of maximal sprint followed by dynamic apnoea a total of 8 times. To interpret the results, we divide the time of maximal sprint by the number of meters covered in dynamic apnoea. Whichever athlete has the lowest sum of all eight indices has the best result.

The performance index was designed to integrate two key components of water polo-specific performance within a single metric: sprint swimming speed and dynamic apnoea capacity. Dividing sprint time by the distance covered during dynamic apnoea provides an index in which lower values represent athletes capable of completing the sprint in less time while simultaneously maintaining longer apnoea performance. Alternative scoring methods were considered; however, this ratio was selected because it combines both components into a simple and practically interpretable field-based measure without requiring specialized equipment.

As this is the first application of this index, future studies should investigate alternative scoring approaches and determine whether they improve the sensitivity and validity of the protocol.

Statistical analysis

Descriptive data are presented as means (M), minimum and maximum values (MIN and MAX), and standard deviations (SD) to provide an overview of performance distribution. Before further analyses, data normality was assessed using the Kolmogorov–Smirnov test (K–S). The stability of the newly developed TP test between the two measurement occasions was evaluated through the intraclass correlation coefficient (ICC), while absolute reliability was additionally described by the coefficient of variation (CV). Possible systematic

 © 2026 ARD Asociación Española

changes in performance between trials were investigated using the paired-samples t-test. To assist in practical interpretation, the minimal detectable change (MDC) was calculated, representing the smallest difference that may be considered real and not attributable to measurement error.

To determine the extent to which the new protocol reflects established indicators of repeated sprint performance, criterion validity was analysed by means of Pearson correlation coefficients between TP outcomes and RSA results. Statistical significance was accepted at the level of $p < .05$. All analyses were performed using Statistica 14.0.0.15 (TIBCO Software Inc., USA).

RESULTS

Table 1. Results of descriptive statistics and test for normality.

Variables	M	MIN	MAX	SD	K-S
TP	8.73	6.47	10.86	1.74	$p > .20$
RTP	7.92	5.05	11.42	2.02	$p > .20$
RSA	115.32	109.15	120.09	3.20	$p > .20$

Note. TP = Sum of eight TP TEST indices, RTP = Retest sum of eight TP test indices. RSA = Sum of eight results from the Repeated Sprint Ability test.

Descriptive statistics for the newly developed TP test, its retest (RTP), and the reference RSA test are presented in Table 1. Mean values (M), minimum (MIN) and maximum (MAX) scores, and standard deviations (SD) are reported for each variable. The Kolmogorov–Smirnov test indicated no significant deviations from normality for any variable ($p > .20$).

Table 2. Reliability parameters of the new test.

Variables	M ± SD	ICC	CV	t	MDC
TP	8.73 ± 1.74				
RTP	7.92 ± 2.02	.86	8.6%	2.5*	1.99
RSA	115.32 ± 3.20				

*Note. ICC = intraclass correlation coefficient; CV = coefficient of variation; t = paired-samples t-test statistic; * Statistical significance; MDC = minimal detectable change; TP = new test (first measurement); RTP = new test (second measurement); RSA = Repeated sprint ability test (reference standard test).*

Descriptive statistics (mean ± SD) were calculated for all variables. Test–retest reliability of the RTP test was assessed using the intraclass correlation coefficient (ICC) and coefficient of variation (CV), while systematic differences were examined using a paired-samples t-test. RTP reliability was high (ICC = .86), with a CV of 8.6%. A significant difference between test and retest was observed (t = 2.50), and MDC was 1.99.

Table 3. Validity parameters of the new test.

Variables	RSA	RSA
TP	.488	
RTP		.543

Note. TP = new test (first measurement); RTP = new test (second measurement); RSA = Repeated sprint ability test (reference standard test).

In Table 3, criterion validity was assessed using Pearson correlation coefficients between the newly constructed tests and the RSA test. The TP test showed a moderate positive correlation with RSA (r = .488), while the RTP test showed a slightly stronger moderate positive correlation with RSA (r = .543).

DISCUSSION

This pilot study aimed to evaluate the metric characteristics of a newly constructed repeated sprint–dynamic apnoea (TP) test, with particular emphasis on its reliability and its relationship with a standard measure of anaerobic performance (RSA). Water polo consists mainly of short-distance, high-intensity movements with partial recovery (Tan et al., 2009). This is why the RSA test has been mostly used so far to determine anaerobic performance. Ecological validity is the biggest strength of the TP test. This test incorporates dynamic apnoea, which replicates water polo-specific respiratory constraints. As a result, the test may provide a more sport-specific assessment of athletes' ability to perform repeated high-intensity efforts under conditions that resemble actual match play. Improving ecological validity is an important consideration in sport-specific test design because it recreates the physiological and psychological demands of the match. This gives coaches a tool for assessment where their athletes are under match-condition demands, and we think this is where the importance of the test really lies.

The main findings indicate good relative reliability, acceptable measurement stability, and moderate criterion-related validity in relation to the reference test. The obtained ICC value (.86) indicates high relative reliability, suggesting that participants largely maintained their ranking between repeated measurements. Values above .80 are interpreted as indicative of good consistency (Atkinson & Nevill, 1998; Hopkins, 2000). Because of this, we can say that the TP test is potentially suitable for distinguishing between players of different performance levels, which is particularly relevant in team selection and talent identification contexts. However, to be relevant for talent selection and identification, this test needs to be researched on a bigger and more heterogeneous sample before we can make those claims.

The coefficient of variation (CV = 8.6%) is relatively high but taking into account that this is a high-demanding sport-specific test which includes both maximal effort and breath-hold components, increasing variability in performance. It is expected to have a higher coefficient of variation in complex sport tests (Impellizzeri et al., 2008). It was their first time performing this test, and for researchers as well. Already when performing the test a second time, they knew what they needed to look after, and they adapted to the test. For that reason, a recommendation would be a familiarization session before formal testing to minimize potential learning effects and improve measurement consistency. Future studies should incorporate third testing in order to distinguish true measurement error from performance improvements related to familiarization. Also, some of the athletes might not give the same effort in the test and retest because some of them were sick between testing.

Minimal detectable change (MDC) is the smallest change that can be interpreted as a true performance adaptation beyond measurement error (Weir, 2005). In our case, MDC was 1.99, which is a bit of a higher number, but taking into account the small sample size and adaptation to the second time of performing the test, also known as the familiarization effect (Hopkins, 2000), we can say it is also expected to be higher. For now, this means only relatively large performance changes can be confidently interpreted as true adaptations, which limits the sensitivity of the test for detecting small longitudinal improvements. At this stage, the proposed protocol should primarily be considered a profiling tool for comparing athletes within similar competitive groups rather than an instrument for talent identification or selection decisions. If the test is used for longitudinal monitoring, it requires strict standardization to minimize potential bias. Also, this can be influenced by a small sample of participants. By expanding the sample and trying different age groups, it is reasonable to expect the numbers would be even more stable.

 © 2026 ARD Asociación Española

Water polo's intermittent nature relies on anaerobic energy systems during explosive actions and aerobic metabolism for recovery (Smith, 1998). This is why the anaerobic system plays a crucial role in water polo monitoring and conditioning. Validity for the first measurement was r = .488, and the retest score was r = .543. These results don't show a significant correlation, but are meaningful because they share similar variables, primarily anaerobic capacity and repeated sprint performance. This is also expected because the frame of the test is the same; just a newly constructed test captures an additional component of dynamic apnoea, which changes the demands of the test. Not only are we testing anaerobic swim performance, but we are also testing the respiratory organs and muscles under load. This goes well with the thesis that performance assessment depends on the degree to which testing protocols reflect sport-specific demands because general standardized tests often overlook the actual demands of a certain sport (Reilly et al., 2000; Pyne et al., 2004). Two tests are different and measure similar but not the same things. The moderate correlations observed between TP and RSA should not necessarily be interpreted as evidence of weak validity. Rather, they likely reflect that the two protocols assess overlapping but not identical constructs. While RSA primarily evaluates repeated-sprint performance under unrestricted breathing conditions, the TP protocol additionally incorporates respiratory stress induced by dynamic apnoea.

Therefore, criterion validity against RSA should be interpreted within this context. Future studies should include complementary physiological measures, such as blood lactate concentration, oxygen saturation, recovery kinetics, or competitive performance indicators, to provide a more comprehensive evaluation of construct validity. Hypoxia and hypercapnia increase cardiovascular and metabolic stress during exercise (Lindholm & Lundgren, 2009). Knowing that there is breath-holding happening during a match and that the hypoxic state increases metabolic stress, we wanted to make a field test that captures sprint under hypoxic and hypercapnic states. We think that apnoea is a very important factor of performance that has been ignored so far in other field tests.

Both tests should be used in monitoring players' condition levels. The newly constructed test showed potential suitability to differentiate players among groups. Long-term monitoring might have potential problems if the testing procedure is not strictly standardized. Considering that this is a pilot study, the findings should be interpreted with caution. The relatively small sample size may have affected the stability of the ICC estimates, correlation coefficients, and MDC values. Future studies including larger samples from different clubs and competitive levels are required to further evaluate the robustness and generalizability of the proposed protocol.

Overall, we strongly believe that the TP test introduces a more ecologically valid assessment of water polo specific performance by combining anaerobic and respiratory demands, comparing it to other testing protocols. This leaves space for exploring new test and use it on different participants to see where their use is most useful. The idea goes beyond just water polo to other water sports such as swimming, synchronized swimming, and freediving. All of these sports have dynamic apnoea as a component of the sport, so future testing should consider different water sports athletes. Thinking even further, the subject of dynamic apnoea is underestimated as a topic and should be investigated even in non-water sports. That was also one of the goals of this research: to create a new form of testing and generate ideas of breath-hold in sports analysis. We hope researchers and coaches will notice our idea and will investigate this topic even in other sports fields.

Limitations and future directions

The study that we did has several limitations that we need to mention. The first limitation was the small sample size because we only tested 10 athletes. Such a sample may reduce the stability of reliability and

validity estimates and limit the generalizability of the findings. So a bigger sample is needed before we can make any general conclusions. This is a pilot study, and in the next research, we plan to test more athletes.

The second limitation was that we tested only one category of players who had a chronological age ranging from 14 to 17. For future research, it would be crucial to test different age groups (older and younger) to see how they react to the newly constructed test.

The third limitation is that most of the athletes tested had a 2-day pause to ensure they were fully recovered. Because of the game schedule and some players playing for the older category, some of them had a bigger pause than 2 days between testing.

The most important limitation of the present study is that normative reference values and meaningful performance thresholds could not be established because the protocol was evaluated in a relatively small and homogeneous sample of junior water polo players. Consequently, the proposed test should currently be interpreted primarily as a profiling tool for comparisons within similar competitive groups rather than as an instrument for absolute performance classification. Future studies involving larger samples across different age categories and competitive levels are needed, as well as physiological measures and performance indicators to establish normative values. To eliminate bias from results, it would be important to strictly follow the testing procedure and try to test everyone on the same day. Also, we tested the elite sample because they won the league last season, so trying it out on lower division players would be a good idea.

And the last limitation was that during the test and retest, some of the players that we prolonged testing with were sick during that pause. When they were tested, they were fully recovered, but still, this affects the results.

Although the proposed index was designed to provide a simple and practical integration of sprint performance and dynamic apnoea capacity, future studies should compare alternative scoring models to determine the most appropriate representation of the interaction between anaerobic and respiratory performance.

CONCLUSION

In conclusion, the newly constructed anaerobic test shows satisfactory reliability and validity. The test shares a meaningful yet not significant correlation with the RSA test. This indicates it measures similar anaerobic components, yet the new test has a component of dynamic apnoea, which adds additional stress on respiratory organs and muscles. CV shows that the result may vary by 8.6% without a change in capacity. The test is an emerging assessment tool that currently shows promise for profiling athletes but requires further validation before being used in high-stakes decision-making contexts.

Although results showed higher CV and MDC, we think that by expanding the sample, we would confirm these results with even more stable numbers and eliminate potential bias. To date, very little attention has been given to this topic. In aquatic sports, there is a very limited number of anaerobic tests. By conducting this pilot research, we created a new water polo specific anaerobic swimming test that represents a sport-specific and practically applicable assessment tool that incorporates both anaerobic and respiratory demands of water polo performance, providing an additional perspective beyond traditional testing approaches. This gives coaches in water sports another potential test option in assessing players' conditioning. Future research could directly evaluate predictive validity by examining relationships between test scores and objective

 © 2026 ARD Asociación Española

performance indicators. Because it doesn't require anything but a stopwatch and duct tape (visual markers), we hope it will be used widely.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Toni Propadalo, Ognjen Uljević. Methodology: Toni Propadalo, Ognjen Uljević. Formal analysis: Toni Propadalo. Investigation: Toni Propadalo, Jakov Marasović. Data curation: Toni Propadalo, Jakov Marasović. Writing – original draft: Toni Propadalo. Writing – review & editing: Toni Propadalo, Ognjen Uljević, Jakov Marasović. Supervision: Ognjen Uljević.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability (ChatGPT). No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error in variables relevant to sports medicine. *Sports Medicine, 26*(4), 217-238. https://doi.org/10.2165/00007256-199826040-00002

Botonis, P. G., Toubekis, A. G., & Platanou, T. I. (2018). Evaluation of physical fitness in water polo players according to playing level and positional role. *Sports, 6*(4), 157. https://doi.org/10.3390/sports6040157

Dalamitros, A. A., Orologas, P., Nousiou, S., Semaltianou, E., Zourladani, A., & Manou, V. (2021). The acute effects of different resistance training loads on repeated sprint ability in water polo players. *Human Movement, 22*(4), 78-82. https://doi.org/10.5114/hm.2021.103293

Elia, A., & Lemaître, F. (2025). The application of breath-holding in sports: physiological effects, challenges, and future directions. *European Journal of Applied Physiology, 125*(8), 2049-2065. https://doi.org/10.1007/s00421-025-05752-y

Faiss, R., Raberin, A., Brocherie, F., & Millet, G. P. (2025). Repeated-sprint training in hypoxia: A review with 10 years of perspective. *Journal of Sports Sciences, 43*(19), 2164-2178. https://doi.org/10.1080/02640414.2024.2416821

Ferretti, G. (2001). Extreme human breath-hold diving. *European Journal of Applied Physiology, 84*(4), 254-271. https://doi.org/10.1007/s004210000377

Galy, O., Zoubir, S. B., Hambli, M., Chaouachi, A., Hue, O., & Chamari, K. (2014). Relationships between heart rate and physiological parameters of performance in top-level water polo players. *Biology of sport, 31*(1), 33-38. https://doi.org/10.5604/20831862.1083277

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15. https://doi.org/10.2165/00007256-200030010-00001

Impellizzeri, F. M., Rampinini, E., & Marcora, S. M. (2008). Physiological assessment of aerobic training in soccer. *Journal of Sports Sciences, 23*(6), 583-592. https://doi.org/10.1080/02640410400021278

Lindholm, P., & Lundgren, C. E. (2009). The physiology and pathophysiology of human breath-hold diving. *Journal of Applied Physiology*, *106*(1):284-292. https://doi.org/10.1152/japplphysiol.90991.2008

McMorris, T., Hale, B. J., Barwood, M., Costello, J., & Corbett, J. (2017). Effect of acute hypoxia on cognition: A systematic review and meta-regression analysis. *Neuroscience & Biobehavioral Reviews, 74*, 225-232. https://doi.org/10.1016/j.neubiorev.2017.01.019

Meckel, Y., Bishop, D., Rabinovich, M., Kaufman, L., Nemet, D., & Eliakim, A. (2013). Repeated sprint ability in elite water polo players and swimmers and its relationship to aerobic and anaerobic performance. *Journal of sports science & medicine, 12*(4), 738.

Mujika, I., McFadden, G., Hubbard, M., Royal, K., & Hahn, A. (2006). The water-polo intermittent shuttle test: a match-fitness test for water-polo players. *International Journal of Sports Physiology and Performance, 1*(1), 27-39. https://doi.org/10.1123/ijspp.1.1.27

Platanou, T. (2004). Time-motion analysis of international level water polo players. *Journal of Human Movement Studies, 46*(4), 319-332.

Platanou, T., & Geladas, N. (2006). The influence of game duration and playing position on intensity of exercise during match-play in elite water polo players. *Journal of Sports Sciences, 24*(11), 1173-1181. https://doi.org/10.1080/02640410500457794

Pyne, D. B., Lee, H., & Swanwick, K. M. (2004). Monitoring the lactate threshold in world-ranked swimmers. *Medicine & Science in Sports & Exercise, 33*(2), 291-297. https://doi.org/10.1097/00005768-200102000-00019

Reilly, T., Bangsbo, J., & Franks, A. (2000). Anthropometric and physiological predispositions for elite soccer. *Journal of Sports Sciences, 18*(9), 669-683. https://doi.org/10.1080/02640410050120050

Rodríguez, FA (1999). Cardiorespiratory and metabolic field testing in swimming and water polo: from physiological concepts to practical methods. Biomechanics and medicine in swimming VIII. *Jyväskylä: Gummerus Printing*, 219-226.

Smith, H. K. (1998). Applied physiology of water polo. *Sports medicine, 26*(5), 317-334. https://doi.org/10.2165/00007256-199826050-00003

Tan, F., Polglaze, T., & Dawson, B. (2009). Activity profiles and physical demands of elite women's water polo match play. *Journal of sports sciences, 27*(10), 1095-1104. https://doi.org/10.1080/02640410903207416

Virués-Ortega, J., Buela-Casal, G., Garrido, E., & Alcázar, B. (2004). Neuropsychological functioning associated with high-altitude exposure. *Neuropsychology review, 14*(4), 197-224. https://doi.org/10.1007/s11065-004-8159-4

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. Journal of Strength and Conditioning Research, 19(1), 231-240. https://doi.org/10.1519/00124278-200502000-00038

 © 2026 ARD Asociación Española

Young, W., Farrow, D., Pyne, D., McGregor, W., I Handke, T. (2011). Validity and reliability of agility tests in junior Australian football players. *J Strength Cond Res, 25*(12), 3399-3403. https://doi.org/10.1519/JSC.0b013e318215fa1c

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Ecological dynamics analysis of muscle synergies and self-organization in rhythmic gymnastics

Claudia Costa. *Department of Neuroscience, Biomedicine and Movement Sciences. University of Verona. Verona, Italy. Department of Political and Social Studies. University of Salerno. Salerno, Italy.*

Silvia Coppola . *Department of Human Sciences, Philosophy & Education. University of Salerno. Salerno, Italy.*

Ester Celentano. *Department of Computer Science. University of Salerno. Salerno, Italy.*

Enrico Serra. *Department of Neuroscience, Biomedicine and Movement Sciences. University of Verona. Verona, Italy. Department of Human Sciences, Philosophy & Education. University of Salerno. Salerno, Italy.*

Maria Teresa Benincasa. *Department of Neuroscience, Biomedicine and Movement Sciences. University of Verona. Verona, Italy. Department of Political and Social Studies. University of Salerno. Salerno, Italy.*

Francesco Coiro. *Department of Neuroscience, Biomedicine and Movement Sciences. University of Verona. Verona, Italy. Department of Translation Biomedicine and Neuroscience (DiBraiN). University of Bari. Bari, Italy.*

Rodolfo Vastola. *Department of Political and Social Studies. University of Salerno. Salerno, Italy.*

ABSTRACT

Muscle synergies can be conceptualized, within ecological dynamics, as a self-organizing process. Studying muscle synergies in rhythmic gymnastics (RG) jumps may provide insight into how intermuscular coordination is organized in response to interacting constraints. Ankle weights are frequently used in RG training with the aim of improving jumping performance, although they may influence lower-limb coordination. Evidence on muscle synergies during RG jumps remains limited; therefore, this exploratory study aimed to examine how intermuscular coordination is organized during split leaps performed with and without 0.5 kg ankle weights, while also assessing selected biomechanical outcomes. The sample included six competitive RG gymnasts (16.5 ± 2.7 years). Data were collected using an integrated multifactorial optoelectronic system. In both conditions, two muscle synergy modules were extracted, showing similar muscle contribution patterns, whereas temporal activation profiles showed inter-individual variability. Pearson correlation coefficients indicated strong correlations between conditions for both muscle contributions ($|r| > .90$) and temporal activations ($.70 < |r| < .97$). S2 vertical displacement and flight time showed no clear systematic differences between conditions. These preliminary findings suggest relative preservation of the recorded lower-limb coordination structure under the additional load, which may be compatible with functional robustness in response to the task constraint.

Keywords: performance analysis, split leap, ankle weights, motor control.

Cite this article as:
Costa, C, Coppola, S., Celentano, E., Serra, E., Benicasa, M. T., Coiro, F., & Vastola, R. (2026). Ecological dynamics analysis of muscle synergies and self-organization in rhythmic gymnastics. *Journal of Human Sport and Exercise, 21*(4), 1568-1584. https://doi.org/10.55860/rhx5pt54

Corresponding author. *Department of Human Sciences, Philosophy & Education. University of Salerno. Salerno, Italy.*
E-mail: sicoppola@unisa.it

Submitted for publication June 29, 2026.
Accepted for publication August 31, 2026.
Published September 30, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/rhx5pt54

© 2026 ARD Asociación Española

INTRODUCTION

Rhythmic gymnastics (RG) is defined as a technical-compositional sport (Liviotti & Hökelmann, 2012) and as a sport characterized by high demands on leap performance (Di Cagno et al., 2008). Accordingly, jumps represent one of the key technical components of RG routines and have received increasing attention in research. Previous research has examined several aspects of RG jumps, including take-off mechanics and technical execution (Coppola et al., 2020; Coppola et al., 2024; Loaiza-Navarro & Gamardo-Hernandez, 2018), landing strategies (Błażkiewicz et al., 2019), jumps performed with apparatus (Akkari-Ghazouani et al., 2020; Akkari-Ghazouani et al., 2023; Coppola et al., 2023), and variability between jumps performed with and without apparatus (Coppola et al., 2025). Jumps can be performed free body or by coordinating the handling of the ball, hoop, clubs, ribbon or rope (Yeh et al., 2019). Regarding run-up techniques, jumps can be performed using a chassé step, running (especially in the early stages of learning the movement), or a pre-jump (Costa et al., 2025).

One of the jumps most frequently performed by rhythmic gymnasts is the split leap (Örs & Turşak, 2020). It involves a sagittal split in flight, with the dominant leg moving forward and the non-dominant leg moving backward, to reach an amplitude of 180°. During the flight phase, the shape of the jump must be fixed and well defined with good elevation (Di Cagno et al., 2008). As described in the Fédération Internationale de Gymnastique (FIG, 2024) RG 2025–2028 Code of Points, this jump has a value of 0.30 points.

Jumps are considered highly dynamic motor tasks (Chiriac et al., 2021) that require strength and flexibility (Agopyan, 2021), adequate elevation and amplitude, balance during flight, and considerable inter- and intramuscular coordination (Marcolin et al., 2018). The ability to coordinate several muscles simultaneously in order to perform a motor task effectively can be investigated through muscle synergies, which consist of the coordinated activation of muscle groups over time and are thought to reduce the computational load associated with movement control (Esmaeili & Maleki, 2019; Ranavolo, 2021). Within the broader motor control literature, muscle synergies have also been proposed as a modular mechanism that may simplify the organization of complex motor actions and reduce the computational demands associated with movement control (d'Avella, 2016; Ting & McKay, 2007). This perspective is particularly relevant in complex sport skills, where multiple muscles must be coordinated under changing task demands while preserving the functional organization of movement.

Within the theoretical framework of ecological dynamics, muscle synergies can be interpreted as a form of self-organization, namely, the functional organization of the body's degrees of freedom in relation to a goal (Button et al., 2020; Davids et al., 2008). Self-organization refers to spontaneous processes of adjustment and adaptation among system components in relation to changes in other parts of the system (Renshaw et al., 2019) and to their interaction with constraints (Rosengren et al., 2003). Among the range of possible movement solutions, a functional solution is one that enables the athlete to adapt effectively to interacting constraints. This adaptability is supported by the synergic organization of degrees of freedom that remain coupled and covary (Gray, 2021). Therefore, the abundance of degrees of freedom should be seen as a possibility to flexibly adapt and respond effectively to environmental variations (Newell & James, 2008; Latash et al., 2008). Furthermore, through the interaction with constraints, adaptive, creative and goal-oriented behaviours may emerge in the individual (Davids et al., 2013).

In this context, the choice to use ankle weights in this exploratory study, as a modification of task constraints (Newell, 1986), stems from their frequent use in RG training, where they are commonly adopted with the aim of enhancing jumping performance. However, although ankle weights introduce an additional external load,

they may also influence the organization of intermuscular coordination. Therefore, investigating muscle synergies during jumps in RG may provide preliminary insights into how intermuscular coordination is organized in response to modifications in task constraints. Integrating selected biomechanical outcomes may also help determine whether similarities in neuromuscular organization are accompanied by comparable characteristics of jump execution.

Some studies have examined the effects of ankle weights on motor performance during walking (Kunugi et al., 2024; Paquet et al., 2015) and taekwondo (Tarigan et al., 2022). However, to date, there appears to be no published research that has analysed muscle synergies during RG jumps or examined how they are influenced by the use of ankle weights. Therefore, the aim of this exploratory study was to investigate, through muscle synergy analysis and within an ecological dynamics framework, how intermuscular coordination is organized during split leaps performed with and without 0.5 kg ankle weights, while also examining selected biomechanical outcomes of jump execution.

MATERIALS AND METHODS

Sample

The study sample included six female competitive gymnasts (age: 16.5 ± 2.7 years; height: 164.2 ± 6.6 cm; body mass: 53.7 ± 4.8 kg; BMI: 19.97 ± 2.23 kg/m²).

Two athletes belonged to the Junior 2 category, while the other four were in the Senior category of the Italian Gymnastics Federation (FGI).

The athletes had competed during the year, had mastered the split leap, and used ankle weights during training. For all gymnasts, the right limb was dominant.

The gymnasts trained three times a week for two hours per session and reported no injuries at the time of data collection.

The athletes signed an informed consent form, authorizing their participation in the study. In the case of underage athletes, the form was signed by their parents.

This study was conducted in accordance with the Declaration of Helsinki (World Medical Association [WMA], 2013) and was approved by the Ethical Committee of the Department of Human Sciences, Philosophy & Education at the University of Salerno (protocol number: 0044170).

Instruments

The BTS Bioengineering integrated multifactorial optoelectronic system was used in this study (BTS S.p.A., Italy). Specifically, the system consisted of seven BTS-6000 force platforms, six BTS FREEEMG surface electromyography sensors (sEMG), six BTS Smart-D video cameras, and two BTS-Vixta video support cameras. Marker trajectories were acquired at 70 Hz, sEMG signals at 1000 Hz, and force-platform data at 1120 Hz.

The force platforms were used to identify foot contact events with the ground. In addition, a passive reflective marker was applied to the athletes' bodies at the level of the second sacral vertebra (S2) to identify the event of maximum jump height.

 © 2026 ARD Asociación Española

Procedures

Data collection was carried out at the Laboratory for Innovative Teaching Methodologies and Analysis of Sports Performance at the University of Salerno (Italy). Before data acquisition, a pilot test was conducted in the same laboratory and with the same technologies on participants with characteristics similar to those of the study sample, to verify the feasibility and correct implementation of the protocol. A meeting was organized with the participating athletes and, in the case of underage athletes, with their parents/tutors, to provide all necessary information regarding the study procedures. For the study, each gymnast performed a standardized task-specific neuromuscular activation protocol.

Subsequently, a marker was placed at S2 on each athlete's body. The skin areas where the sEMG sensors were applied were then shaved and cleaned with alcohol. Six sEMG sensors were attached, three on the right lower limb and three on the left, following SENIAM recommendations (Hermens et al., 2000). Sensors were applied to the rectus femoris, biceps femoris, and gastrocnemius lateralis muscles.

Next, five trials of the split leap without ankle weights (Figure 1) and five trials of the same jump with ankle weights (Figure 2) were performed. Participants wore 0.5 kg ankle weights on each ankle, reflecting the load most commonly used in RG training. A two-minute recovery period was provided between the trials with and without weights. All gymnasts performed split leaps with the right leg leading and the left leg trailing, using a chassé step run-up technique.

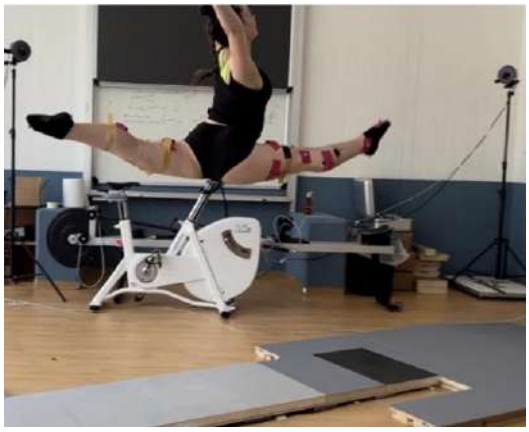


Figure 1. Split leap performed without ankle weights.

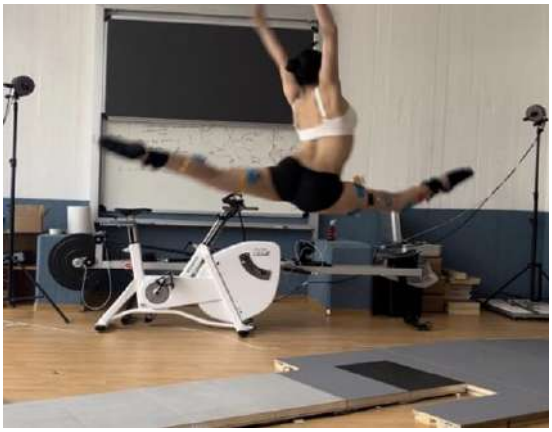


Figure 2. Split leap performed with ankle weights.

Data processing and analysis

SMARTanalyzer (BTS S.p.A., Italy) and MATLAB R2025a (The MathWorks, Inc, Natick, MA, USA) were used for data processing and analysis.

Event identification

Using the SMARTanalyzer software, a calculation protocol was created to identify four events: left foot contact with the force platform before the jump, take-off, maximum jump height, and landing. For muscle synergy analysis, left foot contact was identified from the vertical component of the Ground Reaction Force (GRF) and was defined as the first instant at which the force exceeded the 10 N threshold. Maximum jump height was identified from the vertical trajectory of the S2 marker and was defined as the instant at which the maximum value was recorded after take-off. For the biomechanical analysis, take-off was identified as the subsequent instant at which vertical GRF fell below 10 N, while landing was identified as the first subsequent instant at which vertical GRF exceeded 10 N.

Extraction of muscle synergies using Non-Negative Matrix Factorization (NNMF)

Initially, a high-pass filter at 20 Hz and a low-pass filter at 450 Hz were applied using SMARTanalyzer software. Subsequently, the sEMG signals were rectified, and the linear envelope was obtained by applying a 10 Hz low-pass filter. The sEMG signals were amplitude-normalized to the average of the maximum values recorded across trials. A selection of the sEMG signals was then performed, eliminating *outliers*, i.e. the curves that deviated most from the average signal pattern. This procedure left three trials for analysis. Subsequently, MATLAB R2025a was used to extract muscle synergies and compare the two conditions, namely split leaps with and without ankle weights. The extraction of the synergy modules for both conditions was carried out using *Non-Negative Matrix Factorization* (NNMF) (Lee & Seung, 2000), considering the time window from left foot contact to maximum jump height.

Variance accounted for (VAF) was used to quantify the goodness of fit between the measured and reconstructed data for each number of modules. The optimal number of modules was selected as the minimum number of modules for which the VAF exceeded 90% and the contribution to VAF obtained by adding one more module was less than 5% (Frère & Hug, 2012).

Cluster analysis

After muscle synergy extraction, cluster analysis was performed using MATLAB R2025a software. The obtained synergy modules were assigned to clusters based on the similarity of muscle composition using k-means analysis (Steele et al., 2015). Subsequently, to estimate the optimal number of clusters, silhouette scores were calculated for different *k* values (Hagio et al., 2021). The *k* value that produced the highest mean silhouette score was defined as the optimal number of clusters (Aoyama et al., 2022).

Cosine similarity

Cosine similarity (CS) was used to examine intra-cluster similarity. The cosine similarity for muscle contributions is shown in Figure 4a-b, while the cosine similarity for temporal activations is shown in Figure 5a-b. A cosine similarity threshold of CS > 0.80 was adopted as the criterion for considering two modules similar, in accordance with Oliveira et al. (2014).

Biomechanical analysis

Two biomechanical outcomes were analysed: S2 vertical displacement and flight time. S2 vertical displacement was calculated as the difference between the vertical position of the S2 marker at take-off and its maximum vertical position during the jump. Flight time was calculated as the time interval between take-off and landing. For both outcomes, the mean of three trials was calculated for each gymnast and condition.

 © 2026 ARD Asociación Española

Statistical analysis

To compare the trials with and without weights, the Pearson correlation coefficients were calculated between the clusters of the two conditions for both muscle contributions and temporal activations.

For each biomechanical outcome, the mean of the three selected trials was first calculated for each gymnast and condition, and these individual mean values were subsequently used for the group-level statistical analysis. Normality of the paired differences between conditions was assessed using the Shapiro–Wilk test. As the normality assumption was not violated, S2 vertical displacement and flight time were compared between conditions using paired-samples *t*-tests. Mean paired differences, 95% confidence intervals (CIs), and paired effect sizes (Cohen's d_z) were also calculated. Statistical significance was set at $p < .05$. Statistical analyses were performed using MATLAB R2025a. A schematic overview of the complete analytical workflow used in the study is provided in Figure 3.

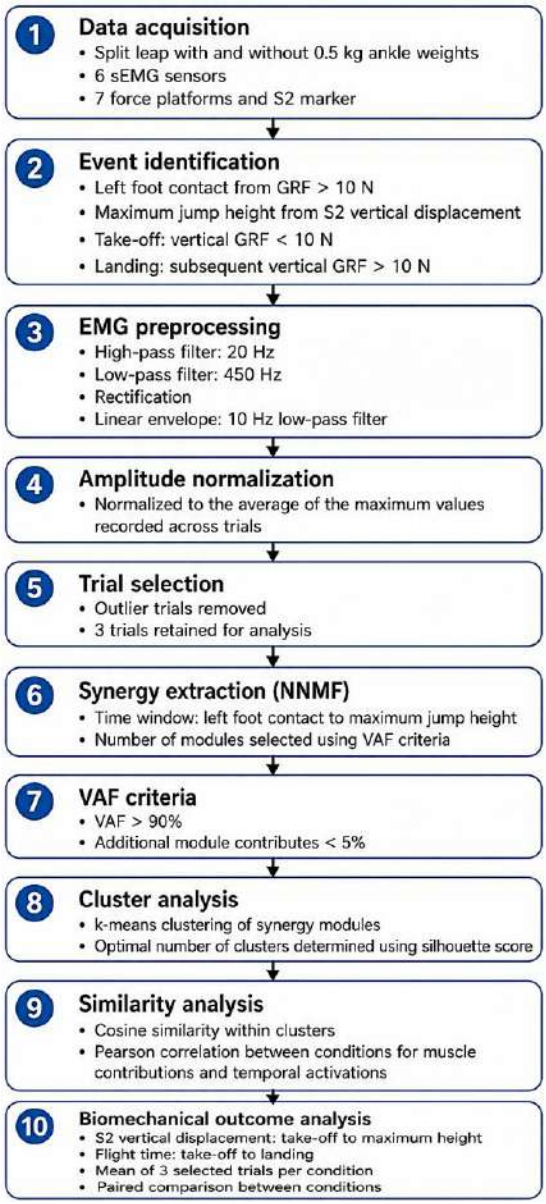


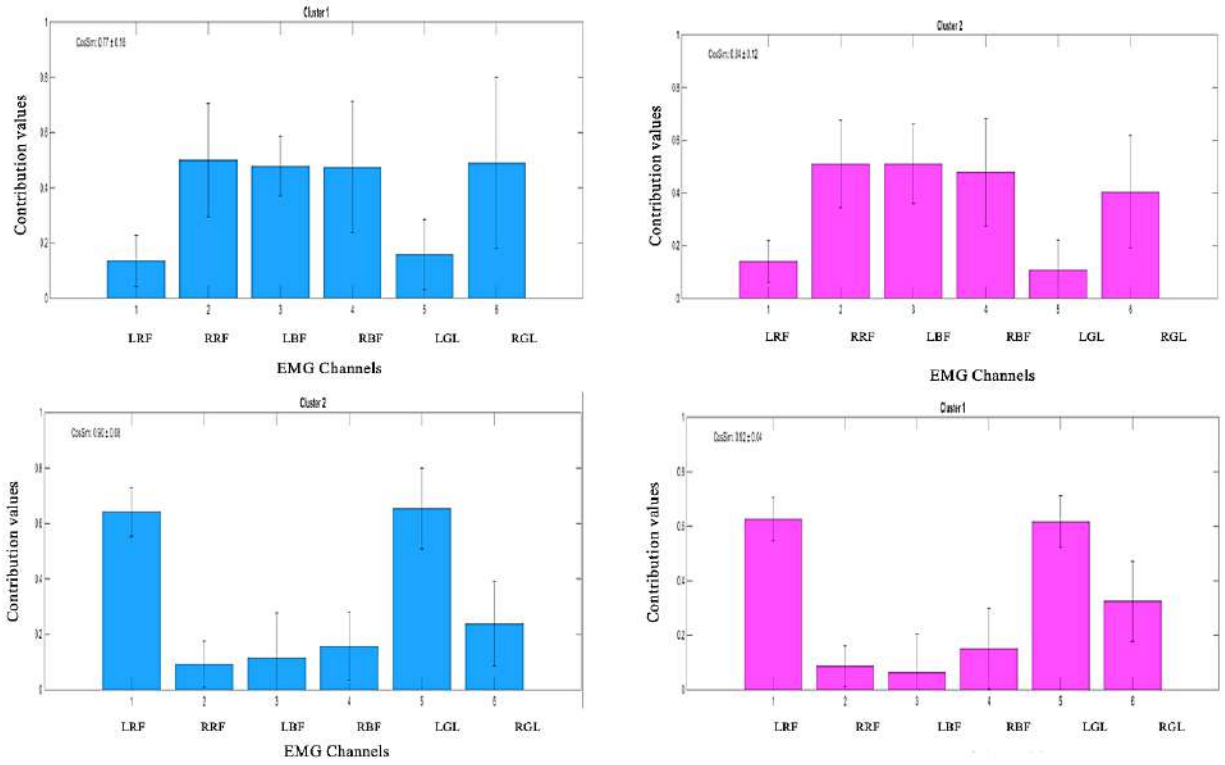
Figure 3. Schematic overview of the complete analytical workflow used in the study.

RESULTS

Muscle synergies

Muscle contributions

Two muscle synergy modules were identified across all gymnasts and in both conditions. The corresponding muscle contribution patterns are presented in Figure 4a-b. The panels were arranged to facilitate visual comparison between the conditions with and without ankle weights.



A. With ankle weights.

B. Without ankle weights.

Note. Muscles: LRF = left rectus femoris; RRF = right rectus femoris; LBF = left biceps femoris; RBF = right biceps femoris; LGL = left gastrocnemius lateralis; RGL = right gastrocnemius lateralis. Panels: (a) blue bars represent jumps performed with 0.5 kg ankle weights: Cluster 1 (top) and Cluster 2 (bottom); (b) pink bars represent jumps performed without ankle weights: Cluster 2 (top) and Cluster 1 (bottom).

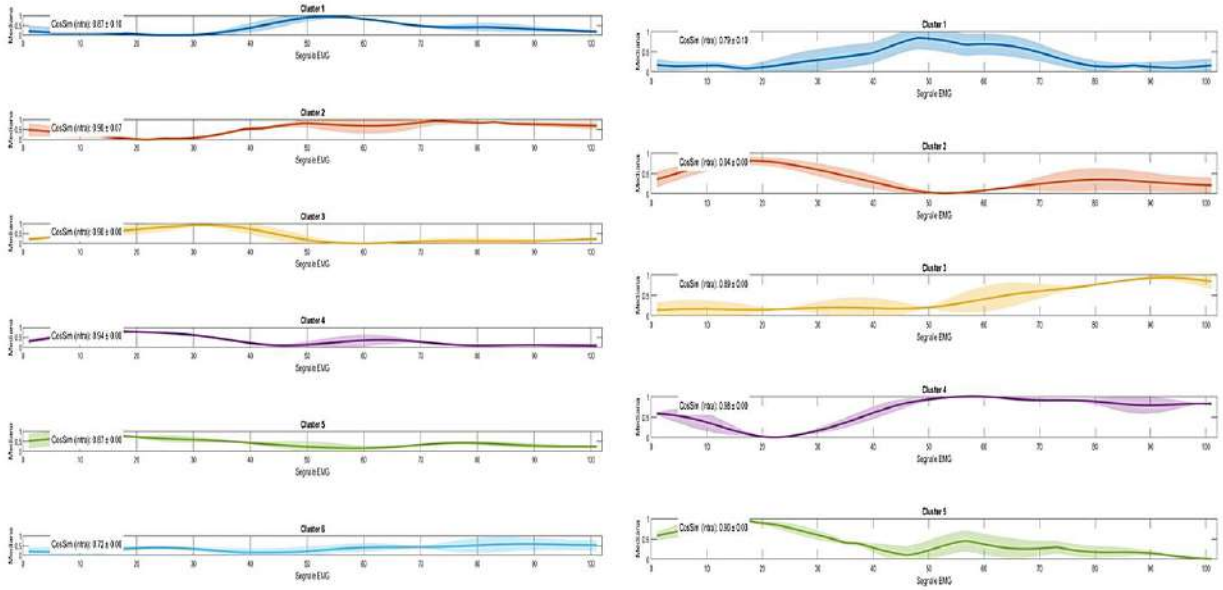
Figure 4. Muscle contributions of the two synergy modules during split leaps with and without ankle weights.

The first synergy pattern, illustrated in the top panels of Figure 4a-b, corresponded to Cluster 1 in the split leap with ankle weights and Cluster 2 in the split leap without ankle weights. This pattern was mainly characterized by the contribution of the right rectus femoris, bilateral biceps femoris, and right gastrocnemius lateralis, with mean CS values of 0.77 ± 0.16 in the condition with ankle weights and 0.84 ± 0.12 in the condition without ankle weights. The second pattern, shown in the bottom panels of Figure 4a-b, corresponded to Cluster 2 in the split leap with ankle weights and Cluster 1 in the split leap without ankle weights. This pattern was characterized by the contribution of the left rectus femoris and left gastrocnemius lateralis, with mean CS values of 0.90 ± 0.08 in the condition with ankle weights and 0.92 ± 0.04 in the condition without ankle weights.

 © 2026 ARD Asociación Española

Temporal activations

For temporal activations, cluster analysis identified six temporal activation clusters in the condition with ankle weights and five temporal activation clusters in the condition without ankle weights (Figure 5a-b).



A. With ankle weights. B. Without ankle weights.

Figure 5. Temporal activations during the split leap with 0.5 kg ankle weights (a) and without ankle weights (b).

CS values for each cluster are reported in the corresponding panels and ranged from 0.72 to 0.94 in the condition with ankle weights, whereas in the condition without ankle weights they ranged from 0.79 to 0.98.

Pearson correlation coefficients between conditions were $|r| > .90$ for muscle contributions, while coefficients for temporal activations ranged from $.70 < |r| < .97$.

Biomechanical outcomes

S2 vertical displacement

Table 1. Individual S2 vertical displacement with and without ankle weights.

Gymnast	With ankle weights (cm)	Without ankle weights (cm)	Δ (with − without ankle weights) (cm)
Athlete 1	12.26 ± 1.39	12.80 ± 0.53	−0.54
Athlete 2	17.17 ± 1.99	18.94 ± 1.91	−1.77
Athlete 3	14.72 ± 1.43	12.82 ± 1.38	+1.90
Athlete 4	13.35 ± 1.45	16.43 ± 2.01	−3.08
Athlete 5	13.42 ± 2.13	16.54 ± 3.45	−3.12
Athlete 6	11.60 ± 3.17	9.54 ± 1.88	+2.06

Note. Values are presented as mean ± SD across the three selected trials for each gymnast. Δ was calculated as the condition with ankle weights minus the condition without ankle weights.

At the group level, mean S2 vertical displacement was 13.75 ± 1.99 cm with ankle weights and 14.51 ± 3.40 cm without ankle weights. The mean paired difference (Δ = with − without ankle weights) was −0.76 cm (95% CI [−3.20, 1.68] cm). The paired differences did not significantly deviate from normality (Shapiro–Wilk W = 0.865, p = .207). The paired-samples t-test yielded p = .461, with d_z = −0.33.

Flight time

Table 2. Individual flight time with and without ankle weights.

Gymnast	With ankle weights (s)	Without ankle weights (s)	Δ (with − without ankle weights) (s)
Athlete 1	0.376 ± 0.007	0.397 ± 0.014	−0.021
Athlete 2	0.446 ± 0.002	0.418 ± 0.045	+0.028
Athlete 3	0.377 ± 0.006	0.367 ± 0.008	+0.010
Athlete 4	0.429 ± 0.013	0.439 ± 0.014	−0.010
Athlete 5	0.412 ± 0.011	0.420 ± 0.015	−0.008
Athlete 6	0.382 ± 0.011	0.371 ± 0.003	+0.011

Note. Values are presented as mean ± SD across the three selected trials for each gymnast. Δ was calculated as the condition with ankle weights minus the condition without ankle weights.

At the group level, mean flight time was 0.404 ± 0.030 s with ankle weights and 0.402 ± 0.029 s without ankle weights. The mean paired difference (Δ = with − without ankle weights) was 0.002 s (95% CI [−0.017, 0.020] s). The paired differences did not significantly deviate from normality (Shapiro–Wilk W = 0.950, p = .742). The paired-samples t-test yielded p = .821, d_z = 0.10.

DISCUSSION

This exploratory study examined the effects of 0.5 kg ankle weights on muscle synergies during the split leap in RG. Evidence on muscle synergies in RG jumps remains limited, particularly regarding the influence of external loading such as ankle weights. Beyond describing similarities in muscle synergies between conditions, the findings were interpreted within an ecological dynamics framework, with particular attention to constraint-induced coordination, inter-individual variability, and functional organization under task constraints.

From the Pearson correlation analysis, very high correlation coefficients ($|r| > .90$) were observed for muscle contributions between jumps performed without ankle weights and those performed with 0.5 kg ankle weights across the entire sample (Yagin et al., 2024). For temporal activations, correlation coefficients ranged from $.70 < |r| < .97$, indicating strong associations between the two conditions (Yagin et al., 2024). These high correlations indicate strong associations between conditions but should not be interpreted as evidence of statistical equivalence.

Collectively, these results suggest that, for the muscles investigated, intermuscular coordination remained similar across conditions despite the addition of 0.5 kg ankle weights. Within this exploratory sample, the recorded lower-limb muscle set appeared to maintain a similar coordination structure across conditions, which may be compatible with functional stability in response to the task constraint and with the maintenance of the technical structure of the skill, as defined by the requirements of the RG 2025-2028 Code of Points. This relative preservation may reflect a degree of functional robustness in the recorded lower-limb coordination.

 © 2026 ARD Asociación Española

According to the constraints-led approach (Newell, 1986), manipulating task constraints, for example by using ankle weights, can be useful for providing a functional level of overload and for challenging performance-related adaptations (Brazil et al., 2020). In this study, the muscle contribution structure remained relatively stable despite the addition of an external load.

The results for muscle contributions show that one synergy pattern (Figure 4a-b) corresponding to Cluster 1 in the split leap performed with ankle weights and Cluster 2 in the split leap without ankle weights, was mainly characterized by higher contributions from the right rectus femoris, bilateral biceps femoris, and right gastrocnemius lateralis. The predominance of right-limb muscles in this pattern may reflect the role of the right leg in producing the forward swing for the jump execution.

A second pattern (Figure 4a-b), corresponding to Cluster 2 in the split leap with ankle weights and Cluster 1 in the split leap without ankle weights, was characterized by the left rectus femoris and the left gastrocnemius lateralis, which may be involved in controlling left-leg contact with the ground.

These results are consistent with the findings of Navacchia et al. (2019) and Alter (2004), who described the main muscles active during jumping as the hamstrings for hip extension, the quadriceps femoris for knee extension, and the gastrocnemius for ankle plantar flexion.

Across the conditions with and without ankle weights, the muscle contribution patterns were largely preserved, whereas the temporal activation profiles differed. Intra-cluster similarity varied across patterns. Most muscle contribution clusters showed mean CS values consistent with or close to the predefined 0.80 similarity threshold (Oliveira et al., 2014). Temporal activation clusters showed greater variability, with some mean CS values falling below the predefined threshold.

Differences observed in temporal activation profiles between gymnasts (Figure 5a-b) may be consistent with the principle of inter-individual variability in muscle coordination (Hug et al., 2010). Within an ecological dynamics framework, in which coordination is understood as emerging through self-organization in relation to interacting constraints (Button et al., 2020; Davids et al., 2008), the observed inter-individual differences may be interpreted as reflecting distinct coordination strategies in response to the task constraints.

From an ecological dynamics perspective, these findings may be interpreted as being compatible with adaptable and constraint-dependent coordination (Button et al., 2020; Davids et al., 2008). The addition of ankle weights modified the task constraints by increasing the external load, while the overall muscle contribution patterns remained largely preserved. This may suggest that coordination was sufficiently stable to accommodate the imposed constraint without requiring a marked reorganization of the recorded lower-limb muscle contributions. At the same time, the variability observed in temporal activation patterns between gymnasts highlights that similar task goals may be achieved through different individual coordination solutions. Such inter-individual variability may be viewed as a functional feature of movement organization rather than merely as noise, reflecting the availability of multiple ways to coordinate the system in relation to the same performance goal (Newell & James, 2008; Latash et al., 2008). Within this theoretical framework, this flexibility is also compatible with the concept of degeneracy, whereby structurally different system configurations may contribute to functionally similar outcomes (Seifert et al., 2016). However, adaptability and degeneracy were not directly measured in the present study and should therefore be considered theoretical interpretations of the observed coordination patterns.

Several studies have analysed muscle synergies in different motor tasks such as walking (Chvatal & Ting, 2013; Escalona et al., 2021; Hagedoorn et al., 2022), running (Coiro et al., 2025; Nishida et al., 2017; Saito et al., 2018), cycling (De Marchis et al., 2013; Esmaeili & Maleki, 2019), jumping (Rodrigues et al., 2017), balance postures (Moiseev & Mikhaylova, 2023), ball throwing (Moiseev & Ivanov, 2024) and ball catching (Moiseev et al., 2026). Across these different motor tasks, muscle synergy research suggests that coordination may retain relatively stable organizational features while also exhibiting task- and individual-specific adjustments. The broadly preserved muscle contribution patterns observed in the present study may be considered consistent with this general perspective. However, direct comparison remains limited because evidence specifically examining muscle synergies during RG jumps is scarce. Nevertheless, findings from other motor tasks may provide a broader context for interpreting how coordination is organized under changing constraints. In this context, rhythmic gymnastics may provide a useful task environment for examining how coordination is maintained or reorganized during technically constrained actions that require precise spatial and temporal organization. Given the exploratory nature and small sample of the present study, these findings should be considered preliminary evidence that may inform future comparative research across complex sport skills.

The biomechanical outcomes provide additional context for these findings. S2 vertical displacement (shown in Table 1) did not show a clear systematic difference between conditions at the group level. Although four of the six gymnasts showed lower values with ankle weights, the 95% CI for the paired difference included zero, indicating that the observed data were compatible with both a reduction and an increase in S2 vertical displacement. Flight time (shown in Table 2) was also very similar between conditions at the group level, with three gymnasts showing longer flight times with ankle weights and three showing shorter flight times. Overall, these findings suggest that the preserved lower-limb synergy structure occurred alongside relatively similar S2 vertical displacement and flight time within the present exploratory sample. However, the absence of statistically significant differences, together with the small effect sizes (d_z = −0.33 for S2 vertical displacement; d_z = 0.10 for flight time) (McGuigan, 2017), should not be interpreted as evidence of biomechanical equivalence between conditions.

From a practical perspective, the present findings suggest that 0.5 kg ankle weights may be used as an additional external load during split-leap practice while preserving both the lower-limb coordination structure and the selected biomechanical characteristics of the jump observed in the unloaded condition. Coaches may therefore consider 0.5 kg ankle weights as a task constraint that may be incorporated into split-leap practice, while taking into account the individual responses observed across gymnasts.

Limitations

The primary limitation of this exploratory study is the small sample size (n = 6), which limits the generalizability of the findings and the extent to which the extracted synergy patterns can be considered stable and reproducible across rhythmic gymnasts. The inter-individual variability observed in the present sample should also be considered when interpreting these findings.

Data collection was carried out in a human movement analysis laboratory, which differs from the typical RG training and competition environment. In addition, the high execution speed of the split leap required the application of adhesive tape to keep the sEMG sensors fixed on the athletes' bodies. A further limitation concerns the restricted EMG muscle set, which included only six lower-limb muscles. Therefore, the extracted synergies represent a partial model of the neuromuscular coordination involved in the split leap and do not capture the contribution of other muscles involved in hip stabilization, trunk control, or upper-body organization.

 © 2026 ARD Asociación Española

CONCLUSIONS

The findings of this exploratory study revealed strong to very strong correlations for both muscle contributions ($|r| > .90$) and temporal activations ($.70 < |r| < .97$) between jumps performed with and without 0.5 kg ankle weights. These preliminary findings suggest that, within the present sample, the recorded lower-limb muscle synergy structure was preserved when split leaps were performed with 0.5 kg ankle weights. Rather than indicating an absence of change in the recorded neuromuscular patterns, this relative preservation may be compatible with a degree of functional stability or robustness of coordination in response to the imposed task constraint. In addition, S2 vertical displacement and flight time did not show clear systematic differences between conditions at the group level, suggesting relatively similar values for these selected biomechanical characteristics of the jump. Taken together, the neuromuscular and biomechanical findings may reflect a degree of functional robustness in response to the modest external task constraint imposed by 0.5 kg ankle weights.

In conclusion, this exploratory study provides preliminary evidence on the organization of lower-limb muscle synergies during split leap execution under an external loading constraint. Future research should include larger and more diverse samples across different competitive levels to determine whether the observed coordination patterns are stable and reproducible across rhythmic gymnasts. Further studies should also extend the analysis to other types of jumps, include a broader set of lower-limb, proximal, trunk, and potentially upper-body muscles, and examine whether training with ankle weights transfers to split-leap execution in competition contexts.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Claudia Costa, Silvia Coppola, Rodolfo Vastola. Methodology: Claudia Costa, Silvia Coppola, Maria Teresa Benincasa, Enrico Serra. Formal analysis: Claudia Costa, Ester Celentano, Maria Teresa Benincasa, Francesco Coiro. Investigation: Claudia Costa, Silvia Coppola, Ester Celentano. Data curation: Claudia Costa, Francesco Coiro, Enrico Serra. Writing – original draft: Claudia Costa, Silvia Coppola. Writing – review & editing: Claudia Costa, Silvia Coppola, Ester Celentano, Enrico Serra, Maria Teresa Benincasa, Francesco Coiro, Rodolfo Vastola. Supervision: Rodolfo Vastola.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

ETHICAL CONSIDERATIONS

These trials were conducted in accordance with the ethical principles of the Declaration of Helsinki (WMA, 2013). The study was approved by the Ethical Committee of the Department of Human Sciences, Philosophy & Education at the University of Salerno (protocol number: 0044170).

CONSENT TO PARTICIPATE

The parents of the underage athletes signed an informed consent form, authorizing their participation in the study. The adult athletes signed the consent form autonomously.

DATA AVAILABILITY STATEMENT

Data available on request.

REFERENCES

Agopyan, A. (2021). An analysis of movements with or without back bend of the trunk or large hip extension in 1st Juniors' Rhythmic Gymnastics World Championship-2019: Is there injury risk for gymnasts? *International Journal of Performance Analysis in Sport, 21*(1), 108–125. https://doi.org/10.1080/24748668.2020.1850038

Akkari-Ghazouani, H., Mkaouer, B., Amara, S., & Chtara, M. (2020). Kinetic and kinematic analysis of three different execution modes of stag leap with and without throw-catch ball in rhythmic gymnastics. *Science of Gymnastics Journal, 12*(3), 255–264.

Akkari-Ghazouani, H., Mkaouer, B., Amara, S., Jemni, M., & Chtara, M. (2023). Effect of glissade-step on kinetic and kinematic variables of stag ring leaps with and without throw-catch of the ball in rhythmic gymnastics. *Sports Biomechanics, 22*(2), 222–234. https://doi.org/10.1080/14763141.2022.2087535

Alter, M. J. (2004). *Science of flexibility*. Human Kinetics.

Aoyama, T., Ae, K., & Kohno, Y. (2022). Interindividual differences in upper limb muscle synergies during baseball throwing motion in male college baseball players. *Journal of Biomechanics, 145*, 111384. https://doi.org/10.1016/j.jbiomech.2022.111384

Błażkiewicz, M., Kępczyński, A., & Wit, A. (2019). Comparative analysis of kinetics parameters during different landing after split front leaps. *Polish Journal of Sport and Tourism, 26*(2), 3–6. https://doi.org/10.2478/pjst-2019-0007

Brazil, A., Exell, T., Wilson, C., & Irwin, G. (2020). A biomechanical approach to evaluate overload and specificity characteristics within physical preparation exercises. *Journal of Sports Sciences, 38*(10), 1140–1149. https://doi.org/10.1080/02640414.2020.1743065

Button, C., Seifert, L., Chow, J. Y., Araujo, D., & Davids, K. (2020). *Dynamics of skill acquisition: An ecological dynamics approach*. Human Kinetics. https://doi.org/10.5040/9781718214125

 © 2026 ARD Asociación Española

Chiriac, Ș., Teodorescu, S., Bota, A., & Mezei, M. (2021). The duration of technical elements in rhythmic gymnastics jumps: A longitudinal and correlational study. *Discobolul—Physical Education, Sport & Kinetotherapy Journal, 60*(3). https://doi.org/10.35189/dpeskj.2021.60.3.6

Chvatal, S. A., & Ting, L. H. (2013). Common muscle synergies for balance and walking. *Frontiers in Computational Neuroscience, 7*, 48. https://doi.org/10.3389/fncom.2013.00048

Coiro, F., Albano, D., Coppola, S., Serra, E., Benincasa, M. T., Costa, C., & Vastola, R. (2025). Differences in self-organizing patterns between acceleration and maximum velocity phases in sprinting: A pilot study based on muscle synergy analysis. *Journal of Physical Education & Sport, 25*(1). https://doi.org/10.7752/jpes.2025.01022

Coppola, S., Albano, D., Sivoccia, I., & Vastola, R. (2020). Biomechanical analysis of a rhythmic gymnastics jump performed using two run-up techniques. *Journal of Physical Education and Sport, 20*(1), 37–42. https://doi.org/10.7752/jpes.2020.01005

Coppola, S., Costa, C., & Vastola, R. (2023). Gold standard motion analysis system for evaluating jumping performance in rhythmic gymnastics. *Journal of Human Sport and Exercise, 18*(3), 596–611. https://doi.org/10.14198/jhse.2023.183.08

Coppola, S., Costa, C., & Vastola, R. (2024). Comparative study of stag leap performance in rhythmic gymnastics: Motion analysis of two different take-off techniques. *Journal of Physical Education & Sport, 24*(5), 1299–1306. https://doi.org/10.7752/jpes.2024.05148

Coppola, S., Costa, C., Albano, D., & Vastola, R. (2025). Evaluating variability in rhythmic gymnastics: Analysis of split leap using the gold standard motion analysis system. *Journal of Human Sport and Exercise, 20*(1), 1–11. https://doi.org/10.55860/dha18m02

Costa, C., Coppola, S., & Vastola, R. (2025). Ecological-dynamic approach in rhythmic gymnastics: Variation and variability for performance improvement. *Journal of Human Sport and Exercise, 20*(3), 905–917. https://doi.org/10.55860/241eef24

d'Avella, A. (2016). Modularity for motor control and motor learning. *Advances in Experimental Medicine and Biology, 957*, 3–19. https://doi.org/10.1007/978-3-319-47313-0_1

Davids, K., Araújo, D., Vilar, L., Renshaw, I., & Pinder, R. (2013). An ecological dynamics approach to skill acquisition: Implications for development of talent in sport. *Talent Development and Excellence, 5*(1), 21–34.

Davids, K., Button, C., & Bennett, S. (2008). *Dynamics of skill acquisition: A constraints-led approach*. Human Kinetics.

De Marchis, C., Schmid, M., Bibbo, D., Bernabucci, I., & Conforto, S. (2013). Inter-individual variability of forces and modular muscle coordination in cycling: A study on untrained subjects. *Human Movement Science, 32*(6), 1480–1494. https://doi.org/10.1016/j.humov.2013.07.018

Di Cagno, A., Baldari, C., Battaglia, C., Brasili, P., Merni, F., Piazza, M., & Guidetti, L. (2008). Leaping ability and body composition in rhythmic gymnasts for talent identification. *The Journal of Sports Medicine and Physical Fitness, 48*(3), 341–346.

Escalona, M. J., Bourbonnais, D., Goyette, M., Le Flem, D., Duclos, C., & Gagnon, D. H. (2021). Effects of varying overground walking speeds on lower-extremity muscle synergies in healthy individuals. *Motor Control, 25*(2), 234–251. https://doi.org/10.1123/mc.2020-0008

Esmaeili, J., & Maleki, A. (2019). Comparison of muscle synergies extracted from both legs during cycling at different mechanical conditions. *Australasian Physical & Engineering Sciences in Medicine, 42*, 827–838. https://doi.org/10.1007/s13246-019-00767-0

Fédération Internationale de Gymnastique. (2024). *Code of points: Rhythmic gymnastics 2025–2028*.

Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. *Frontiers in Computational Neuroscience, 6*, 99. https://doi.org/10.3389/fncom.2012.00099

Gray, R. (2021). *How we learn to move: A revolution in the way we coach and practice sports skills*. Perception Action Consulting & Education.

Hagedoorn, L., Zadravec, M., Olenšek, A., van Asseldonk, E., & Matjačić, Z. (2022). The existence of shared muscle synergies underlying perturbed and unperturbed gait depends on walking speed. *Applied Sciences, 12*(4), 2135. https://doi.org/10.3390/app12042135

Hagio, S., Nakazato, M., & Kouzaki, M. (2021). Modulation of spatial and temporal modules in lower limb muscle activations during walking with simulated reduced gravity. *Scientific Reports, 11*(1), 14749. https://doi.org/10.1038/s41598-021-94201-9

Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Block, J., Rau, G., Disselhorst, C., & Hagg, G. (2000). *SENIAM: European Recommendations for Surface Electromyography*. C.L.U.T. Editions-Torino.

Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *Journal of Applied Physiology, 108*(6), 1727–1736. https://doi.org/10.1152/japplphysiol.01305.2009

Kunugi, S., Akatsu, H., & Watanabe, K. (2024). Effect of ankle weight loading and walking speed on metabolic and neuromuscular responses and lower limb kinematics during treadmill walking. *Sport Sciences for Health, 20*(1), 157–164. https://doi.org/10.1007/s11332-023-01084-6

Latash, M. L., Gorniak, S., & Zatsiorsky, V. M. (2008). Hierarchies of synergies in human movements. *Kinesiology, 40*(1), 29–38.

Lee, D., & Seung, H. S. (2000). Algorithms for non-negative matrix factorization. *Advances in Neural Information Processing Systems, 13*.

Liviotti, G., & Hökelmann, A. (2012). Quantitative choreography analysis of the group competition medallists at the Rhythmic Gymnastics World Championship 2011. *International Journal of Performance Analysis in Sport, 12*(2), 246–257. https://doi.org/10.1080/24748668.2012.11868597

Loaiza-Navarro, M., & Gamardo-Hernández, P. (2018). Factores biomecánicos que influyen en la ejecución del salto jeté en gimnasia rítmica. *Actividad física y ciencias/physical activity and science, 9*(1).

Marcolin, G., Rizzato, A., Zuanon, J., Bosco, G., & Paoli, A. (2018). Expertise level influences postural balance control in young gymnasts. *The Journal of Sports Medicine and Physical Fitness, 59*(4), 593–599. https://doi.org/10.23736/S0022-4707.18.08014-3

McGuigan, M. (2017). *Monitoring training and performance in athletes*. Human Kinetics. https://doi.org/10.5040/9781492595618

Moiseev, S. A., & Ivanov, S. M. (2024). Spatial-temporal structure features of muscle synergies during profiling elements implementation in rhythmic gymnastics. *Journal of Evolutionary Biochemistry and Physiology, 60*(3), 1050–1063. https://doi.org/10.1134/S0022093024030165

Moiseev, S. A., & Mikhaylova, E. A. (2023). Motor synergies in the control system of complex sports balance postures. *Journal of Evolutionary Biochemistry and Physiology, 59*(3), 841–854. https://doi.org/10.1134/S0022093023030171

Moiseev, S., Gorodnichev, R., & Gerasimenko, Y. (2026). Modular organization of intermuscular and interjoint interaction during ball catching. *Experimental Brain Research, 244*(2), 27. https://doi.org/10.1007/s00221-025-07228-z

Navacchia, A., Ueno, R., Ford, K. R., Di Cesare, C. A., Myer, G. D., & Hewett, T. E. (2019). EMG-informed musculoskeletal modeling to estimate realistic knee anterior shear force during drop vertical jump in female athletes. *Annals of Biomedical Engineering, 47*, 2416–2430. https://doi.org/10.1007/s10439-019-02318-w

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341–360). Martinus Nijhoff. https://doi.org/10.1007/978-94-009-4460-2_19

 © 2026 ARD Asociación Española

Newell, K. M., & James, E. G. (2008). The amount and structure of human movement variability. In *Routledge handbook of biomechanics and human movement science* (pp. 93–104). Routledge.

Nishida, K., Hagio, S., Kibushi, B., Moritani, T., & Kouzaki, M. (2017). Comparison of muscle synergies for running between different foot strike patterns. *PLOS ONE, 12*(2), e0171535. https://doi.org/10.1371/journal.pone.0171535

Oliveira, A. S., Gizzi, L., Farina, D., & Kersting, U. G. (2014). Motor modules of human locomotion: Influence of EMG averaging, concatenation, and number of step cycles. *Frontiers in Human Neuroscience, 8*, 335. https://doi.org/10.3389/fnhum.2014.00335

Örs, B. S., & Turşak, C. (2020). The relationship between passive lower limb flexibility and kinematic determinants of split leap performance in rhythmic gymnastics. *Spor Bilimleri Araştırmaları Dergisi, 5*(1), 76–82. https://doi.org/10.25307/jssr.718164

Paquet, N., Taillon-Hobson, A., & Lajoie, Y. (2015). Effect of ankle weight on blind navigation. *Perceptual and Motor Skills, 120*(2), 502–518. https://doi.org/10.2466/25.PMS.120v10x0

Ranavolo, A. (2021). Principi di elettromiografia di superficie*:* Dal potenziale d'azione alle applicazioni nei diversi settori della medicina e dell'ingegneria. Gaia srl.

Renshaw, I., Davids, K., Newcombe, D., & Roberts, W. (2019). *The constraints-led approach: Principles for sport coaching and practice design*. Routledge. https://doi.org/10.4324/9781315102351

Rodrigues, C., Correia, M., Abrantes, J. M., Nadal, J., & Rodrigues, M. A. B. (2017, July). Consistency of surface electromyography assessment at lower limb selected muscles during vertical countermovement. In *2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 402–405). IEEE. https://doi.org/10.1109/EMBC.2017.8036847

Rosengren, K. S., Savelsbergh, G. J., & van der Kamp, J. (2003). Development and learning: A TASC-based perspective of the acquisition of perceptual-motor behaviors. *Infant Behavior and Development, 26*(4), 473–494. https://doi.org/10.1016/j.infbeh.2003.08.001

Saito, A., Tomita, A., Ando, R., Watanabe, K., & Akima, H. (2018). Muscle synergies are consistent across level and uphill treadmill running. *Scientific Reports, 8*(1), 5979. https://doi.org/10.1038/s41598-018-24332-z

Seifert, L., Komar, J., Araújo, D., & Davids, K. (2016). Neurobiological degeneracy: A key property for functional adaptations of perception and action to constraints. *Neuroscience & Biobehavioral Reviews, 69*, 159–165. https://doi.org/10.1016/j.neubiorev.2016.08.006

Steele, K. M., Rozumalski, A., & Schwartz, M. H. (2015). Muscle synergies and complexity of neuromuscular control during gait in cerebral palsy. *Developmental Medicine & Child Neurology, 57*(12), 1176–1182. https://doi.org/10.1111/dmcn.12826

Tarigan, H., Kasyifa, K., Wicaksono, L., & Cahyadi, A. (2022). The Effect of "Ankle Weight" and "Resistance Band" Training on Increasing Kick Speed of Nare Chagi Athletes Club Taekwondo Harapan Jaya Lampung. *International Journal of Social Research Methodology, 5*(7), 3089-3093. https://doi.org/10.47191/ijsshr/v5-i7-43

Ting, L. H., & McKay, J. L. (2007). Neuromechanics of muscle synergies for posture and movement. *Current Opinion in Neurobiology, 17*(6), 622–628. https://doi.org/10.1016/j.conb.2008.01.002

World Medical Association. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *JAMA, 310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Yagin, F. H., Pinar, A., & de Sousa Fernandes, M. S. (2024). Statistical effect sizes in sports science. *Journal of Exercise Science & Physical Activity Reviews, 2*(1), 164–171. https://doi.org/10.5281/zenodo.12601138

Yeh, T. T., Chang, H. Y., Ju, Y. Y., & Chen, H. Y. (2019). The use of a dual-task paradigm to identify superior sensory organisation ability in rhythmic gymnasts. *Journal of Sports Sciences, 37*(7), 772–778. https://doi.org/10.1080/02640414.2018.1526759

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

ORIGINAL ARTICLE

Inclusion rates of motor abilities in artistic gymnastics apparatus: A content analysis of FIG Technical Manuals

Milaim Berisha. *Department of Sports and Movement Science. University for Business and Technology. Pristina, Kosovo.*
Pablo Prieto Gonzalez . *Sport Sciences and Diagnostics Research Group. College of Sciences and Humanities. Prince Sultan University. Riyadh, Saudi Arabia.*

ABSTRACT

As the inclusion rate of motor abilities in artistic gymnastics apparatus is crucial for the determination of the training program and the learning process of each ability in this branch, the study aims to analyse and determine the representation frequency of motor abilities in each apparatus of artistic gymnastics based on the updated content of techniques given by FIG. This research employs a descriptive quantitative approach to investigate the current state of motor abilities in 239 techniques outlined in the FIG Technical Manual across both genders. Each technique was analysed to identify and highlight specific motor abilities, including coordination, strength, speed, mobility, flexibility, balance, endurance, and agility. The findings are presented using descriptive and frequency statistics, organized into charts for clarity. When the results were examined, it appears that, although there are similarities in motor skills across artistic gymnastics disciplines, each discipline has its own specific requirements. The requirements also vary depending on the difficulty level of the movements. Therefore, as the discipline evolves, the apparatus requirements need to be constantly updated. The study concludes that as the difficulty of techniques changes and new skills are introduced into the Code of Points, along with advancements in gymnastics-related technology, the representation frequency of motor abilities may shift, requiring updates to training programs.

Keywords: performance analysis; motor skills; artistic gymnastics apparatus; representation frequency of motor abilities; training programs; physical conditioning.

Cite this article as:
Berisha, M., & Prieto Gonzalez, P. (2026). Inclusion rates of motor abilities in artistic gymnastics apparatus: A content analysis of FIG Technical Manuals. *Journal of Human Sport and Exercise, 21*(4), 1585-1600. https://doi.org/10.55860/5h0dj159

Corresponding author. *Sport Sciences and Diagnostics Research Group, College of Sciences and Humanities, Prince Sultan University, P.O. Box No. 66833, Rafha Street, Riyadh 11586, Saudi Arabia.*
E-mail: pprieto@psu.edu.sa
Submitted for publication July 12, 2026.
Accepted for publication September 07, 2026.
Published September 30, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/5h0dj159

INTRODUCTION

Artistic gymnastics is a sport that encompasses many disciplines and therefore places high demands on motor skills. The wide variety of disciplines further complicates the motor skill requirements. In addition, because the techniques used depend on multiple motor skills, involve varying difficulty levels, and are applied along different axes of the body, the sport's complexity increases further. As a result, it is challenging to determine which motor skills are required for each apparatus and to what extent. However, to achieve success, it is necessary to determine the dominant motor skills for each apparatus. Several authors have raised concerns regarding strength and motor skill requirements in artistic gymnastics (Gasparetto et al., 2022).

Although books and research studies indirectly assess motor skill representation frequency, these studies may not be fully up to date for several reasons. In the past, the difficulty of techniques in artistic gymnastics was lower than it is today, and the motor skill representation frequency, determined by the sport's earlier structure, may not accurately reflect the demands of modern gymnastics. Fifty or sixty years ago, gymnastics was characterised primarily by positions that required flexibility. Nowadays, due to advancements in technology and medical sciences, the difficulty of movement has increased significantly, with a greater emphasis on the mechanical structure of techniques rather than flexibility (Fédération Internationale de Gymnastique, 2017a, 2017b). For example, at the 2019 Artistic Gymnastics World Championship in Stuttgart, several new techniques were added to the Code of Points. These techniques, such as The Petz (Uneven Bars), The Biles (Uneven Bars), The Biles (Balance Beam), The Sanne Wevers 2 (Balance Beam), The Biles 2 (Floor), The Volleman 2 (Floor), The Lieke Wevers (Floor), The Volleman-Lieke Wevers (Floor), The Brooklyn Moors (Floor), and The Laney Madsen (Floor), are not defined solely by flexibility. They also require high levels of mobility, coordination, strength, and other motor abilities. Consequently, the inclusion of motor abilities in movement execution is more complex than treating each ability in isolation. During the execution of gymnastics techniques, motor abilities interact, giving rise to complex capabilities such as coordination and mobility.

Based on this, it appears that the representation frequency of motor skills reported in the literature does not reflect the difficulty levels of modern artistic gymnastics techniques. Therefore, prioritising motor skills that do not represent the sport's current demands may lead to errors in applied training programs. Since all studies and training programs are developed based on the sport's requirements and the representation frequency of motor skills, it is essential to update the representation frequency ratios of motor skills for each apparatus, taking into account the evolving difficulty levels and demands of artistic gymnastics techniques.

The emergence of revolutionary techniques such as 'The Biles' (on Vault, Balance Beam, and Floor) or 'The Petz' (on Uneven Bars) demonstrates that modern gymnastics is no longer defined solely by flexibility, but rather by a complex interaction of mobility, coordination, and explosive strength. However, despite this technical advancement, the current scientific literature lacks a precise quantification of how these innovations have reconfigured motor demands across each apparatus.

In this context, it is hypothesised that the technical evolution of the FIG Code of Points has shifted traditional motor representation frequency, positioning coordination and strength as the most critical transversal abilities in current performance, surpassing the passive flexibility parameters prevalent in previous decades.

Consequently, the objective of this research is to systematically determine and analyse the inclusion rates of motor abilities across different artistic gymnastics apparatus by examining 239 techniques from the FIG

 © 2026 ARD Asociación Española

Technical Manual. By developing percentage representation frequency indicators, this study seeks to provide an updated empirical basis for optimising the design of training programs in the contemporary sporting cycle.

METHODS

Study model

This research is a descriptive study using quantitative content analysis to systematically evaluate the current technical requirements and motor demands in artistic gymnastics. This study involves the analysis of publicly available technical manuals and did not involve human participants or animals; therefore, institutional ethical approval was not required.

Analysed content

The analysed Technical Manuals and Code of Points have been updated for the years 2022-2024 and include all evaluation procedures in artistic gymnastics, the mechanical understanding of each technique, prerequisite elements, related skills, physical qualities, physical preparation, teaching methodology, and more.

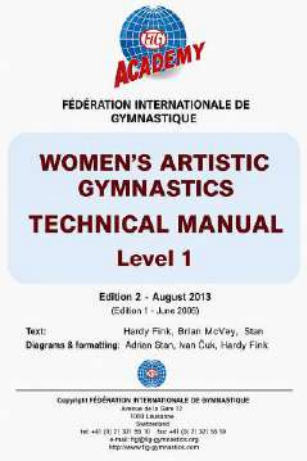


Figure 1. Women's artistic gymnastics technical manual analysed (Level 1).

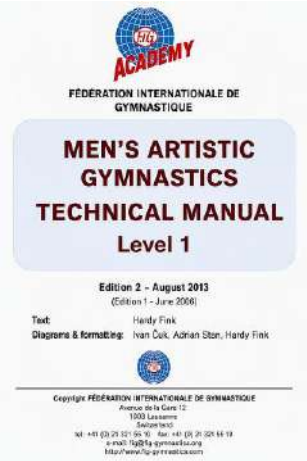


Figure 2. Men's artistic gymnastics technical manual analysed (Level 1).

Figure 3. Analysed 2022-2024 Code of Points (Women's Artistic Gymnastics).

Figure 4. Analysed 2022-2024 Code of Points (Men's Artistic Gymnastics).

This comprehensive information enabled the classification of each motor skill and the determination of the inclusion ratio for each motor quality.

Method of determining dominant motor abilities

The artistic gymnastics techniques presented in the technical manuals mentioned above require a wide range of motor abilities for proper performance. These manuals specify the physical qualities needed to execute each technique. Based on this, we identified the required motor abilities for each technique and apparatus in order to determine the representation frequency ratio of motor abilities in artistic gymnastics.

To examine the representation frequency of specific motor abilities for each apparatus, an extensive analysis was conducted using 239 techniques (Floor: MAG 30, WAG 45; Vault: MAG 17, WAG 17; Pommel Horse: MAG 5; Rings: MAG 27; Parallel Bars: MAG 17; Horizontal Bar: MAG 28; Asymmetric Bars: WAG 22; Beam: WAG 31) described in the *Women's Artistic Gymnastics Technical Manual (Level 1)* and the *Men's Artistic Gymnastics Technical Manual (Level 1)*. These manuals provide a detailed list of techniques and clearly indicate the motor abilities required to execute them. Motor abilities are categorised as physical qualities such as strength, coordination, flexibility, balance, and endurance. This classification, illustrated in Example 1, provides a clear basis for understanding the physical preparation required for each technique.

 © 2026 ARD Asociación Española

The analysis involved extracting and summarising data for each technique to identify how frequently specific motor abilities were required. In particular, the techniques were evaluated according to their demands for strength, coordination, flexibility, and other relevant motor abilities. This quantitative approach enabled the determination of the extent to which each motor ability is represented across different techniques.

As a result, percentages were calculated to show the prevalence of each motor ability within the analysed techniques. These findings were used to define the dominant motor abilities for each apparatus. The results provide a strong basis for developing training programs that reflect the technical demands of artistic gymnastics and help ensure alignment with the most important motor ability requirements.

This detailed understanding of the demands of motor ability can help coaches and athletes design more targeted and scientifically supported training strategies, which may contribute to improved performance in artistic gymnastics. To achieve a more complete understanding of these demands, a detailed analysis of the technical manuals is essential.

Lastly, the motor ability classifications were derived directly from the FIG Academy Technical Manuals, where the required physical qualities for each technique had already been established by FIG expert working groups. Therefore, motor abilities were not interpreted by the researchers; coding involved transferring these stated abilities into a structured table and calculating their frequency of occurrence across the 239 techniques analysed. The extraction was completed by the first author and then checked entry by entry by a second author against the source manuals, with any differences corrected by referring back to the original documents. Since the ability categories were already defined by the FIG source rather than created by the researchers, the values reported here can still be directly checked against the published manuals.

Table 1. Example of motor abilities representation frequency: Swing to handstand technique.

Physical qualities
Strength
Speed
Endurance
Mobility
Coordination

Note. Included motor abilities are highlighted in orange.

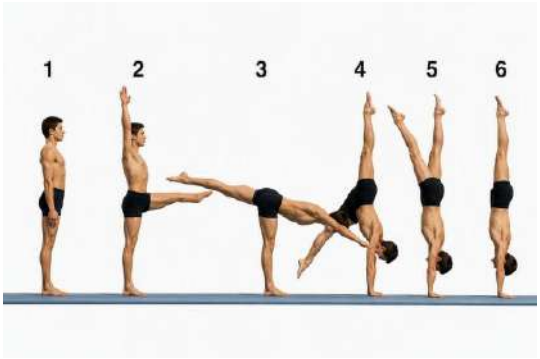


Figure 5. Swing to handstand technique.

Table 1 and Figure 5 illustrate an example from the 239 gymnastics techniques included in the study. The motor qualities highlighted in orange represent the abilities required to perform the Swing-to-Handstand

technique. Each technique is accompanied by a unique table detailing the necessary motor abilities. These tables and figures, presented in the Findings section, show the inclusion ratio for each motor ability across specific techniques.

Analysis of the results

The data were analysed using SPSS version 26.0. Descriptive statistics were performed in SPSS, while the percentages of motor ability inclusion for each apparatus and technique were calculated in Excel. Figures were also created using Excel. The analysis of the results is based on the percentage of inclusion of each motor ability across all techniques.

RESULTS

To determine the inclusion ratio of each motor quality across various gymnastics techniques, all techniques were classified according to the Technical Manuals described in the Methods section (FIG Academy MAG and WAG Level 1 Technical Manuals). For each apparatus, each technique was assessed for its involvement of each motor quality, and a single technique could involve more than one motor quality. "*Nr.*" indicates the number of techniques requiring that motor quality, out of the total number of techniques for that apparatus (shown in the column heading). "*%*" is calculated as Nr. divided by the total number of techniques for that apparatus. Because a technique can require multiple motor qualities, the percentages within a given apparatus column do not sum to 100%. Table 2 presents data for the apparatus specific to women's gymnastics (Beam and Asymmetric Bars), together with Floor and Vault, where the analysed techniques combine the men's and women's programmes for shared apparatus. Table 3 presents data for the apparatus specific to men's gymnastics (Rings, Parallel Bars, Horizontal Bar, Pommel Horse), together with Vault. The "*General*" column is the average percentage for each motor quality across the eight distinct apparatus (Floor, Vault, Beam, Asymmetric Bars, Rings, Parallel Bars, Horizontal Bar, Pommel Horse), with Vault counted once.

Table 2. Motor quality inclusion ratios by women's gymnastics apparatus.

Physical	**Floor**		**Vault**		**Beam**		**Asymmetric Bars**		**General**
qualities	Nr.	%	Nr.	%	Nr.	%	Nr.	%	**Avg %**
Coordination	34	76	17	100	21	68	20	91	88.57
Strength	12	27	14	82	11	35	16	73	73.07
Speed	16	36	14	82	5	16	18	82	62.83
Mobility	10	22	7	41	12	39	8	36	46.5
Flexibility	32	71	6	35	15	48	4	18	42.71
Balance	25	56	5	29	22	71	5	23	34.19
Endurance	0	0	1	6	2	6	0	0	3.92
Agility	3	7	0	0	0	0	0	0	0.83

Note. The Floor column includes the floor exercise techniques of both the men's and women's programmes (MAG 30, WAG 45), as the apparatus is common to both.

Table 2 shows that coordination dominates across all apparatus, peaking at 100% in Vault and averaging 88.57%, confirming it as the universal prerequisite for technique execution. Strength and speed form a secondary cluster, with both reaching 82% in Vault and Asymmetric Bars, reflecting the explosive demands of these apparatuses. Flexibility and balance instead follow apparatus-specific patterns: flexibility peaks on Floor (71%) due to acrobatic and dance content, while balance peaks on Beam (71%) due to its narrow base of support. Mobility remains moderate throughout (22-41%), whereas endurance and agility are minimally represented, indicating they are not structurally embedded in women's gymnastics technique.

 © 2026 ARD Asociación Española

Table 3. Motor quality inclusion ratios by men's gymnastics apparatus.

Physical Qualities	Vault		Rings		Parallel Bars		Horizontal Bar		Pommel Horse		General
	Nr.	%	Nr.	%	Nr.	%	Nr.	%	Nr.	%	Avg %
Coordination	17	100	22	81	17	100	26	93	5	100	88.57
Strength	14	82	23	85	17	100	23	82	5	100	73.07
Speed	14	82	13	48	9	53	24	86	5	100	62.83
Mobility	7	41	14	52	14	82	11	39	3	60	46.5
Flexibility	6	35	7	26	8	47	10	36	3	60	42.71
Balance	5	29	2	7	2	12	10	36	2	40	34.19
Endurance	1	6	1	4	2	12	1	4	0	0	3.92
Agility	0	0	0	0	0	0	0	0	0	0	0.83

Table 3 shows that coordination and strength are the leading qualities across the men's apparatuses. Both reach 100% on the Parallel Bars, while coordination, strength, and speed each reach 100% on the Pommel Horse, highlighting the strong integration of strength, coordination, and speed required for this apparatus. Speed varies by apparatus, peaking at 100% on Pommel Horse and 86% on Horizontal Bar but dropping to 48-53% on Rings and Parallel Bars, where strength-based elements dominate. Mobility and flexibility play secondary roles (39-82% and 26-60%, respectively), while balance is comparatively low (7-40%), suggesting men's apparatus rely more on dynamic strength-speed combinations than static equilibrium. As in the women's data, endurance is minor, and agility is entirely absent, confirming both as peripheral qualities in men's artistic gymnastics. The graphs show the inclusion ratios (%) of motor abilities in artistic gymnastics techniques for each apparatus.

Figure 6. Representation frequency of motor abilities on the floor apparatus. Coordination, followed by flexibility, balance, speed, strength, and mobility, plays the most important role in floor techniques.

Figure 7. Representation frequency of motor abilities on the Pommel Horse apparatus. Strength is the dominant ability on the pommel horse, followed by coordination, speed, mobility, and flexibility.

Figure 8. Representation frequency of motor abilities on Rings. Strength appears to be the dominant ability on the rings, followed by coordination, mobility, and speed.

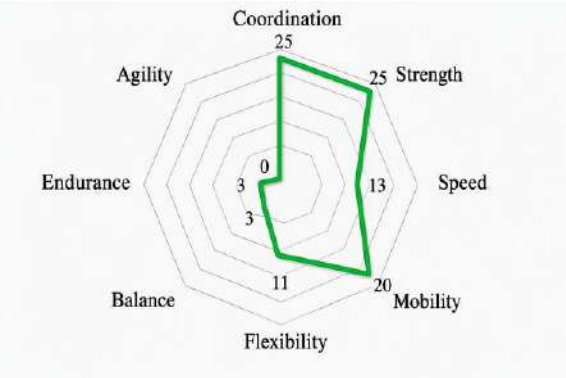


Figure 9. Representation frequency of motor abilities on Parallel Bars. The parallel bars rely on both strength and coordination, followed by mobility, speed, and flexibility.

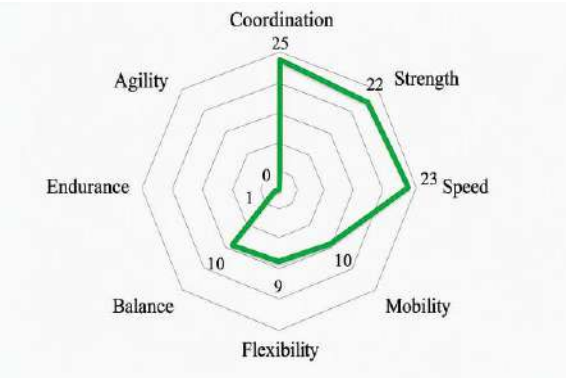


Figure 10. Representation frequency of motor abilities on the Horizontal Bar. The horizontal bar appears to be primarily characterised by coordination, speed, and strength. Balance and mobility, followed by flexibility, also play important roles.

 © 2026 ARD Asociación Española

Figure 11. Representation frequency of motor abilities on Vault. The vault appears to involve a broad range of motor abilities, with coordination being the most dominant, followed by strength, speed, and mobility.

Figure 12. Representation frequency of motor abilities on the Balance Beam. Although the apparatus is characterised by balance, coordination is the most represented ability on the balance beam, followed by balance, flexibility, mobility, and strength.

Figure 13. Representation frequency of motor abilities on Asymmetric Bars. Similar to the vault, the asymmetric bars are dominated by coordination, followed by speed, strength and mobility.

As Figures 14 and 15 show, the inclusion ratio of motor abilities in artistic gymnastics is presented as percentages. Coordination appears to be the most important ability, followed by strength and speed. As discussed in the Discussion section, coordination is a complex motor ability that includes multiple motor skills,

which is why it emerges as the most critical skill. These three motor abilities are also accompanied by mobility, flexibility, and balance, which play important roles in artistic gymnastics. However, endurance and agility do not appear to be significantly involved in the sport, even though factors such as force endurance and reaction time are relevant. These aspects are analysed as components of strength and speed.

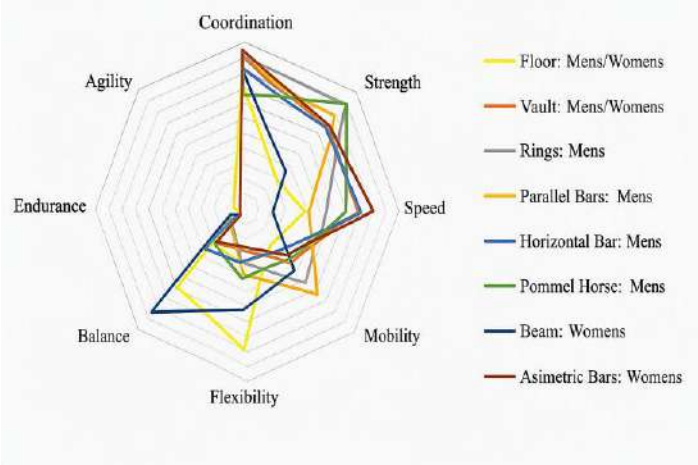


Figure 14. Representation frequency of motor abilities across artistic gymnastics apparatus.

Figure 15. Generalised representation frequency of motor abilities across artistic gymnastics apparatus.

DISCUSSION

As the study aimed to determine the inclusion rate of motor abilities in each apparatus, the results suggest that coordination plays a more significant role in artistic gymnastics than previously believed, particularly in mastering techniques outlined by the FIG (Fink & Hofmann, 2015; Fink et al., 2015). In the past, the demands on flexibility in artistic gymnastics were lower, with simpler movements focusing on poses and stretches. This can be seen in the earlier editions of the Code of Points, which recognised only three difficulty categories in men's gymnastics and two in women's, described the beam exercise mainly as an exercise of balance, allowed a maximum of three stops, and instructed gymnasts only to avoid too many lying and sitting positions (Fédération Internationale de Gymnastique, 1968, 1970). In the current editions, both disciplines use ten difficulty values from A to J, and handstands and holds may no longer be used to meet the composition requirements, which instead require dance connections with a 180° split, turns, an acrobatic series containing a jump, and acrobatic elements performed in different directions (Fédération Internationale de Gymnastique,

 © 2026 ARD Asociación Española

2025a, 2025b). Accordingly, advancements in technology and medicine have contributed to major progress in the sport, leading to increasingly complex movements that require greater mobility, coordination, strength, and speed (Fink & Hofmann, 2015; Fink et al., 2015; Fédération Internationale de Gymnastique, 2017a, 2017b). Although the literature sometimes confuses flexibility with mobility, flexibility remains an important component, even if it is usually ranked fourth after coordination, strength, and speed. Flexibility is essential for achieving the required joint range of motion, particularly in techniques such as splits and floor bridges (Fink et al., 2013; Fink, 2013). Flexibility can be measured both statically and dynamically: static flexibility involves external forces, such as gravity or partner assistance, while dynamic flexibility is actively controlled by the muscles (McGuigan, 2016). The relationship between static and dynamic flexibility is still being researched (Jeffreys, 2016; Cook, 2010). Passive flexibility provides the basis for active flexibility, which in turn supports overall mobility (Jeffreys, 2016; Cook, 2010).

Coordination involves combining motor skills and activating multiple muscles simultaneously, which is essential for performing synchronised movements (Foran, 2000; Çetin & Flock, 2014). Therefore, optimal coordination between body parts and equipment is crucial; for example, the parallel bars require high levels of hand and spatial coordination. In artistic gymnastics, the three main facets of coordination (difficulty level, accuracy, and acquisition time) are closely interconnected with various motor skills. Additionally, coordination is influenced by factors such as body weight, height, timing, sensory perception, balance, movement direction and distance, and visual targeting (Karabina & Pirselimoğlu, 2017). On the parallel bars, coordination between the body and space must be at the highest level to successfully link close-bar techniques, long-hanging elements, and flying movements. Similarly, on the balance beam, coordination among the extremities, the body, the apparatus, and the surrounding space is critical. In floor exercise, demonstrating coordination is essential to ensure fluency, adequate speed, and continuous execution of high-difficulty techniques without pause. In vaulting, maximum running, jumping, body coordination, and aerial orientation are all important components. Therefore, the development of coordination skills should be prioritised, as their inclusion rate on each apparatus highlights their significant importance in gymnastics training.

In artistic gymnastics, athletes must maintain control of their body weight throughout routines, with relative strength playing a pivotal role, as it reflects an individual's strength relative to their body size or lean mass (Fleck & Kraemer, 2014; Bompa, 2015; Ratamess, 2012). This ability is fundamental across all gymnastics disciplines (Bompa, 2015), and performance on apparatus such as the rings is highly dependent on adequate relative strength (Bompa, 2015). Studies suggest that women tend to develop greater relative strength than men under similar training regimes (Kell, 2011), emphasising the importance of this difference, particularly in artistic gymnastics. In disciplines like the parallel bars, where gravity significantly influences technique, both relative and absolute strength are crucial, with some research indicating that improvements in relative strength can contribute to gains in absolute strength (Kell, 2011).

In analysing movements on the rings, a sequence of concentric, eccentric, and isometric contractions occurs, highlighting the significance of these types of strength (Fédération Internationale de Gymnastique, 2017a). The stretch-shortening cycle (SSC) is also pivotal, as it involves muscles contracting, shortening, then immediately lengthening, which is crucial for performing movements such as holding positions on the rings for at least two seconds (Fédération Internationale de Gymnastique, 2017a). The SSC is also vital in floor jumps, impacting performance during rapid ground contacts such as round-off Tsukahara, double jump, Deferr, and Morandi, which occur in less than 250 milliseconds (Potach & Chu, 2016). It contributes to performance through the elastic properties of muscles and tendons, the amortisation phase, and the storage and release of energy, enhancing the efficiency of the eccentric phase. In artistic gymnastics, especially on apparatuses such as the balance beam, techniques are closely interconnected, with coordination playing a

crucial role; however, the physiological basis of force is equally important. Speed, following coordination and strength, facilitates both movement execution and the connection of elements.

Techniques on apparatuses such as the high bar, parallel bars, asymmetric bars, balance beam, and vault rely on achieving height through rapid and powerful swings. Speed, which follows coordination and strength in importance, is crucial in artistic gymnastics and directly impacts performance (McGuigan, 2016). Explosive power, which depends on speed, must be highly developed (Fink et al., 2013). Maximal speed is essential for successful vault jumps, as horizontal velocity significantly influences the vertical flight phases (Potach & Chu, 2016). The stretch-shortening cycle (SSC), which is vital in movements such as the round-off Tsukahara, improves performance by reducing ground contact times to less than 250 milliseconds. Speed also plays a key role in initiating each technique and is essential for executing skills such as somersaults on the vault and balance beam, as well as bar changes on asymmetric bars (Fédération Internationale de Gymnastique, 2017b).

Mobility in artistic gymnastics refers to the freedom of movement within a joint's range of motion (DeWeese & Nimphius, 2016). It encompasses the functional balance between active and passive flexibility. Demonstrating mobility requires applying flexibility during movements that demand strength, motor control, and dynamic joint balance (Karabina & Pirselimoğlu, 2017). Mobility, which integrates flexibility, strength, and motor skills, is a key component in artistic gymnastics and is particularly prominent in parallel apparatus techniques due to their demand for a wide range of motion (Fink & Hofmann, 2015). Functional flexibility is crucial for dynamic movements on the balance apparatus, indicating the importance of mobility skills in these techniques (Fink et al., 2015). Although mobility is typically ranked fourth, following coordination, strength, and speed, its comprehensive nature indirectly enhances the application of techniques that require these skills. Since mobility encompasses flexibility, it is also addressed within the flexibility section below.

Balance is the ability to maintain static and dynamic equilibrium or to support the body's centre of gravity over its base of support (Miller, 2012; Reilly & Waterhouse, 2009; McGuigan, 2016). Balance skills are particularly prominent on the balance beam, where the centre of gravity must be carefully maintained above the narrow support base, and they are also crucial in floor exercises. Although balance is important on apparatus such as the horizontal bar, parallel bars, and pommel horse, these exercises rely less on maintaining balance, as most movements occur with the centre of gravity below the support base. Instead, the focus shifts to adjusting the direction, tempo, and other characteristics, using swings and oscillations to transition from the bar to elevated positions rather than solely maintaining balance. Static balance, which involves keeping the centre of gravity above the support point, is commonly involved in floor exercises, the balance beam, and other apparatus events. Dynamic balance, on the other hand, is required when transitioning between balance positions, such as Alvirano or Menichelli, and regaining the same position. In particular, achieving different positions in the fourth movement group demands a high level of dynamic balance (Fink & Hofmann, 2015; Fink et al., 2015). Successfully performing movements in other groups and regaining lost positions, whether consciously or unconsciously, also depends on advanced dynamic balance. Although balance is typically ranked fifth in artistic gymnastics, its importance increases when considering its direct relationship with second-ranked static strength in dynamic balance. Similarly, the close relationship between dynamic balance and coordination, ranked first in importance, further highlights the significance of this characteristic.

Endurance in artistic gymnastics is primarily associated with the aerobic energy system, which depends on aerobic capacity, the maximum rate of energy production through the oxidation of energy sources (McArdle et al., 2015; McGuigan, 2016). However, because routines are relatively short, endurance is generally less critical. Instead, the sustained application of strength over periods of approximately 30 to 90 seconds

 © 2026 ARD Asociación Española

emphasises the importance of anaerobic capacity (McArdle et al., 2015; McGuigan, 2016). Endurance becomes significant in competition settings that involve multiple series, despite the dominant role of the phosphagen system and anaerobic capacity in gymnastics performance (McArdle et al., 2015; McGuigan, 2016). It is particularly relevant for apparatus such as the parallel bars and balance beam, although it is considered less important than other motor skills (Fink & Hofmann, 2015; Fink et al., 2015).

Agility is generally considered more important in collective sports, which involve manoeuvring ability, deceleration, acceleration, and changes of direction (Sheppard & Young, 2006; Stewart et al., 2014; McGuigan, 2016). When the components and underlying principles of agility are examined, it becomes clear that it plays a limited role in gymnastics apparatus performance. Similarly, as shown in Figure 14, agility does not appear to have a significant level of representation frequency in any apparatus, except for the floor. Compared to other apparatuses, agility is more involved in floor exercise; however, it has a relatively low impact compared to other motor skills (Fink & Hofmann, 2015; Fink et al., 2015).

From a conditioning perspective, the frequency of different motor abilities in artistic gymnastics techniques provides an apparatus-specific guide for program design rather than one general gymnastics profile. Since coordination is the most represented ability, conditioning should stay closely linked to skill performance, focusing on the rate of force development and inter-muscular coordination over general muscle hypertrophy training. Strength should be trained according to the type of muscle contraction rather than treated as one general category, with greater focus on isometric and eccentric-concentric strength on the rings and on relative strength wherever body mass must be controlled. On vault and floor, where the stretch-shortening cycle occurs during ground contacts of less than 250 ms, short-contact plyometrics exercises are more suitable than slow strength work. Mobility and flexibility should be trained through active range of motion under load, while balance work is most relevant on the beam and floor and can be combined with static strength work. Endurance training should mainly focus on anaerobic capacity during efforts lasting 30 to 90 seconds, while agility requires less attention beyond floor preparation.

Limitations

This study contains limitations. Since coordination is a broad, multi-component ability encompassing spatial orientation, timing, and inter-limb coordination, its high representation frequency percentage (25.3%) may not be directly comparable to more narrowly defined abilities such as balance or endurance. Future research could subdivide coordination into specific sub-components for a finer-grained analysis. The study is based on FIG Level 1 Technical Manuals, which predominantly cover foundational and intermediate techniques. The motor ability profiles of elite-level D–G difficulty elements may differ substantially, limiting generalisability to top-level competitive gymnastics. All techniques were assigned equal analytical weight regardless of their FIG difficulty value, meaning that an A-difficulty element and an F-difficulty element contribute equally to the representation frequency, which may underrepresent the true demands of modern high-difficulty gymnastics. The findings represent a static snapshot of the 2022–2024 Code of Points. As the FIG continues to introduce new techniques and revise its Code, the motor-ability representation frequency reported here will require periodic updates to remain applicable to contemporary gymnastics training.

CONCLUSION

An examination of the graphs reveals that, despite certain similarities in motor skill requirements across artistic gymnastics disciplines, each apparatus presents its own distinct demands. These demands appear to be shaped by the structural characteristics of the apparatus, the techniques performed on it, and the FIG regulations governing its execution, and they also vary with the difficulty of the movements involved.

Consequently, as the discipline continues to evolve, the motor skill requirements for each apparatus must be periodically reassessed and updated.

When considered overall, taking into account the importance of all apparatuses in artistic gymnastics, the most dominant motor skill is coordination, followed by strength, speed, mobility, flexibility, balance, and, finally, endurance and agility. Since the representation frequency of motor skills evolves alongside the sport's development, older sources may present outdated or overlapping information. Therefore, it is necessary to update these findings in parallel with the discipline's ongoing development.

As a result, it has been found that the representation frequency of motor skills in artistic gymnastics has changed due to the sport's ongoing development. This study was conducted based on current literature from FIG, NSCA, and other sources. When the representation frequency percentages of motor skills across each apparatus were generalised, coordination emerged as the dominant skill with 25.3%, followed by strength (21.3%), speed (17.1%), mobility (13.1%), flexibility (11.8%), balance (10.2%), endurance (0.9%), and agility (0.3%). The primary motor skills were identified as coordination, strength, speed, mobility, flexibility, and balance. Additionally, due to interrelationships among motor skills, abilities ranked fourth or fifth in representation frequency can also contribute to those ranked first. For instance, relationships such as mobility-flexibility, mobility-strength, dynamic balance-coordination, and static balance-static strength can increase the difficulty of certain techniques.

Currently, training programs in artistic gymnastics are often designed around motor skill representation frequency established when the sport was less developed than it is today. Therefore, outdated information about skill representation frequency can undermine the effectiveness of these programs. In this regard, it is recommended that training programs be designed in line with the updated representation frequency of motor skills identified in this study. Gymnasts' performance can be improved by focusing on motor skills such as intramuscular and intermuscular coordination, spatial orientation, the stretch-shortening cycle (SSC), elastic force, relative strength, pre-activation, mobility, and flexibility.

Finally, future analyses should include weighted scores based on the difficulty values of the analysed techniques. Since techniques with different difficulty values do not place the same motor demands on gymnasts, giving them equal weight may hide the actual importance of certain motor abilities. A difficulty-weighted approach would therefore provide a more realistic determination of which motor abilities are most important in contemporary artistic gymnastics.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Milaim Berisha. Methodology: Milaim Berisha, Pablo Prieto Gonzalez. Formal analysis: Milaim Berisha. Investigation: Milaim Berisha, Pablo Prieto Gonzalez. Data curation: Milaim Berisha. Writing – original draft: Milaim Berisha, Pablo Prieto Gonzalez. Writing – review & editing: Milaim Berisha, Pablo Prieto Gonzalez. Supervision: Pablo Prieto Gonzalez.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

 © 2026 ARD Asociación Española

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. Prince Sultan University provided the resources for the conduct of this study and will fund the Article Processing Charges (APCs) associated with its publication.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Bompa, T. O. (2015). *Periodization training for sports* (3rd ed.). Human Kinetics.

Çetin, H. N., & Flock, T. (2014). *Genel kondüsyon antrenmanı ve sporda performans kontrolü* (7th ed.). Turna Yayınları.

Cook, G. (2010). *Movement: Functional movement systems: Screening, assessment, and corrective strategies*. On Target Publications.

DeWeese, B. H., & Nimphius, S. (2016). Program design and technique for speed and agility training. In G. G. Haff & N. T. Triplett (Eds.), *Essentials of strength training and conditioning* (4th ed.). Human Kinetics.

Fédération Internationale de Gymnastique. (1968). Code of points: Men's artistic gymnastics. FIG.

Fédération Internationale de Gymnastique. (1970). *Code of points: Women's artistic gymnastics*. FIG.

Fédération Internationale de Gymnastique. (2017a). *2017 code of points: Men's artistic gymnastics*. FIG.

Fédération Internationale de Gymnastique. (2017b). *2017–2020 code of points: Women's artistic gymnastics*. FIG.

Fédération Internationale de Gymnastique. (2025a). *2025–2028 code of points: Men's artistic gymnastics*. FIG. https://www.gymnastics.sport/publicdir/rules/files/en_1.1%20-%20MAG%20Code%20of%20Points%202025-2028.pdf

Fédération Internationale de Gymnastique. (2025b). *2025–2028 code of points: Women's artistic gymnastics*. FIG. https://www.gymnastics.sport/publicdir/rules/files/en_1.1%20-%20WAG%20COP%202025-2028.pdf

Fink, H. (2013). *Men's artistic gymnastics technical manual* (Level 1, 2nd ed.). Fédération Internationale de Gymnastique. http://www.fig-gymnastics.com

Fink, H., & Hofmann, D. (2015). *Age group development and competition program for men's artistic gymnastics*. Fédération Internationale de Gymnastique. http://www.fig-gymnastics.com

Fink, H., Hofmann, D., & López, L. O. (2015). *Age group development and competition program for women's artistic gymnastics*. Fédération Internationale de Gymnastique. http://www.fig-gymnastics.com

Fink, H., McVey, B., & Stan, A. (2013). *Women's artistic gymnastics technical manual* (Level 1, 2nd ed.). Fédération Internationale de Gymnastique. http://www.fig-gymnastics.com

Fleck, S. J., & Kraemer, W. J. (2014). *Designing resistance training programs*. Human Kinetics. https://doi.org/10.5040/9781718225107

Foran, B. (Ed.). (2000). *High-performance sports conditioning*. Human Kinetics.

Gasparetto, Z., Julião, A. L., Thuany, M., Martinez, P. F., de Mendonça Bacciotti, S., & de Oliveira-Junior, S. A. (2022). Concerns about strength tests in gymnastics: A systematic review. *Science of Gymnastics Journal, 14*(2), 225–236. https://doi.org/10.52165/sgj.14.2.225-236

Jeffreys, I. (2016). Warm-up and flexibility training. In G. G. Haff & N. T. Triplett (Eds.), *Essentials of strength training and conditioning* (4th ed.). Human Kinetics.

Karabina, F., & Pirselimoğlu, R. T. (2017). *Antrenman bilgisi* (1st ed.). Devlet Kitapları.

Kell, R. T. (2011). The influence of periodized resistance training on strength changes in men and women. *Journal of Strength and Conditioning Research, 25*(3), 735–744. https://doi.org/10.1519/JSC.0b013e3181c69f22

McArdle, W. D., Katch, F. I., & Katch, V. L. (2015). *Exercise physiology: Energy, nutrition, and human performance* (8th ed.). Lippincott Williams & Wilkins.

McGuigan, M. (2016). Administration, scoring, and interpretation of selected tests. In G. G. Haff & N. T. Triplett (Eds.), *Essentials of strength training and conditioning* (4th ed.). Human Kinetics.

Miller, T. (2012). *NSCA's guide to tests and assessments*. Human Kinetics. https://doi.org/10.5040/9781718225398

Potach, D. H., & Chu, D. A. (2016). Program design and techniques for plyometric training. In G. G. Haff & N. T. Triplett (Eds.), *Essentials of strength training and conditioning* (4th ed.). Human Kinetics.

Ratamess, N. A. (2012). *ACSM's foundations of strength training and conditioning*. Lippincott Williams & Wilkins.

Reilly, T., & Waterhouse, J. (2009). Sports performance: Is there evidence that the body clock plays a role? *European Journal of Applied Physiology, 106*(3), 321–332. https://doi.org/10.1007/s00421-009-1066-x

Sheppard, J. M., & Young, W. B. (2006). Agility literature review: Classifications, training and testing. *Journal of Sports Sciences, 24*(9), 919–932. https://doi.org/10.1080/02640410500457109

Stewart, P. F., Turner, A. N., & Miller, S. C. (2014). Reliability, factorial validity, and interrelationships of five commonly used change of direction speed tests. *Scandinavian Journal of Medicine & Science in Sports, 24*(3), 500–506. https://doi.org/10.1111/sms.12019

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española

ORIGINAL ARTICLE

Seasonal changes in physical fitness and body composition and their associations with external match load in elite youth football players

Rodrigo Villaseca-Vicuña. *School of Educational Sciences and Technology. Faculty of Education. Silva Henríquez Catholic University (UCSH). Santiago, Chile.*

Pablo Merino-Muñoz. *Research Centre for Human Movement Sciences. Chilean Adventist University. Chile.*
Department of Physical Activity, Sports and Health Sciences. Faculty of Medical Sciences. Santiago de Chile University (USACH). Santiago, Chile.

Rodrigo Yáñez-Sepúlveda. *School of Sport Sciences. Faculty of Education and Humanities. Andrés Bello University. Viña del Mar, Chile.*
School of Medicine. Espíritu Santo University. Ecuador.

Guillermo Cortés-Roco. *Master's Program in Evaluation and Planning of Sports Training. Faculty of Life Sciences. Viña del Mar University. Viña del Mar, Chile.*

Marcelo Muñoz. *School of Education. Faculty of Humanities. Bernardo O'Higgins University. Santiago, Chile.*

Jorge Pérez-Contreras . *School of Sports Science. Faculty of Health. Santo Tomás University. Chile.*
Department of Physical Education, Sport and Recreation. Faculty of Arts and Physical Education. Metropolitan University of Educational Sciences. Chile.

ABSTRACT

Purpose: To compare seasonal changes in body composition and physical fitness and examine their associations with external match load in elite youth football players. Methods: Twenty-nine players from the U18 (n = 14) and U21 (n = 15) squads were assessed during two competitive periods (First and Second Phase). Body composition included muscle mass (%MM), fat mass (%FM), and the sum of 6 skinfolds (6skf). Physical fitness assessments comprised countermovement jump (CMJ), 10-m (T10) and 30-m sprint time (T30), change-of-direction ability (COD), kicking velocity (KV), and maximal oxygen uptake (VO_{2max}). External match load was quantified using GPS technology. Results: Both categories showed significant improvements in body composition, with higher %MM and lower %FM and 6skf ($p < .05$). CMJ, T30, and KV also improved significantly, whereas VO_{2max} remained unchanged. Correlation analyses identified significant associations between physical fitness, body composition, and external match load, with more relationships observed in U18 than U21 players. Conclusions: Elite youth football players improved primarily in neuromuscular performance and body composition across the season. The greater number of associations observed in U18 players represents an exploratory pattern and should not be interpreted as evidence of stronger relationships between physical qualities and match performance compared with U21 players.

Keywords: performance analysis; athletic performance; monitoring; physiologic; muscle strength; anthropometry; physical endurance.

Cite this article as:
Villaseca-Vicuña, R., Merino-Muñoz, P., Yáñez-Sepúlveda, Cortés-Roco, G., Muñoz, M., & Perez-Contreras, J. (2026). Seasonal changes in physical fitness and body composition and their associations with external match load in elite youth football players. *Journal of Human Sport and Exercise, 21*(4), 1601-1621. https://doi.org/10.55860/zrfqrb31

Corresponding author. *Departamento de Educación Física, Deportes y Recreación, Facultad de Artes y Educación Física, Universidad Metropolitana de Ciencias de la Educación, Chile.*
E-mail: joperezc@gmail.com

Submitted for publication July 17, 2026.
Accepted for publication August 31, 2026.
Published September 30, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/zrfqrb31

INTRODUCTION

Performance in football is a multifactorial phenomenon resulting from the interaction of physical, technical, tactical, and physiological variables during competition (Villaseca-Vicuña, Barrera-Díaz, et al., 2026). Among these determinants, physical fitness and body composition play a fundamental role in meeting the intermittent high-intensity demands inherent to the game (Villaseca-Vicuña, Molina-Sotomayor, et al., 2021). Modern football requires players to perform repeated accelerations, decelerations, sprints, and changes of direction while simultaneously maintaining high levels of aerobic capacity and neuromuscular performance (Bangsbo et al., 2006). Consequently, the assessment of neuromuscular variables such as countermovement jump performance, linear sprint speed, change of direction ability, kicking velocity, and maximal oxygen uptake has become common practice in high-performance environments (Pérez-Contreras et al., 2022; Villaseca-Vicuña, Medrano, et al., 2025). In addition, body composition indicators such as percentage of muscle and adipose mass have also been associated with physical fitness and match demands, as higher levels of body fat may negatively affect sprinting speed, acceleration capacity, and overall competitive performance (Rios-Limas et al., 2025).

Throughout a competitive season, football players are exposed to fluctuations in training and match loads that may induce adaptations in physical fitness and neuromuscular performance (Clemente et al., 2019; Malone et al., 2015). Several studies have reported improvements in variables such as neuromuscular and sprint performance during the competitive period, particularly in young players who are still undergoing physical development (Buchheit & Mendez-Villanueva, 2013). Simultaneously, advances in monitoring technologies have enabled the accurate quantification of external load during competition through variables such as total distance covered, high-speed running distance, sprint distance, the number of accelerations and decelerations, and inertial sensor-derived metrics such as player load (Cummins et al., 2013). Within this context, some investigations suggest that players with higher levels of physical fitness tend to tolerate greater competitive demands or exhibit higher external load values during matches, highlighting the close relationship between physical capacities and match performance outcomes (Rios-Limas et al., 2025; Villaseca-Vicuña, Otero-Saborido, et al., 2021).

Despite the growing number of studies examining match demands and physical profiles in football, there remains limited evidence simultaneously investigating seasonal changes in physical fitness, body composition, and their relationship with external match load in elite youth players. Understanding these interactions is particularly relevant in players approaching senior professional football, as they are exposed to demanding competitive schedules while continuing to experience biological development and physical maturation processes (Villaseca-Vicuña, Otero-Saborido, et al., 2021). Furthermore, identifying which physical qualities are associated with greater competitive demands may provide valuable information for optimising training programmes, improving performance monitoring strategies, and supporting players' long-term development (Ford et al., 2020). However, evidence describing these relationships across different competitive periods within the same season remains scarce, particularly in South American youth football settings. Moreover, much of the available evidence on longitudinal physical development and match-load demands in academy football has been derived from European cohorts. Evidence from South American professional academies remains comparatively limited, despite differences in competitive structures, developmental pathways, and training environments that may influence the expression of physical performance (Villaseca-Vicuña, Cursach, et al., 2025; Villaseca-Vicuña, Merino-Muñoz, et al., 2026). Therefore, examining players from a South American professional academy provides an opportunity to extend the geographical scope of the existing literature while identifying context-specific patterns that warrant validation across different academy environments.

 © 2026 ARD Asociación Española

Therefore, the present study had two aims: (i) to compare changes in body composition and physical fitness between two competitive periods (First Phase vs. Second Phase) in elite youth football players; and (ii) to analyse the associations between physical fitness, body composition, and external load variables during official competition through a category-stratified analysis (U18 and U21), to explore potential age-category-specific patterns in the coupling between physical profiles and external match-load expression. Based on previous literature, it was hypothesised that: (i) neuromuscular performance and sprint capacity would improve throughout the competitive season; and (ii) players with higher levels of physical fitness and lower levels of adiposity would exhibit greater external load values during official competition, with these associations potentially differing according to competitive category.

MATERIAL AND METHODS

Design

The present study adopted a longitudinal observational design with repeated measures collected across two competitive periods within the same season (First Phase and Second Phase). Body composition and physical fitness were assessed at two time points: prior to the start of the First Competitive Phase and prior to the start of the Second Competitive Phase. In addition, external match load variables were recorded during official matches throughout each competitive period.

This design enabled the analysis of within-subject changes in body composition and physical fitness across the season, as well as the examination of the relationships between players' physical profiles and the external load demands experienced during competition. To account for differences associated with biological development and competitive context, all analyses were conducted separately for the U18 and U21 categories.

Training programme and weekly microcycle. Throughout the observation period, both age categories followed a structured match-day-based weekly microcycle. The typical microcycle included post-match recovery or compensatory work (MD+2), lower-body strength training (MD−4), duration-oriented conditioning (MD−3), speed-oriented training (MD−2), pre-match activation (MD−1), official competition (MD), and passive recovery (MD+1). Physical preparation was integrated with technical and tactical contents according to the proximity to match day. Conditioning included continuous aerobic work, intermittent running prescribed relative to YYIRT-L1 performance, small-sided games, strength training, sprinting, and change-of-direction exercises. The general structure and main training contents were maintained across the First and Second Phases and are detailed in Supplementary Table S1. Each observation phase comprised 10 official matches, resulting in a comparable number of competitive fixtures between phases. Official competition was generally scheduled once per weekly microcycle (MD), although individual match exposure varied according to player selection and playing time. Individual session-level internal and external training loads were not included in the present analysis; therefore, the programme description provides contextual information regarding training exposure rather than a quantitative assessment of the specific training dose received by each player.

Participants

A non-probabilistic convenience sampling approach was employed, involving youth football players from the academy system of a professional first-division football club in Chile. The competitive categories were defined by the national football federation according to players' year of birth. For the purposes of the present study, players from the U18 (n = 14) and U21 (n = 15) categories were included. The U18 players had a mean body mass of 71.90 ± 7.74 kg and a mean height of 178.43 ± 5.81 cm, while the U21 players presented a mean body mass of 72.22 ± 8.01 kg and a mean height of 175.79 ± 7.47 cm.

Table S1. Schematic representation of the microcycle structure according to the training tasks and contents implemented.

MD + 2	MD − 4	MD − 3	MD − 2	MD − 1	MD	MD + 1
Active recovery/ compensation	**Strength**	**Duration**	**Velocity**	**Activation**	**Match day**	**Off**
Physical training Core training (10') dynamic and isometric contraction exercises Upper-body strength 3–5 sets/3–6 r 30–60% 1RM Bench Press Pull-Ups TRX Pull-Ups Shoulder Push-Ups Recovery Work (>60 min players): —Aerobic continuous run or bike: 15–20' at 60–65% HRmax —Stretching and mobility (10–15'): assisted and with foam roller Complementary Work (<60 min players): —Small-sided games (3 × 4', 2' rec, 6v6–8v8) —Intermittent runs: 1–2 sets × 6–8 reps of 100 m (90–120% YYIRT-L1)	Physical training Core training (10') dynamic and isometric contraction exercises Lower-body strength 3–5 sets/3–6 r 30–60% 1RM Squat Deadlift Hip thrust TEC/TAC (~60') Duelling actions, few players in small spaces <60 m^2 pp	Physical training Core training (10') dynamic and isometric contraction exercises Upper-body strength 3–5 sets/3–6 r 30–60% 1RM Bench Press Pull-Ups TRX Pull-Ups Shoulder Push-Ups Intermittent training 1–2 sets × 6–8 reps of 100 m at 90–120% YYIRT-L1 TEC/TAC (~90') A greater number of players in larger playing spaces >90 m^2 pp	Physical training Core training (10') dynamic and isometric contraction exercises Speed Block (20'): Unresisted sprints Linear sprints from 10 m to 30 m Change of direction and agility training from 10 m to 20 m TEC/TAC (~80') Fewer players in larger playing spaces >90 m^2 pp Defensive set plays	Physical training Coordination drills (15') Individual and collective techniques with the ball TEC/TAC (~50') Few players in small spaces <60 m^2 pp Offensive set plays	Football warm up (25') General exercises for joint mobility, control, and passing, games in reduced spaces, defensive block work, and offensive block work Competition	Passive recovery
Cool-down (10')	Cool-down (10')	Cool-down (10')	Cool-down (10')	Cool-down (10')	Cool-down (10')	

 © 2026 ARD Asociación Española

Procedures

Physical fitness and body composition were assessed at two time points during the competitive season: immediately prior to the First Competitive Phase and immediately prior to the Second Competitive Phase. Subsequently, 10 official matches were monitored during each competitive period. For each player, external match-load variables were averaged across the 10 monitored matches within each competitive phase, generating one representative value per external match-load variable for each phase. For the association analyses, each physical fitness and body composition assessment was paired exclusively with the average external match-load data obtained during the corresponding competitive phase. Thus, First Phase assessments were associated with First Phase match-load data, whereas Second Phase assessments were associated with Second Phase match-load data. Fitness assessments and match-load data from temporally different phases were not paired. Data were structured at the player-phase level. Each of the 14 U18 players and 15 U21 players contributed one record from the First Phase and one record from the Second Phase, resulting in 28 and 30 player-phase observations, respectively. Each record paired the physical fitness and body-composition assessment performed for that competitive phase with the corresponding average external match-load data from the 10 monitored matches. Therefore, individual player-match observations were not entered as separate cases in the correlation analyses. All assessments were conducted in the morning under controlled environmental conditions (approximately 15°C and 75% relative humidity). To minimise the effects of fatigue, participants were instructed to refrain from strenuous physical activity for at least 24 hours prior to testing (Villaseca-Vicuña, Medrano, et al., 2025). Before the assessments, each category completed a standardised warm-up protocol supervised by its strength and conditioning coach, consisting of a general phase (light running, multidirectional movements, and dynamic stretching), followed by a specific phase including exercises related to the requirements of each test.

All players were familiar with the testing procedures, as these assessments form part of the club's annual physical fitness and body composition testing battery within its youth development programme (Figure 1). Participants were instructed to perform each test with maximal effort. All physical assessments were conducted on an artificial turf surface, with players wearing football boots appropriate for this type of playing surface.

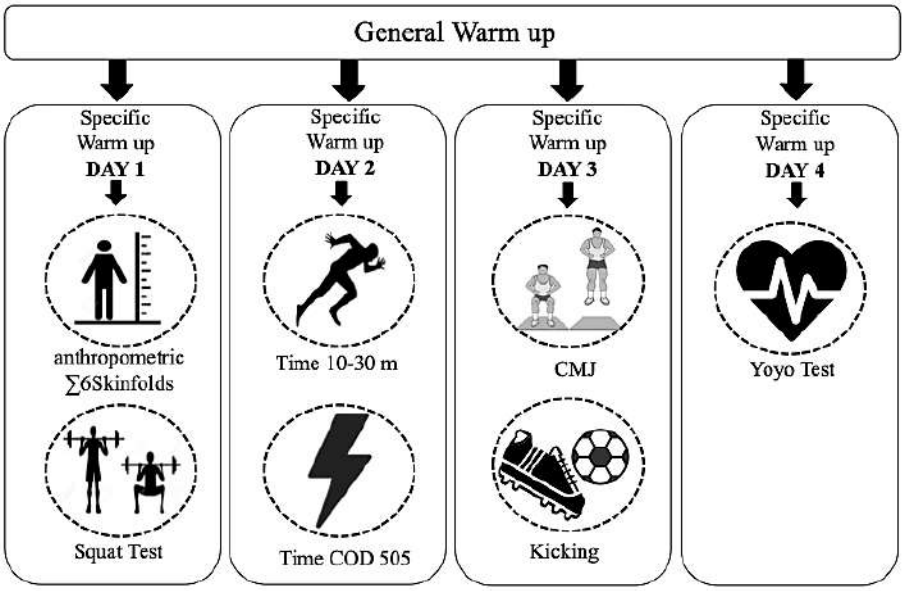


Figure 1. Body composition and physical fitness assessments.

Body composition

The weight and height of each player were measured using a scale with a height gauge (Seca 700®, Hamburg, Germany). In addition, the sum of 6 skinfolds (6skf: tricipital, subscapular, supraspinal, abdominal, medial thigh and calf maximum) was recorded, using these data to estimate the percentage of fat mass (%FM) and the percentage of muscle mass (%MM). All procedures were performed in accordance with the standards of the International Society for the Advancement of Kineanthropometry (ISAK) and were performed by a certified ISAK III specialist, belonging to the football club's staff. Skinfold measurements were performed with a high-precision (0.2 mm) thin-guide caliper (Rosscraft®, British Columbia, Canada).

Squat test

This test has been validated to assess lower limb muscle strength levels in footballers (Pareja-Blanco et al., 2017). Before the measurement, each player performed a specific warm-up of 3 sets and 3 repetitions with a load of 20 kg. In the evaluation, each player performed 1 set of 3 repetitions, with each load of: 20, 30, 40, 50, 60, 70 and 80 kg respectively, with a recovery of 3 minutes between sets. The concentric phase of the exercise was required to be executed at the maximum possible speed. The incremental test was completed after the final absolute load of 80 kg, and no repetitions were performed to muscular failure. Two variables were recorded: a) relative strength (RS), obtained from the ratio between estimated 1RM and body weight; and b) estimated one-repetition maximum (1RM), determined from the mean propulsive velocity (MPV) recorded during the final absolute load of 80 kg using the equation proposed by Pareja-Blanco et al. (2020). No within-set velocity-loss criterion was applied, as the purpose of the incremental test was to estimate 1RM from the MPV recorded at the final absolute load rather than to determine muscular failure or terminate the test according to a predefined velocity-loss threshold. The aforementioned variables were determined using the linear encoder (ADR encoder®, Toledo, Spain). Equation to calculate the 1RM in the squat from the MPV at the last load:

$$\%1RM = (-42.196 \times MPV^2) - (31.018 \times MPV) + 112.937$$

Linear sprint time in 10 (T10) and 30 meters (T30)

This test is commonly used to assess maximum running speed in footballers (Villaseca-Vicuña et al., 2024). Prior to the evaluation, the players performed a specific warm-up, which included five progressive 30-meter runs. Each player performed three 30-m attempts, with three minutes of recovery between attempts. The starting position was standing, with the forward foot placed just behind a line located 0.5 meters from the first photoelectric cell (Witty gate, Microgate®, Bolzano, Italy), to avoid premature interruptions of the light beam with the head or arms. Photoelectric cells were placed at the starting line, 10 meters, and 30 meters, recording the time from 0 to 10 meters (T10) and from 0 to 30 meters (T30). For the analysis, the best time of the three attempts was considered.

Change of direction 505 modified (COD)

Prior to the test, a standardised warm-up was carried out by the physical trainer, which consisted of 6 accelerations and a 5-m deceleration. The protocols for this test have already been documented in the literature (Pérez-Contreras et al., 2024). Using a single-beam photocell (Witty gate, Microgate®, Bolzano, Italy), positioned at the start/finish gate at a vertical height of 1 meter, players began with one foot 0.5 meters behind the gate, sprinted forward, stepped on the 5-m mark (white tape), and returned through the gate. A mark was placed beyond the gate to encourage players to continue running through the finish, and a researcher verbally encouraged them not to stop until they crossed the mark. Four attempts were performed, with two changes of direction completed for each side; the result was obtained by averaging the two valid attempts for each side. When a player did not reach the indicated 5-m mark, the attempt was considered null and repeated until two valid attempts were obtained. Players had 2 minutes of rest between attempts.

 © 2026 ARD Asociación Española

Countermovement jump (CMJ)

This test is usually done to measure the power of the lower limbs of football players (Kobal et al., 2016; Romero-Caballero et al., 2021). Before performing the test, each player performed a specific 5-jump warm-up to a jump box, the target surface of which was 40 cm from the ground. In the test, participants made 3 attempts. The starting position is upright with the hands on the waist throughout the test to eliminate any influence of arm swing. From this position the participant quickly bends the knees to approximately 90° and then immediately pushes off to jump vertically as high as possible, landing on both feet at the same time and with the knees extended (Kobal et al., 2016; Romero-Caballero et al., 2021). If the evaluator observed an execution error, the jump was invalidated and the execution was repeated. This test was evaluated using an infrared platform (Optojump Microgate® contact platform, Bolzano, Italy), with 3 minutes of rest between repetitions. The jump height (cm) was recorded and the best result was selected.

Kicking velocity (KV)

This physical-technical test assesses kicking velocity, a parameter widely analysed in footballers (Rada et al., 2019). Before the measurement, each player performed a specific warm-up, which consisted of 10 long passes with the instep. During the evaluation, the players executed three attempts with the dominant leg, using the full instep and with three minutes of recovery between each attempt. For the statistical analysis, the highest recorded velocity was considered. The players were instructed to kick the ball with the maximum possible speed, directing it towards a target of 1 meter in diameter, located in the centre of the goal (Rada et al., 2019). The ball remained static 8 meters from the goal (Molten Vantaggio 5000® ANFP 2023 Professional Ball, Hiroshima, Japan), allowing an approach run of 1 meter. A speed measuring radar (Supido Multideporte®, Blackpool, United Kingdom) was used. The radar was positioned 1 m behind the goal, according to the specific instructions of the radar (Díez-Fernández et al., 2022). If the execution did not meet the established criteria (e.g., contact with an inappropriate area of the foot or lack of precision in the direction of the shot), the attempt was discarded and repeated.

Maximal oxygen uptake (VO_{2max})

VO_{2max} was estimated using the Yo-Yo Intermittent Recovery Test Level 1, a field-based test widely used to assess intermittent endurance capacity in football players (Pérez-Contreras et al., 2022). Prior to testing, all players completed a standardised warm-up consisting of 10 submaximal 20-m shuttle runs with changes of direction. Participants performed one maximal attempt following the protocol described by Bangsbo et al. (2006). The total distance covered (m) during the Yo-Yo IR1 was recorded and subsequently used to estimate maximal oxygen uptake (VO_{2max}; $ml \cdot kg^{-1} \cdot min^{-1}$) using the following equation:

$$VO_{2max} = [\text{Yo-Yo IR1 distance (m)} \times 0.0084] + 36.4.$$

The estimated VO_{2max} value was used as the aerobic performance indicator in the statistical analyses (Bangsbo et al., 2006).

External load: GPS monitoring

Players' external load during each training session and match was monitored using GPS devices (WIMU Pro®, RealTrack Systems, Almería, Spain), with a sampling frequency of 10 Hz and an integrated 3D accelerometer operating at 100 Hz. Each device was secured in a neoprene vest worn tightly between the scapulae to ensure accurate data collection. The variables considered for analysis included total distance (TD), high-speed running (HSR; >19.8 km/h), peak speed (PS), number of accelerations (ACC) and decelerations (DEC) greater than 3 m/s^2, and player load (PL). These metrics are commonly used to monitor

training load and to assess and report player performance during official football matches in men's football (Stevens et al., 2017).

Statistical analysis

Data are presented as mean ± standard deviation (M ± SD). Normality was assessed using the Shapiro–Wilk test, and homogeneity of variance was examined using Levene's test when appropriate. Changes between the First and Second Competitive Phases were assessed using paired-samples t-tests for normally distributed variables and Wilcoxon signed-rank tests when normality assumptions were not met.

The magnitude of within-player differences between competitive phases was quantified using Cohen's d for paired samples, calculated as the mean of the paired differences divided by the standard deviation of the paired difference scores. Effect-size signs were expressed in the direction of change from the First Phase to the Second Phase (Second Phase − First Phase), consistent with the percentage-change calculation. Ninety-five percent confidence intervals (95% CI) for Cohen's d were reported to indicate the precision of the effect-size estimates. Effect sizes were interpreted according to their absolute magnitude as trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥2.00). To complement the group-level pre–post comparisons, individual within-player changes were also visualized for each physical fitness and body-composition variable. Individual paired trajectories were displayed by connecting each player's First Phase and Second Phase values, thereby illustrating the direction and inter-individual variability of seasonal changes. Percentage change (Δ%) was calculated as [(Second Phase − First Phase) / First Phase] × 100. These individual trajectories were used descriptively and were not intended to classify players as responders or non-responders.

For the association analyses, data were structured at the player-phase level. Each of the 14 U18 players and 15 U21 players contributed one phase-specific record from the First Phase and one from the Second Phase, resulting in 28 and 30 player-phase observations, respectively (14 × 2 for U18 and 15 × 2 for U21). Thus, the analytical unit represented a player within a specific competitive phase rather than an individual match observation. Pearson's correlation coefficients were used to examine relationships between body composition, physical fitness, and external match-load variables when normality assumptions were met, whereas Spearman's rho was applied when these assumptions were not satisfied. Correlation magnitudes were interpreted as trivial (<.10), small (.10 – .29), moderate (.30 – .49), large (.50 – .69), very large (.70 – .89), and nearly perfect (≥.90).

Given the exploratory nature of the association analyses, correlation coefficients were primarily used to describe the magnitude and direction of potential relationships between physical and anthropometric characteristics and external match-load variables within each category. Accordingly, these analyses were considered hypothesis-generating rather than confirmatory. Statistically significant associations identified in the correlation analyses were subsequently explored using simple linear regression models to further characterise the strength and direction of these relationships. Statistical significance was set at $p \leq .05$. All statistical analyses were conducted separately for U18 and U21 players using JASP version 0.19.1 (JASP Team, University of Amsterdam, The Netherlands). Graphical representations of the simple linear regression analyses were generated using GraphPad Prism version 10.3.1 (GraphPad Software, LLC, Boston, MA, USA).

Ethical considerations

All participants were informed about the assessment and monitoring procedures conducted throughout the competitive season and provided informed consent. For players under 18 years of age, parents or legal

 © 2026 ARD Asociación Española

guardians were informed, prior to the beginning of the season and through the club's institutional meetings, about the routine physical assessment and performance-monitoring procedures implemented throughout the season, and provided informed consent for the players' participation in these procedures. The players were also informed about the assessments and their use as part of the club's performance-monitoring system. All measurements analysed in this study were part of the club's routine physical, anthropometric, and match-load monitoring procedures and were not introduced specifically for research purposes. Therefore, the study involved no experimental interventions, modifications to regular training practices, or additional procedures or risks beyond those inherent to routine football training, testing, and competition. All players held valid federation licences and had completed the medical evaluations required by the Chilean Football Federation before the beginning of the season. All procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki (World Medical Association, 2013). The study was conducted using data obtained as part of the club's routine performance assessment and monitoring practices, following the ethical considerations applicable to sports science research and monitoring (Winter & Maughan, 2009).

RESULTS

Table 1 presents the changes in body composition and physical fitness variables between the First Phase and Second Phase in U21 players. Significant improvements were observed in %MM, CMJ, KV, and T30, together with significant reductions in %FM and 6skf (all $p < .001$), with moderate-to-large effect sizes. Conversely, T10 increased significantly, indicating a decline in short-distance acceleration performance. No significant changes were found in VO_{2max}, COD Right and Left and 1RM.

Table 1. Changes in body composition and physical fitness in U21 players.

Variable	First phase (M ± SD)	Second phase (M ± SD)	%	*p* value	Cohen's d [95% CI]	Magnitude
MM (%)	50.1 ± 1.94	51.1 ± 2.39	1.89	<.001	1.685 [0.875, 2.472]	Large
FM (%)	20.9 ± 2.53	19.3 ± 2.66	-7.74	<.001	−1.543 [−2.290, −0.772]	Large
6skf (mm)	43.0 ± 13.2	38.5 ± 13.1	-10.2	<.001	−1.227 [−1.892, −0.538]	Large
CMJ (cm)	39.7 ± 3.86	44.2 ± 5.30	11.48	<.001	1.367 [0.643, 2.068]	Large
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	60.7 ± 3.77	60.6 ± 3.80	-0.26	.789	−0.071 [−0.576, 0.437]	Trivial
T30 (s)	4.09 ± 0.14	3.96 ± 0.14	-3.04	<.001	−1.826 [−2.653, −0.975]	Large
T10 (s)	1.60 ± 0.10	1.67 ± 0.09	3.81	.005	0.860 [0.253, 1.446]	Moderate
COD right (s)	2.40 ± 0.09	2.45 ± 0.08	1.83	.097	0.460 [−0.081, 0.986]	Small
COD left (s)	2.39 ± 0.08	2.44 ± 0.08	2.09	.212	0.337 [−0.189, 0.853]	Small
1RM (kg)	155 ± 17.1	158 ± 26.3	1.67	.618	0.132 [−0.379, 0.638]	Trivial
Kicking (km/h)	103 ± 4.59	108 ± 3.42	4.76	<.001	1.473 [0.721, 2.202]	Large

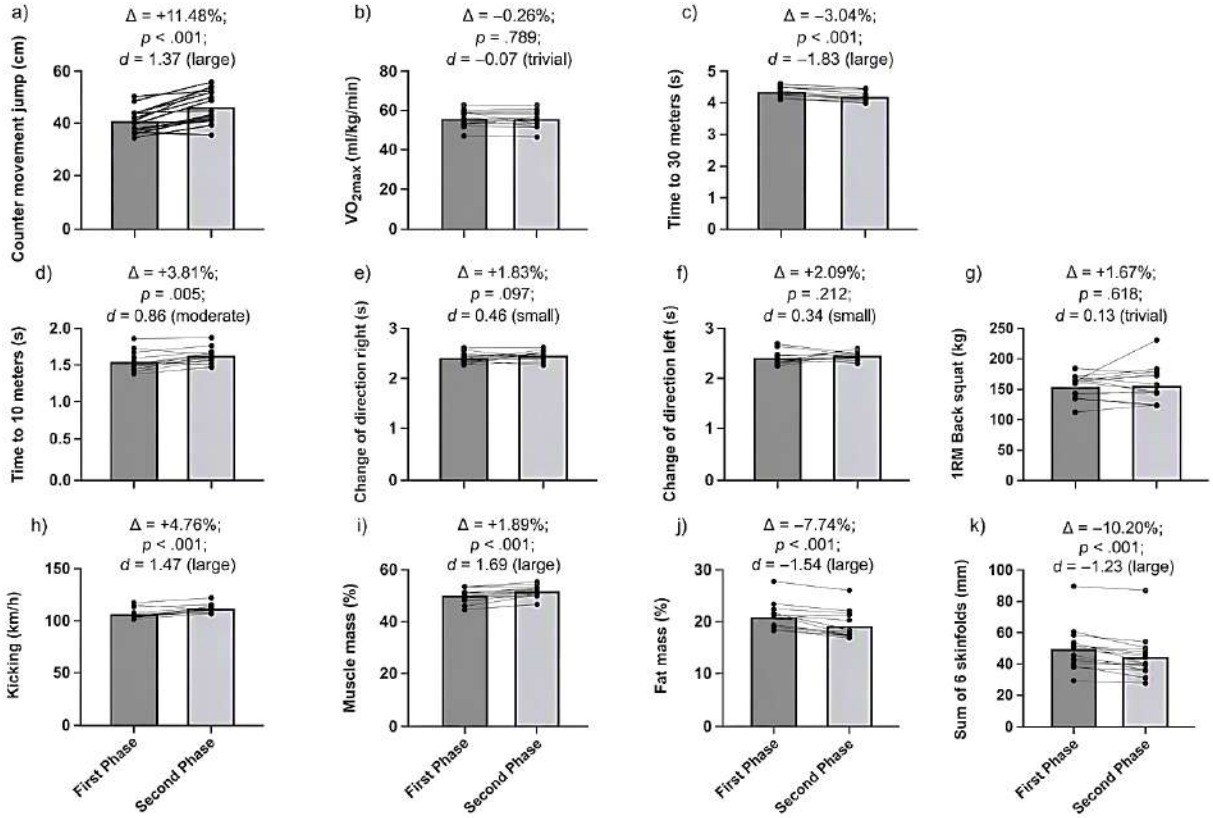
Note. M = mean; SD = standard deviation; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; CI = confidence interval. Cohen's d = standardised effect size for paired samples. Effect-size magnitude was interpreted using the absolute value of Cohen's d: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥2.00).

Table 2 presents the changes in body composition and physical fitness variables between the First Phase and Second Phase in U18 players. Significant improvements were observed in %MM, CMJ, KV, and T30, together with significant reductions in %FM and 6skf (all $p < .05$), with moderate-to-large effect sizes. However, T10 and COD Right increased significantly, indicating a decline in acceleration and change-of-direction performance, respectively. No significant changes were observed in VO_{2max}, COD Left, and 1RM.

Table 2. Changes in body composition and physical fitness in U18 players.

Variable	First phase (M ± SD)	Second phase (M ± SD)	%	*p* value	Cohen's d [95% CI]	Magnitude
MM (%)	50.41 ± 1.74	51.3 ± 1.61	1.89	.014	0.754 [0.146, 1.341]	Moderate
FM (%)	20.1 ± 1.39	19.1 ± 1.54	-4.96	.003	−0.959 [−1.585, −0.308]	Moderate
6skf (mm)	40.6 ± 7.42	36.0 ± 6.55	-11.2	<.001	−1.272 [−1.972, −0.546]	Large
CMJ (cm)	38.8 ± 4.41	41.9 ± 4.69	7.90	<.001	1.519 [0.726, 2.285]	Large
VO_{2max} (ml·kg^{-1}·min^{-1})	60.2 ± 3.14	61.2 ± 2.65	1.31	.357	0.255 [−0.282, 0.783]	Small
T30 (s)	4.18 ± 0.13	4.06 ± 0.09	-2.72	<.001	−1.183 [−1.861, −0.480]	Moderate
T10 (s)	1.61 ± 0.04	1.66 ± 0.09	3.17	.010	0.810 [0.191, 1.407]	Moderate
COD right (s)	2.40 ± 0.07	2.47 ± 0.09	2.66	.040	0.950 [0.301, 1.574]	Moderate
COD left (s)	2.49 ± 0.11	2.50 ± 0.10	0.32	.702	0.105 [−0.423, 0.628]	Trivial
1RM (kg)	149 ± 17.1	156 ± 31.0	5.08	.393	0.236 [−0.300, 0.763]	Small
Kicking (km/h)	96.5 ± 7.59	101 ± 6.46	5.32	<.001	1.458 [0.682, 2.208]	Large

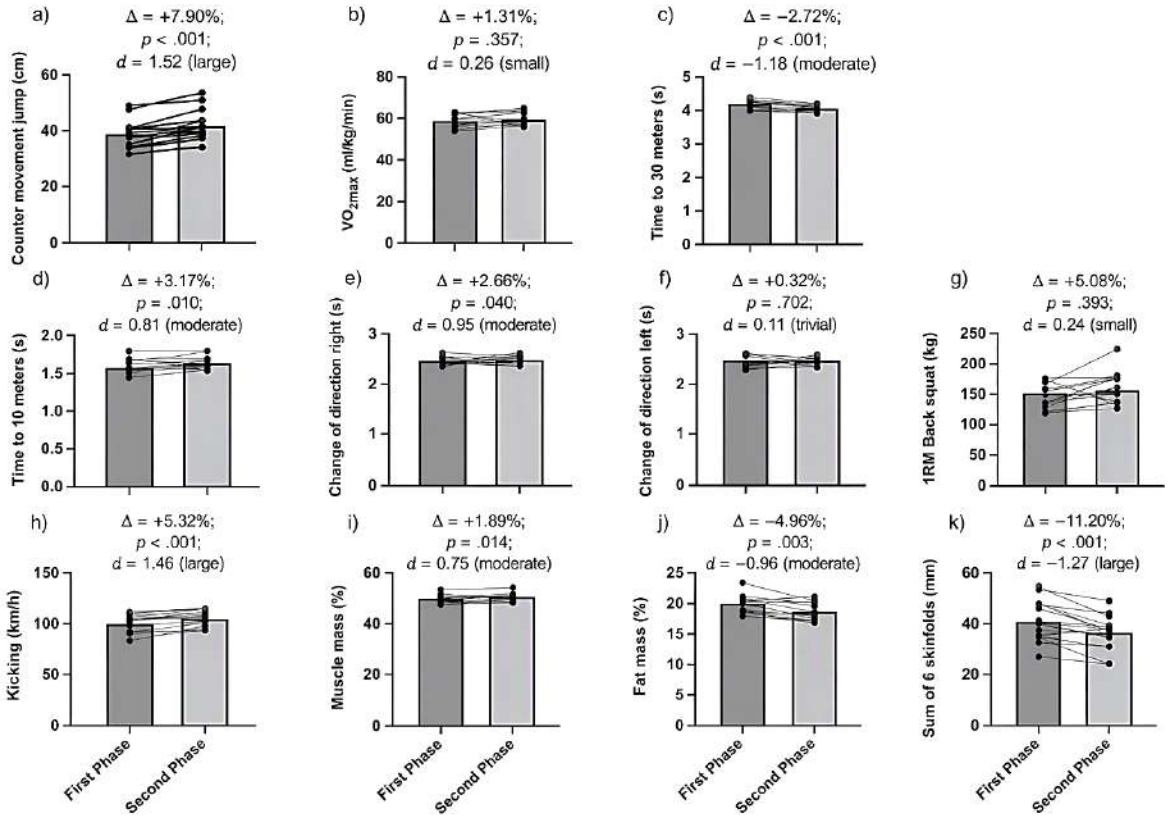
Note. M = mean; SD = standard deviation; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; CI = confidence interval. Cohen's d = standardised effect size for paired samples. Effect-size magnitude was interpreted using the absolute value of Cohen's d: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥2.00).



Note. Bars represent group mean values for the First and Second Phases, while individual data points connected by lines represent each player's paired observations across the two assessment periods. Percentage change (Δ%), p values, and Cohen's d effect sizes with qualitative magnitude are reported for each variable. For time-based tests (T10, T30, and COD), negative percentage changes indicate faster performance, whereas positive changes indicate slower performance. Detailed descriptive statistics and 95% confidence intervals for Cohen's d are presented in Table 1.

Figure 2. Individual within-player seasonal changes in physical fitness and body-composition variables in U21 players.

 © 2026 ARD Asociación Española



Note. Bars represent group mean values for the First and Second Phases, while individual data points connected by lines represent each player's paired observations across the two assessment periods. Percentage change (Δ%), p values, and Cohen's d effect sizes with qualitative magnitude are reported for each variable. For time-based tests (T10, T30, and COD), negative percentage changes indicate faster performance, whereas positive changes indicate slower performance. Detailed descriptive statistics and 95% confidence intervals for Cohen's d are presented in Table 2.

Figure 3. Individual within-player seasonal changes in physical fitness and body-composition variables in U18 players.

Individual paired trajectories further illustrated the within-player variability underlying the group-level seasonal changes in both categories (Figures 2 and 3). In U21 players, improvements were generally observed in CMJ, T30, kicking velocity, muscle mass, fat mass, and the sum of 6 skinfolds, whereas VO_{2max} and 1RM showed comparatively stable group-level responses and T10 performance declined. A broadly similar pattern was observed in U18 players, although individual variability was evident across several variables, particularly 1RM and change-of-direction performance. These individual trajectories support the interpretation that physical qualities did not follow a uniform seasonal pattern across players or performance domains.

Table 3 presents the correlations between physical fitness, body composition, and external match-load variables in the U21 category. CMJ was positively associated with PS (r = .418, $p < .01$), whereas T30 was negatively correlated with PS (r = −.633, $p < .01$), SPRINT (r = −.358, $p < .05$), and NSPRINT (r = −.346, $p < .05$). No other statistically significant correlations were identified between physical fitness, body composition, and external match-load variables.

Table 3. Correlations between physical fitness, body composition, and external match load variables during official competition in U21 players.

	TD	ACC	DEC	PS	PL	HSR	SPRINT	NSPRINT
CMJ (cm)	-.108	.125	-.093	**.418****	-.256	.058	.158	.176
VO_{2max} (ml·kg^{-1}·min^{-1})	.239	.039	.135	-.293	.226	-.044	-.208	-.191
T30 (s)	.176	-.088	.069	**-.633****	.253	-.006	**-.358***	**-.346***
T10 (s)	.046	-.195	-.064	-.286	-.023	.022	-.121	-.147
COD right (s)	-.263	-.304	-.123	-.239	-.304	-.021	-.057	-.036
COD left (s)	-.182	-.320	-.061	.019	-.309	.220	.084	.067
1RM (kg)	-.136	.154	.022	.145	.070	.235	.032	.030
Kicking (km/h)	-.081	-.541	-.475	-.150	-.22	.351	-.187	-.150
%MM	.288	.066	.033	.142	.345	-.061	.038	.020
%FM	-.270	-.222	-.209	-.149	-.362	.238	-.134	-.106
6skf (mm)	-.164	-.225	-.230	-.325	-.170	.316	-.353	-.325

*Note. CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; TD = total distance; ACC = accelerations; DEC = decelerations; PS = peak speed; PL = player load; HSR = high-speed running; SPRINT = sprint distance; NSPRINT = number of sprints. **p < .01; *p < .05 (two-tailed).*

Table 4 presents the correlations between physical fitness, body composition, and external match-load variables during official competition in U18 players. CMJ was negatively associated with PL (r = −.536, p < .01) and positively associated with SPRINT (r = .406, p < .05) and NSPRINT (r = .454, p < .05). VO_{2max} was positively associated with TD (r = .528, p < .01). T30 was positively associated with PL (r = .398, p < .05) and negatively associated with SPRINT (r = −.396, p < .05) and NSPRINT (r = −.405, p < .05). In addition, 1RM was positively associated with PS (r = .477, p < .05), whereas kicking velocity was negatively associated with PS (r = −.468, p < .05). Finally, 6skf was negatively associated with PS (r = −.454, p < .05), SPRINT (r = −.514, p < .01), and NSPRINT (r = −.500, p < .01). No other statistically significant associations were identified.

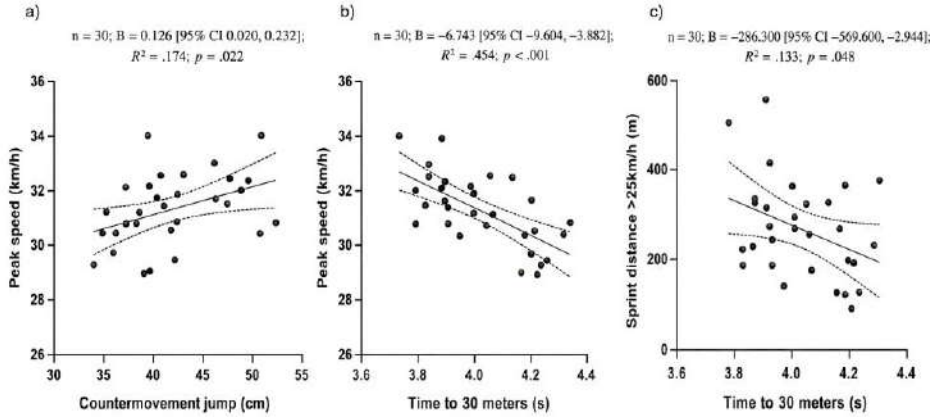
Table 4. Correlations between physical fitness, body composition, and external match load variables during official competition in U18 players.

	TD (m)	ACC	DEC	PS	PL	HSR	SPRINT	NSPRINT
CMJ (cm)	-.278	-.088	-.011	.312	**-.536****	-.017	**.406***	**.454***
VO_{2max} (ml·kg^{-1}·min^{-1})	**.528****	.134	.228	.193	.266	.262	-.042	-.066
T30 (s)	.165	.196	.088	-.348	**.398***	.116	**-.396***	**-.405***
T10 (s)	.297	.096	.209	-.215	.110	-.359	-.061	-.056
COD right (s)	.160	.295	.263	.063	.010	-.302	.323	.338
COD left (s)	.048	.337	.364	.123	.091	.054	.214	.302
1RM (kg)	-.116	.037	-.172	**.477***	-.258	-.123	.241	.278
Kicking (km/h)	.120	-.057	-.366	**-.468***	-.289	-.276	-.278	-.294
%MM	-.058	-.040	.023	.125	-.186	-.082	.311	.265
%FM	.016	-.060	-.242	-.261	-.015	.050	-.326	-.340
6SKF (mm)	.104	-.374	-.335	**-.454***	.063	-.025	**-.514****	**-.500****

*Note. Abbreviations: CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; TD = total distance; ACC = accelerations; DEC = decelerations; PS = peak speed; PL = player load; HSR = high-speed running; SPRINT = sprint distance; NSPRINT = number of sprints. **p < .01; *p < .05 (two-tailed).*

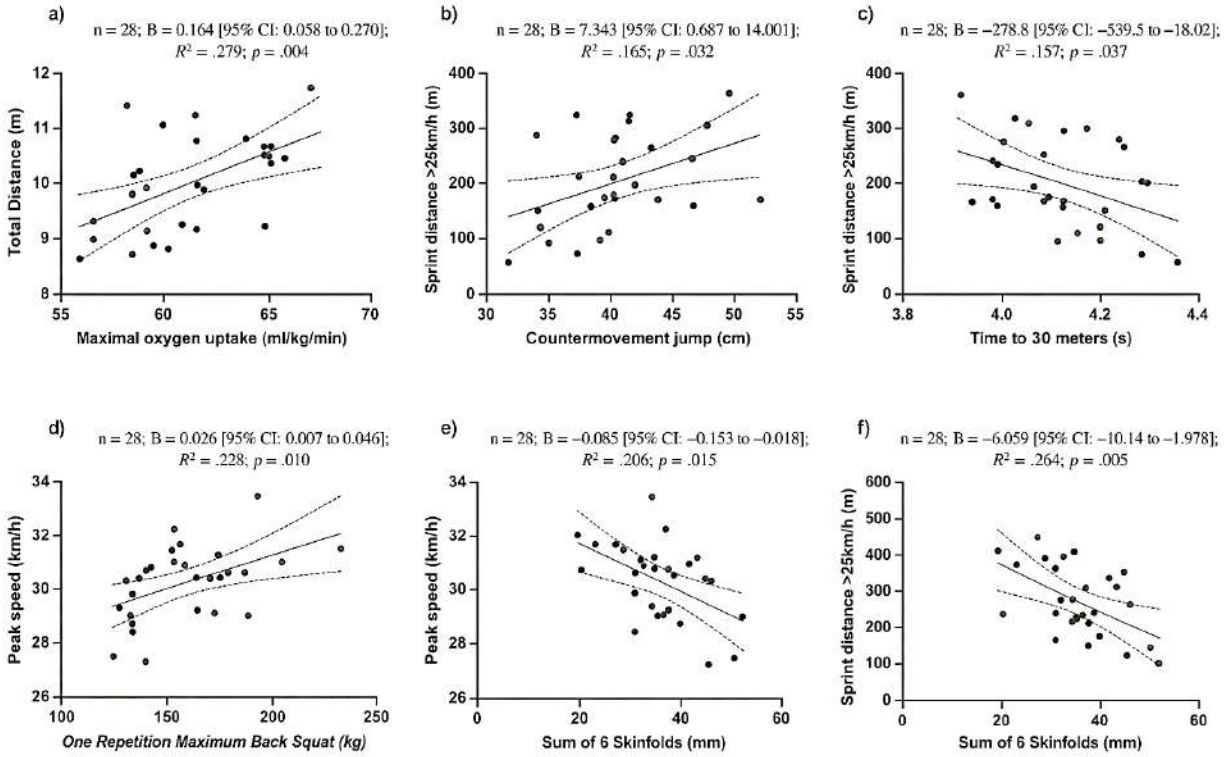
Figures 4 and 5 present scatterplots of the significant associations explored using simple linear regression analyses in U21 and U18 players, respectively.

 © 2026 ARD Asociación Española



Note. (a) Countermovement jump with peak speed; (b) time to 30 meters with peak speed; and (c) time to 30 meters with sprint distance. Solid lines represent the fitted linear regression, while dashed lines represent the 95% confidence intervals. Each panel reports the number of player-phase observations (n), the unstandardized regression coefficient (B) with its 95% confidence interval (95% CI), the coefficient of determination (R^2), and the exact p value.

Figure 4. Significant simple linear regressions between physical fitness and external match-load variables in U21 football players.



Note. (a) Maximal oxygen uptake with total distance; (b) countermovement jump with sprint distance; (c) time to 30 meters with sprint distance; (d) one-repetition maximum back squat with peak speed; (e) sum of 6 skinfolds with peak speed; and (f) sum of 6 skinfolds with sprint distance. Solid lines represent the fitted linear regression, while dashed lines represent the 95% confidence intervals. Each panel reports the number of player-phase observations (n), the unstandardized regression coefficient (B) with its 95% confidence interval (95% CI), the coefficient of determination (R^2), and the exact p value.

Figure 5. Significant simple linear regressions between physical fitness, body composition, and external match-load variables in U18 football players.

To provide an integrated overview of the observed relationships, Table 5 summarizes the exploratory coupling patterns between physical-profile domains and external match-load expression across U18 and U21 players.

Table 5. Integrative summary of exploratory coupling patterns between physical-profile domains and external match-load expression in U18 and U21 players.

Physical-profile domain	Representative measure	U18 external match-load expression	U21 external match-load expression	Integrated interpretation
Aerobic fitness	VO_{2max}	↑ Total distance	No significant associations	Aerobic fitness showed a specific association with locomotor volume in U18 players.
Neuromuscular performance	CMJ	↑ Sprint exposure	↑ Peak speed	Neuromuscular performance was associated with high-intensity match expression, although the specific external-load outcome differed by age category.
Speed performance	T30	↑ Sprint exposure	↑ Peak speed and sprint exposure	Sprint performance showed the most consistent coupling with speed-related match demands across both categories.
Maximal strength	1RM back squat	↑ Peak speed	No significant associations	Maximal strength showed a category-specific association with peak-speed expression in U18 players.
Adiposity	Sum of 6 skinfolds	↓ Peak speed and sprint exposure	No significant associations	Greater adiposity was negatively associated with high-intensity match expression in U18 players.

Note. ↑ and ↓ indicate the direction of statistically significant associations. The table provides an integrative summary of representative exploratory associations rather than evidence of causal, predictive, or statistically confirmed between-category differences. Playing position, biological maturation, and match context should be considered potential moderators requiring further investigation.

DISCUSSION

The aim of the present study was to examine seasonal changes in body composition and physical fitness, as well as to explore the relationships between these variables and external match load during official competition in U18 and U21 football players. The main findings indicate that both categories demonstrated significant improvements in neuromuscular performance and body composition variables between the First Phase and the Second Phase. Furthermore, exploratory analyses revealed age-category-specific patterns in the coupling between physical profiles and external match-load expression, with a greater number of nominally significant associations observed in U18 players. These findings reinforce the need for integrated monitoring approaches in youth football, where the interaction between physical, anthropometric, and contextual factors contributes to competitive performance (Villaseca-Vicuña, Molina-Sotomayor, et al., 2021; Villaseca-Vicuña, Otero-Saborido, et al., 2021).

When considered collectively, the longitudinal findings indicate that the assessed physical qualities did not follow a uniform trajectory across the observation period. In both U18 and U21 players, improvements in body-composition indicators, CMJ, T30, and kicking velocity occurred alongside relatively stable aerobic fitness and maximal strength, whereas T10 performance declined. This pattern highlights the specificity of seasonal changes across different physical domains during the later stages of academy development, rather

 © 2026 ARD Asociación Española

than a homogeneous improvement in overall physical fitness. Such differentiated trajectories are consistent with the multidimensional nature of youth physical development, in which neuromuscular, speed, strength, aerobic, and body-composition characteristics may evolve differently according to biological development and accumulated training and competitive exposure (Lloyd et al., 2015; Moran et al., 2018). Importantly, although the typical weekly microcycle and competition density were documented in the present study, the specific internal and external training dose received by each player was not quantified. Therefore, the observed changes should be interpreted as seasonal trajectories rather than adaptations attributable to particular training stimuli.

In the U21 category, significant improvements were observed in body composition and neuromuscular performance, including increases in %MM (+1.89%; $p < .001$; ES = 1.685), reductions in %FM (-7.74%; $p < .001$; ES = 1.543) and 6skf (-10.2%; $p < .001$; ES = 1.227), alongside improvements in CMJ (+11.48%; $p < .001$; ES = 1.367) and T30 (-3.04%; $p < .001$; ES = 1.826). These findings are consistent with previous studies reporting positive adaptations throughout the competitive season in highly trained youth football players, particularly in neuromuscular capacities and body composition (Clemente et al., 2020). However, given the observational design of the present study, these changes cannot be attributed exclusively to the training programme and may reflect the combined influence of training exposure, competitive participation, biological development, and other contextual factors. Therefore, the absence of significant changes in VO_{2max} ($p = .789$) may suggest a ceiling effect or stabilisation of aerobic fitness during the competitive season, which has previously been reported in environments where training is predominantly focused on tactical and competitive demands (Malone et al., 2017). Moreover, the decline in T10 (+3.81%; $p = .005$) indicates a reduction in short-distance acceleration performance across the competitive season. Potential explanations may include differences in acceleration-specific training exposure, competitive demands, or other contextual factors; however, these mechanisms were not directly assessed in the present study and should therefore be considered hypothetical (Gualtieri et al., 2023).

A similar pattern was observed in the U18 category, with significant increases in %MM (+1.89%; $p = .014$), reductions in %FM (-4.96%; $p = .003$) and 6skf (-11.2%; $p < .001$), together with improvements in CMJ, T30, and KV. However, T10 and COD Right showed significant declines, indicating reduced acceleration and change-of-direction performance. These findings are in agreement with the literature identifying adolescence as a critical period for the development of physical capacities, influenced by the interaction between biological maturation and training exposure (Lloyd et al., 2015; Moran et al., 2018). Nevertheless, the deterioration in COD Right (+2.66%; $p = .040$) indicates a reduction in right-sided change-of-direction performance across the competitive season. Although factors such as accumulated fatigue, training exposure, or sport-specific stimulus could potentially contribute to this pattern, these mechanisms were not directly assessed and should therefore be considered hypothetical. Previous studies have highlighted that COD depends not only on strength but also on technical, coordinative, and neuromuscular control factors, which may not develop optimally without targeted training interventions (Dos'Santos et al., 2018).

In the U21 category, the correlational analysis revealed that neuromuscular and speed-related variables were the principal physical characteristics associated with external match load. CMJ was positively related to PS ($r = .418$; $p < .01$), whereas T30 was negatively associated with PS ($r = -.633$; $p < .01$), SPRINT ($r = -.358$; $p < .05$), and NSPRINT ($r = -.346$; $p < .05$). These findings suggest that greater lower-limb neuromuscular performance and faster 30-m sprint performance may be associated with the ability to reach higher peak speeds and accumulate greater sprint-related demands during competition, supporting previous evidence highlighting the relevance of power and sprint capacity in football (Djaoui et al., 2017). In contrast, VO_{2max} and body composition variables were not significantly associated with the external match-load variables

examined in U21 players. Therefore, within this category, the observed relationships were primarily concentrated in neuromuscular and sprint-related performance characteristics.

Exploratory correlation analyses revealed a greater number of nominally significant associations in the U18 category; however, given the number of bivariate comparisons performed, these findings should be interpreted cautiously and considered hypothesis-generating. Notably, CMJ was positively associated with SPRINT and NSPRINT and negatively associated with PL, while VO_{2max} was positively associated with TD. T30 was positively associated with PL and negatively associated with SPRINT and NSPRINT, whereas 1RM was positively associated with PS. The greater number of associations observed in U18 players should be interpreted as an exploratory pattern rather than evidence that physical capacities exert a stronger influence on competitive performance in younger players. As no formal between-category comparison of correlation coefficients or regression slopes was performed, differences in the number of significant associations cannot establish developmental differentiation between U18 and U21 players. Furthermore, 6skf was negatively associated with selected high-intensity external match-load variables, including PS, SPRINT, and NSPRINT, supporting the potential relevance of adiposity-related characteristics to high-intensity match-load expression (Rios-Limas et al., 2025). The greater number of associations observed in U18 players may reflect differences in physical variability, sample characteristics, or developmental heterogeneity; however, these potential explanations remain speculative and require confirmation through formal between-category analyses (Moran et al., 2018).

When the associations are considered within an integrated monitoring framework (Table 5), distinct exploratory coupling patterns emerge between physical-profile domains and external match-load expression across the two age categories. Speed-related and neuromuscular qualities showed the most consistent relationships with high-intensity match demands across both groups, supporting the relevance of sprint and neuromuscular capacities within the multidimensional physical demands of football (Clemente et al., 2019; Villaseca-Vicuña, Molina-Sotomayor, et al., 2021). In U18 players, this pattern extended to additional physical domains, with aerobic fitness associated with total locomotor volume, maximal strength with peak-speed expression, and greater adiposity with lower peak-speed and sprint exposure. These findings are consistent with the multidimensional nature of physical development during adolescence, where training exposure and biological maturation interact with the development and expression of different physical capacities (Lloyd et al., 2015; Moran et al., 2018). In contrast, significant associations in U21 players were concentrated primarily within neuromuscular and speed-related domains. Importantly, these patterns should not be interpreted as evidence of stronger physical determinants in U18 players or reduced physical relevance in U21 players, because between-category differences in association strength were not formally tested. Rather, they provide preliminary evidence that the coupling between physical profiles and external match-load expression may be age-category specific. Playing position, biological maturation, and match context may further influence these relationships and should therefore be incorporated into future multilevel and multi-club investigations (Lloyd et al., 2015; Villaseca-Vicuña, Otero-Saborido, et al., 2021). The present findings also extend the geographical context of the available academy-football literature by providing longitudinal and match-derived evidence from a South American professional academy. While several of the observed patterns are broadly consistent with previous research from European youth-development environments, the present results should be interpreted within the specific training, competitive, and developmental context of this academy. Accordingly, the potentially transferable principle is not the magnitude of the individual changes or associations observed in this cohort, but rather the value of integrating longitudinal physical profiling with match-derived external-load monitoring to characterize player development. Whether the specific seasonal trajectories and physical–match-load coupling patterns observed here generalize across academy systems requires further investigation.

 © 2026 ARD Asociación Española

Limitations

First, the observational design precludes the establishment of causal relationships. Second, the sample was drawn from a single South American professional football academy; therefore, the observed seasonal trajectories and physical–match-load associations should be considered context-specific rather than representative of youth football more broadly. Multi-club studies across different academy and geographical contexts are required to examine the transferability of these findings, incorporating biological maturation, playing position, and relevant match-context variables as potential sources of variation. Furthermore, biological maturation status was not assessed, despite being a key determinant of physical development and performance in youth football players (Lloyd et al., 2015). Additionally, although the association analyses were based on phase-specific rather than individual match observations, each player contributed data from two competitive phases. Therefore, the potential within-player dependency of these repeated seasonal observations should be considered when interpreting the correlational findings. Future studies with larger samples should examine these relationships using multilevel approaches. Furthermore, the exploratory association analyses involved multiple bivariate comparisons without formal adjustment for multiplicity, which may increase the probability of type I error. Therefore, particularly small-to-moderate associations close to the conventional significance threshold should be interpreted cautiously and considered hypothesis-generating. Future studies with larger samples should confirm these relationships using prespecified hypotheses and appropriate multiplicity-control procedures. In addition, the association and simple regression analyses performed in the present study were not designed to establish predictive validity or identify performance thresholds. Future studies with larger samples should develop cross-validated multivariable models to determine whether physical-fitness and body-composition markers provide incremental predictive value for external match-load outcomes beyond age category, playing position, playing time, and contextual match variables. Although the typical weekly microcycle structure and competition density were documented, individual session-level internal and external training loads were not quantified within the present analysis. Therefore, the observed seasonal changes cannot be attributed to specific training stimuli or training-load characteristics. Future studies should quantify individual accumulated training and competition exposure to determine how specific loading patterns may contribute to the distinct seasonal trajectories observed across physical qualities. Finally, contextual variables such as playing position, quality of opposition, and match location were not controlled, despite their recognised influence on external match load (Villaseca-Vicuña, Merino-Muñoz, et al., 2026).

The findings highlight the importance of integrating body composition, physical fitness, and external load monitoring within youth football development programmes. Variables related to countermovement jump and sprint performance showed associations with selected high-intensity external match-load outcomes, suggesting that these assessments may serve as potentially informative monitoring markers when interpreted alongside match-derived external-load data. However, these associations should not be interpreted as evidence of predictive validity, and the present findings do not establish performance thresholds or demonstrate that these tests independently predict competitive match demands. Likewise, maintaining optimal body composition appears fundamental for maximising physical fitness during competition. The exploratory pattern of associations observed across U18 and U21 players highlights the potential value of considering competitive category when interpreting the relationships between physical characteristics and external match load, although formal between-category comparisons are required before developmental differences can be established. Consequently, integrated monitoring systems are recommended to facilitate individualised training prescription and optimise player development in the short, medium, and long term (Lloyd et al., 2015).

CONCLUSION

In conclusion, this study provides context-specific evidence from a South American professional football academy regarding seasonal changes in physical fitness and body composition and their associations with external match-load expression in U18 and U21 players. The findings indicate that different physical qualities followed distinct seasonal trajectories and showed exploratory age-category-specific coupling patterns with competitive external-load outcomes. Rather than representing predictive indicators of competitive performance, the observed associations support the potential value of selected physical assessments as informative monitoring markers when interpreted alongside match-derived external-load data. Overall, integrating longitudinal physical profiling with competition monitoring may provide a useful framework for supporting player development during the later stages of academy football. However, the magnitude and specific patterns observed in this cohort should not be generalised to youth football more broadly, and multi-club replication across different geographical and developmental contexts is required.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualization: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz, Jorge Pérez-Contreras. Methodology: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz, Jorge Pérez-Contreras, Guillermo Cortés-Roco. Formal analysis: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz. Investigation: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz, Guillermo Cortés-Roco, Marcelo Muñoz. Data curation: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz. Writing – original draft: Rodrigo Villaseca-Vicuña. Writing – review & editing: Pablo Merino-Muñoz, Rodrigo Yáñez-Sepúlveda, Guillermo Cortés-Roco, Marcelo Muñoz, Jorge Pérez-Contreras. Supervision: Jorge Pérez-Contreras.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

 © 2026 ARD Asociación Española

REFERENCES

Bangsbo, J., Mohr, M., & Krustrup, P. (2006). Physical and metabolic demands of training and match-play in the elite football player. *Journal of Sports Sciences, 24*(7), 665–674. https://doi.org/10.1080/02640410500482529

Buchheit, M., & Mendez-Villanueva, A. (2013). Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: Effect of age and maturation. *Journal of Sports Sciences, 31*(12), 1332–1343. https://doi.org/10.1080/02640414.2013.781662

Clemente, F. M., Nikolaidis, P. T., Rosemann, T., & Knechtle, B. (2019). Dose-response relationship between external load variables, body composition, and fitness variables in professional soccer players. *Frontiers in Physiology, 10*, Article 443. https://doi.org/10.3389/fphys.2019.00443

Clemente, F. M., Silva, R., Castillo, D., Los Arcos, A., Mendes, B., & Afonso, J. (2020). Weekly load variations of distance-based variables in professional soccer players: A full-season study. *International Journal of Environmental Research and Public Health, 17*(9), Article 3300. https://doi.org/10.3390/ijerph17093300

Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. *Sports Medicine, 43*(10), 1025–1042. https://doi.org/10.1007/s40279-013-0069-2

Díez-Fernández, D. M., Rodríguez-Rosell, D., Gazzo, F., Giráldez, J., Villaseca-Vicuña, R., & González-Jurado, J. A. (2022). Can the Supido radar be used for measuring ball speed during soccer kicking? A reliability and concurrent validity study of a new low-cost device. *Sensors, 22*(18), Article 7046. https://doi.org/10.3390/s22187046

Djaoui, L., Chamari, K., Owen, A. L., & Dellal, A. (2017). Maximal sprinting speed of elite soccer players during training and matches. *Journal of Strength and Conditioning Research, 31*(6), 1509–1517. https://doi.org/10.1519/JSC.0000000000001642

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sports Medicine, 48*(10), 2235–2253. https://doi.org/10.1007/s40279-018-0968-3

Ford, P. R., Hodges, N. J., Broadbent, D., O'Connor, D., Scott, D., Datson, N., Andersson, H. A., & Williams, A. M. (2020). The developmental and professional activities of female international soccer players from five high-performing nations. *Journal of Sports Sciences, 38*(11–12), 1432–1440. https://doi.org/10.1080/02640414.2020.1789384

Gualtieri, A., Rampinini, E., Dello Iacono, A., & Beato, M. (2023). High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. *Frontiers in Sports and Active Living, 5*, Article 1116293. https://doi.org/10.3389/fspor.2023.1116293

Kobal, R., Loturco, I., Gil, S., Cal Abad, C. C., Cuniyochi, R., Barroso, R., & Tricoli, V. (2016). Comparison of physical performance among Brazilian elite soccer players of different age-categories. *Journal of Sports Medicine and Physical Fitness, 56*(4), 376–382.

Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Howard, R., De Ste Croix, M. B. A., Williams, C. A., Best, T. M., Alvar, B. A., Micheli, L. J., Thomas, D. P., Hatfield, D. L., Cronin, J. B., & Myer, G. D. (2015). Long-term athletic development: Part 1: A pathway for all youth. *Journal of Strength and Conditioning Research, 29*(5), 1439–1450. https://doi.org/10.1519/JSC.0000000000000756

Malone, J. J., Di Michele, R., Morgans, R., Burgess, D., Morton, J. P., & Drust, B. (2015). Seasonal training-load quantification in elite English Premier League soccer players. *International Journal of Sports Physiology and Performance, 10*(4), 489–497. https://doi.org/10.1123/ijspp.2014-0352

Malone, J. J., Lovell, R., Varley, M. C., & Coutts, A. J. (2017). Unpacking the black box: Applications and considerations for using GPS devices in sport. *International Journal of Sports Physiology and Performance, 12*(Suppl. 2), S2-18–S2-26. https://doi.org/10.1123/ijspp.2016-0236

Moran, J., Parry, D. A., Lewis, I., Collison, J., Rumpf, M. C., & Sandercock, G. R. H. (2018). Maturation-related adaptations in running speed in response to sprint training in youth soccer players. *Journal of Science and Medicine in Sport, 21*(5), 538–542. https://doi.org/10.1016/j.jsams.2017.09.012

Pareja-Blanco, F., Sánchez-Medina, L., Suárez-Arrones, L., & González-Badillo, J. J. (2017). Effects of velocity loss during resistance training on performance in professional soccer players. *International Journal of Sports Physiology and Performance, 12*(4), 512–519. https://doi.org/10.1123/ijspp.2016-0170

Pareja-Blanco, F., Walker, S., & Häkkinen, K. (2020). Validity of using velocity to estimate intensity in resistance exercises in men and women. *International Journal of Sports Medicine, 41*(14), 1047–1055. https://doi.org/10.1055/a-1171-2287

Pérez-Contreras, J., Villaseca-Vicuña, R., Miarka, B., Merino-Muñoz, P., Hermosilla-Palma, F., & Aedo-Muñoz, E. (2024). Intratest reliability of the modified 505 test in adult male professional soccer players. *Journal of Physical Education and Sport, 24*(2), 407–411. https://doi.org/10.7752/jpes.2024.02049

Pérez-Contreras, J., Villaseca-Vicuña, R., Zapata-Huenullán, C., Benavides-Roca, L., Merino-Muñoz, P., & Vidal-Maturana, F. (2022). Condición física de futbolistas adultos y jóvenes de un equipo profesional de Nicaragua. *Revista Ciencias de la Actividad Física, 23*(2), 1–14. https://doi.org/10.29035/rcaf.23.2.4

Rada, A., Kuvačić, G., De Giorgio, A., Sellami, M., Ardigò, L. P., Bragazzi, N. L., & Padulo, J. (2019). The ball kicking speed: A new, efficient performance indicator in youth soccer. *PLOS ONE, 14*(5), Article e0217101. https://doi.org/10.1371/journal.pone.0217101

Rios-Limas, I., Herrera-Amante, C. A., Carvajal-Veitía, W., Yáñez-Sepúlveda, R., Ayala-Guzmán, C. I., Ortiz-Hernández, L., López-Sagarra, A., Lorente-Solá, P., & López-Gil, J. F. (2025). Relating anthropometric profile to countermovement jump performance and external match load in Mexican national team soccer players: An exploratory study. *Sports, 13*(7), Article 236. https://doi.org/10.3390/sports13070236

Romero-Caballero, A., Varela-Olalla, D., & Loëns-Gutiérrez, C. (2021). Fitness evaluation in young and amateur soccer players: Reference values for vertical jump and aerobic fitness in men and women. *Science & Sports, 36*(2), 141.e1–141.e7. https://doi.org/10.1016/j.scispo.2020.04.004

Stevens, T. G. A., de Ruiter, C. J., Twisk, J. W. R., Savelsbergh, G. J. P., & Beek, P. J. (2017). Quantification of in-season training load relative to match load in professional Dutch Eredivisie football players. *Science and Medicine in Football, 1*(2), 117–125. https://doi.org/10.1080/24733938.2017.1282163

Villaseca-Vicuña, R., Barrera-Díaz, J., Otero-Saborido, F., Zabaloy, S., Palorames, E., & Sarmento, H. (2026). Key performance indicators in elite female football: Associations between sprints, duels, and match results. *International Journal of Sports Physiology and Performance, 21*(3), 448–455. https://doi.org/10.1123/ijspp.2025-0408

Villaseca-Vicuña, R., Cursach, J., Medrano, V., Lobos, C., Rojas Moya, C., Faúndez Saavedra, D., Merino Muñoz, P., Cortés-Roco, G., Brooklyn Campbell, B., & Pérez-Contreras, J. (2025). Assessment of weekly workload in relation to match workload in U-21 football: Analysis of ten competition microcycles. *Journal of Physical Education and Sport, 25*(12), 2503–2510. https://doi.org/10.7752/jpes.2025.12277

Villaseca-Vicuña, R., Gayán-Candia, A., Gazzo, F., Giráldez, J., Zabaloy, S., & González-Jurado, J. A. (2024). Comparison of two warm-up protocols for physical and technical-decisional performance in

 © 2026 ARD Asociación Española

young football players. *Physical Activity Review, 12*(1), 1–12. https://doi.org/10.16926/par.2024.12.01

Villaseca-Vicuña, R., Medrano, V., Lobos, C., Rojas Moya, C., Cursach, J., Faúndez Saavedra, D., Merino Muñoz, P., Cortés-Roco, G., Brooklyn Campbell, B., & Pérez-Contreras, J. (2025). Comparison of physical fitness and body composition by age categories in young professional football players in Chile. *Retos, 72*, 445–457. https://doi.org/10.47197/retos.v72.116780

Villaseca-Vicuña, R., Merino-Muñoz, P., Cortés-Roco, G., Escobar, N., Lara, M. M., Sepúlveda, R. Y., Barrera-Díaz, J., & Pérez-Contreras, J. (2026). Differences in physical performance according to contextual variables in U21 football players. *Physiologia, 6*(1), Article 8. https://doi.org/10.3390/physiologia6010008

Villaseca-Vicuña, R., Molina-Sotomayor, E., Zabaloy, S., & González-Jurado, J. A. (2021). Anthropometric profile and physical fitness performance comparison by game position in the Chile women's senior national football team. *Applied Sciences, 11*(5), Article 2004. https://doi.org/10.3390/app11052004

Villaseca-Vicuña, R., Otero-Saborido, F. M., Pérez-Contreras, J., & González-Jurado, J. A. (2021). Relationship between physical fitness and match performance parameters of Chile women's national football team. *International Journal of Environmental Research and Public Health, 18*(16), Article 8412. https://doi.org/10.3390/ijerph18168412

Winter, E. M., & Maughan, R. J. (2009). Requirements for ethics approvals. *Journal of Sports Sciences, 27*(10), 985. https://doi.org/10.1080/02640410903178344

World Medical Association. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *JAMA, 310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Physical activity as a predictor of cardiorespiratory fitness in medical students in Lima, Peru

Pedro Juan Cazorla Salinas. *Doctoral Program in Nutrition and Food. School of Medicine. Faculty of Health Sciences. San Ignacio de Loyola University. Lima, Peru.*

Carlos Eduardo Alvarado Ortiz Ureta†. *Doctoral Program in Nutrition and Food. San Ignacio de Loyola University. Lima, Peru.*
† Deceased author.

María Mercedes Saravia Bartra. *School of Medicine. Faculty of Health Sciences. San Ignacio de Loyola University. Lima, Peru.*

Felipe León Ignacio Cconchoy . *School of Medicine. Faculty of Health Sciences. San Ignacio de Loyola University. Lima, Peru. Internal Medicine Service. Alberto Sabogal Sologuren National Hospital. Lima, Peru.*

Vicente Aleixandre Benites Zapata. *Research Unit for the Generation and Synthesis of Health Evidence. Vice- Rectorate for Research. San Ignacio de Loyola University. Lima, Peru.*

Wilver Omero Rodriguez López. *School of Medicine. Faculty of Health Sciences. San Ignacio de Loyola University. Lima, Peru.*

Patrick Sebastian Cazorla Saravia. *Department of Sport, Health and Exercise Sciences. College of Health, Medicine and Life Sciences. Brunel University of London. Uxbridge, United Kingdom.*

ABSTRACT

Background: Cardiorespiratory fitness (CRF) is a key indicator of cardiovascular health, particularly in young populations such as medical students, who face high academic stress and sedentary lifestyles. This study aimed to evaluate the association between physical activity (PA) and CRF among medical students in Lima, Peru. Methods: A cross-sectional study was conducted with 92 medical students (57 women and 35 men). PA was assessed using the International Physical Activity Questionnaire, and CRF was measured using the Bruce protocol. Logistic regression analyses (crude and adjusted) were performed to assess the association between PA and CRF, adjusting for sex, age group, and body mass index (BMI). Results: A total of 78.3% of participants exhibited reduced CRF. Low and moderate PA levels were observed in 33.7% and 39.1% of students, respectively. Low PA was significantly associated with reduced CRF in both crude (OR = 12.69; 95% CI: 2.19–73.42; p = .005) and adjusted analyses (aOR = 9.66 (95% CI: 1.70–54.91; p = .011)). Moderate PA was also associated with reduced CRF in the adjusted model (aOR = 2.77 (95% CI: 0.77–9.95; p = .118)). Female sex was associated with a higher likelihood of reduced CRF in the adjusted model (aOR = 6.06 (95% CI: 1.81–20.33; p = .004)). Conclusions: Physical activity is associated with cardiorespiratory fitness in medical students, although the cross-sectional design and wide confidence intervals preclude strong causal interpretation.

Keywords: sport medicine; exercise; physical fitness; exercise test; sedentary behaviour; young adult.

Cite this article as:
Cazorla Salinas, P. J, Alvarado Ortiz Ureta, C. E., Saravia Bartra, M. M., Ignacio Cconchoy, F. L., Benites Zapata, V. A., Rodriguez López, W. O., & Cazorla Saravia, P. S. (2026). Physical activity as a predictor of cardiorespiratory fitness in medical students in Lima, Peru. *Journal of Human Sport and Exercise, 21*(4), 1622-1634. https://doi.org/10.55860/zxs6y849

Corresponding author. *School of Medicine. Faculty of Health Sciences. San Ignacio de Loyola University. Lima, Peru.*
E-mail: ignaciocc1105@gmail.com

Submitted for publication April 27, 2026.
Accepted for publication September 01, 2026.
Published September 30, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/zxs6y849

© 2026 ARD Asociación Española

INTRODUCTION

Cardiorespiratory fitness (CRF) is a key indicator of cardiovascular health, defined as the body's capacity to transport and utilize oxygen during sustained exercise. It is a stronger predictor of mortality than traditional risk factors such as smoking, hypertension, and diabetes mellitus (Myers et al., 2002; Kaminsky et al., 2013), leading the American Heart Association to propose CRF as a clinical vital sign (Ross et al., 2016).

Over the past six decades, CRF has declined globally (Tomkinson et al., 2019), with only 40% of young Americans achieving healthy levels (Raghuveer et al., 2020). Low CRF is associated with a two- to three-fold higher risk of premature cardiovascular death (Franklin & Jae, 2024), and each 1-MET increase in CRF reduces all-cause mortality by approximately 13% (Kodama et al., 2009). In young populations, CRF is also linked to cardiometabolic health, academic performance, and mental well-being (Lubans et al., 2016).

Medical students are particularly vulnerable to adopting sedentary and unhealthy lifestyles during their training, with increased academic stress, poor dietary habits, and reduced physical activity (PA) (Fan et al., 2020; Bhatti et al., 2020). These factors contribute to a decline in CRF, which is concerning given that both low PA and reduced CRF are associated with higher cardiovascular morbidity and mortality (DeFina et al., 2015; Lee et al., 2012). In Latin America, the prevalence of low CRF is growing, especially among adolescents (Prieto-Benavides et al., 2019), yet evidence on the PA–CRF relationship in medical students from this region remains scarce. No previous study has examined this association in Peru.

Promoting sustained healthy behaviours during medical training may help reduce future cardiovascular and cerebrovascular risk, particularly in contexts where sedentary habits begin early and persist into adulthood (Zyriax & Windler, 2023).

This cross-sectional study aimed to evaluate whether PA levels are associated with CRF in medical students at a university in Lima, Peru, after adjusting for sex, age group, and body mass index.

METHODS

Participants

An observational cross-sectional study was conducted between July and September 2023. A total of 92 second and third year medical students from the Faculty of Health Sciences at San Ignacio de Loyola University, Lima, Peru (mean age: 19.31 ± 3.04 years; 62% female), were recruited through convenience sampling and voluntarily participated. All second- and third-year medical students enrolled at the institution during the study period were invited to participate, and those who met the eligibility criteria and agreed to participate were included in the final sample. For descriptive and adjustment purposes, age was additionally categorized into two groups (16–19 and ≥20 years).

Prior to the start of the study, participants were informed about the objectives of the research and invited to participate voluntarily by signing an informed consent form. Inclusion criteria were: second and third year medical students of both sexes, aged 16 and 35 years, without documented medical conditions that would contraindicate an exercise stress test.

Participants with pre-existing medical conditions or any disability that would prevent maximal effort, as well as those who did not complete the questionnaire, the cardiorespiratory fitness test, or the exercise data records, were excluded. Anonymity was ensured, and participation had no influence on academic performance.

Measurements

Physical activity (PA)

Physical activity (PA) was assessed using the short version of the International Physical Activity Questionnaire (IPAQ) (Mantilla Toloza & Gómez-Conesa, 2007), administered virtually via Google Forms. This instrument consists of seven questions that evaluate the frequency, duration, and intensity of activities performed over the past seven days, including walking time and sedentary time. PA was classified into low, moderate, and high levels. The IPAQ short form has demonstrated moderate-to-good test–retest reliability, with Spearman's ρ values clustering around .8 across countries, and acceptable criterion validity against accelerometry, with median correlations of approximately ρ ≈ .30 (Craig et al., 2003).

Body mass index (BMI)

Weight (kg) and height (meters) were measured using a scale and a stadiometer by trained personnel at an authorized clinic. Measurements were taken twice, and if differences exceeded 5%, a third measurement was conducted. The average of the two closest measurements was used.

The BMI was calculated using the formula weight (kg) / height (m)² and classified according to World Health Organization (WHO) criteria as normal weight (18.5–24.9 kg/m²), overweight (25–29.9 kg/m²), and obesity (≥30 kg/m²) (World Health Organization, 2000). For analysis, elevated BMI was defined as overweight or obesity.

Cardiorespiratory Fitness (CRF)

CRF was assessed using the Bruce treadmill protocol, which consists of three-minute stages with progressive increases in speed and incline. The test started at 2.7 km/h with a 10% incline and continued until one of the predefined termination criteria was met.

Maximum speed achieved, total distance covered, and total test duration were recorded. To estimate maximal oxygen uptake (VO_{2max}), we used the equations derived by Foster et al. (1984) and Pollock et al. (1982) for the Bruce treadmill protocol:

- For men: VO_{2max} (mL/kg/min) = 14.76 – (1.379 × T) + (0.451 × T²) – (0.012 × T³)
- For women: VO_{2max} (mL/kg/min) = 4.38 × T - 3.9

where T is the total test time in minutes.

All participants were encouraged to exert maximal effort. Test termination criteria included: (a) reaching ≥85% of age-predicted maximum heart rate (220 – age), (b) a rating of perceived exertion (RPE) ≥17 on the Borg 6–20 scale, or (c) voluntary exhaustion. No adverse events occurred.

Functional capacity was evaluated based on metabolic equivalents (METs). For descriptive purposes, we categorized fitness as <5 METs (poor), 5–8 METs (average), 9–11 METs (good), and ≥12 METs (excellent), using commonly reported Bruce protocol norms.

For the purposes of this study, reduced cardiorespiratory fitness was operationally defined as achieving <8 METs on the Bruce treadmill protocol. This pragmatic threshold was informed by the exercise-capacity strata reported by Myers et al. (2002), who demonstrated progressively higher mortality risk at lower exercise capacities (<5 and 5–8 METs) compared with individuals achieving >8 METs. Importantly, <8 METs was not established by Myers et al. as a diagnostic threshold for reduced CRF but was adopted in the present study as an operational cutoff. This approach is broadly consistent with evidence summarized by the American

 © 2026 ARD Asociación Española

Heart Association identifying low CRF as an important clinical risk marker (Ross et al., 2016). However, <8 METs is not an established age- or sex-specific diagnostic threshold, and the source evidence was derived from older, clinically referred populations rather than healthy young adults. Given the young and presumably healthy profile of medical students in the present sample, this fixed cutoff should therefore be interpreted as a pragmatic operational definition rather than a validated normative criterion for this age group.

Procedures

Data collection was conducted in a controlled clinical setting under the supervision of a medical professional, with an automated external defibrillator (AED) available on site. To minimize measurement bias, all anthropometric measurements and treadmill assessments were performed by trained personnel using standardized equipment and protocols, and the same IPAQ questionnaire and Bruce protocol procedures were applied uniformly to all participants.

The evaluation process was carried out in a single session per participant. Initially, participants completed the IPAQ questionnaire virtually through the Google Forms platform. Subsequently, anthropometric measurements, including weight and height, were obtained following the procedures previously described. Finally, participants performed the treadmill exercise test using the Bruce protocol, as described in the measures section.

The study was approved by the Research Ethics Committee of San Ignacio de Loyola University (code: 2021004) and was conducted in accordance with the principles of the Declaration of Helsinki. Confidentiality and anonymity of the participants were ensured throughout the entire process.

Statistical analysis

Means and standard deviations were calculated for continuous variables, while frequencies and percentages were used for categorical variables.

Sample size was calculated based on the events per variable (EPV > 10) criterion. Considering an expected prevalence of reduced CRF greater than 80% and four predictor variables, a minimum of 50 participants was required. Ultimately, 92 participants were included to ensure adequate statistical power.

To assess the association between PA and CRF, binary logistic regression was applied. Additionally, multivariable logistic regression was performed adjusting for sex, age group, and BMI. Odds ratios (ORs) with 95% confidence intervals were calculated, and a p-value < .05 was considered statistically significant.

All analyses were conducted using the Statistical Package for the Social Sciences (SPSS), version 25 for Windows.

This study is reported following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement for cross-sectional studies (von Elm et al., 2007). The completed STROBE checklist is provided as Supplementary Table 1 (Appendix 1).

RESULTS

Participant characteristics

A total of 92 medical students participated in the study; 57 (62%) were female and 35 (38%) were male, with a mean age of 19.31 ± 3.04 years. Among all participants, 31 (33.7%) had low levels of physical activity (PA),

36 (39.1%) had moderate PA, 25 (27.2%) had high PA, 72 (78.3%) presented reduced cardiorespiratory fitness (CRF), and 33 (35.9%) had elevated body mass index (BMI) (Table 1). No missing data were recorded for any of the variables of interest, as participants with incomplete questionnaires or exercise test data were excluded prior to analysis (see Participants section). In terms of fitness categories, 20 students (21.7%) achieved <5 METs, 58 (63.0%) achieved 5–8 METs, 8 (8.7%) achieved 9–11 METs, and 6 (6.5%) achieved ≥12 METs.

Table 1. Participant characteristics.

Variable	**N = 92**	**%**
Age (years)	19.31 (±3.04)	
Sex		
Female	57	62.0
Male	35	38.0
Age Group		
≥20 years	29	31.5
16–19 years	63	68.5
BMI (kg/m²)		
Elevated	33	35.9
Normal	59	64.1
Physical activity		
Low	31	33.7
Moderate	36	39.1
High	25	27.2
Cardiorespiratory fitness		
Reduced	72	78.3
Normal	20	21.7

Note. Values for age are presented as mean ± standard deviation. BMI = Body Mass Index.

Table 2. Bivariate analysis of physical activity, sex, age group, BMI and cardiorespiratory fitness.

Variable	**Reduced CRF n = 72**	**Normal CRF n = 20**	**Total n = 92**	**Crude OR**	**95% CI**	***p***
Physical activity						
Low	29 (93.5%)	2 (6.5%)	31	9.67	1.87–49.89	.007
Moderate	28 (77.8%)	8 (22.2%)	36	2.33	0.76–7.16	.139
High	15 (60.0%)	10 (40.0%)	25	Reference		
Sex						
Female	51 (89.5%)	6 (10.5%)	57	5.67	1.92–16.74	.002
Male	21 (60.0%)	14 (40.0%)	35	Reference		
Age group						
≥20 years	24 (82.8%)	5 (17.2%)	29	1.50	0.49–4.62	.480
16–19 years	48 (76.2%)	15 (23.8%)	63	Reference		
BMI (kg/m²)						
Elevated	27 (81.8%)	6 (18.2%)	33	1.40	0.48–4.08	.537
Normal	45 (76.3%)	14 (23.7%)	59	Reference		

Note. CRF: Cardiorespiratory Fitness. BMI: Body Mass Index. OR = Odds Ratio. CI = 95% Confidence Interval.

 © 2026 ARD Asociación Española

Table 3. Multivariable logistic regression for the association between physical activity and cardiorespiratory fitness, adjusted for sex, age group, and body mass index.

Variable	Reduced CRF	Normal CRF	Total	Adjusted OR	95% CI	*p*
Physical activity						
Low	29 (93.5%)	2 (6.5%)	31	9.66	1.70–54.91	.011
Moderate	28 (77.8%)	8 (22.2%)	36	2.77	0.77–9.95	.118
High	15 (60.0%)	10 (40.0%)	25	Reference		
Sex						
Female	51 (89.5%)	6 (10.5%)	57	6.06	1.81–20.33	.004
Male	21 (60.0%)	14 (40.0%)	35	Reference		
Age group						
≥20 years	24 (82.8%)	5 (17.2%)	29	1.82	0.51–6.44	.353
16–19 years	48 (76.2%)	15 (23.8%)	63	Reference		
BMI (kg/m²)						
Elevated	27 (81.8%)	6 (18.2%)	33	2.08	0.55–7.81	.278
Normal	45 (76.3%)	14 (23.7%)	59	Reference		

Note. CRF: Cardiorespiratory Fitness. BMI: Body Mass Index. OR = Odds Ratio. CI = 95% Confidence Interval.

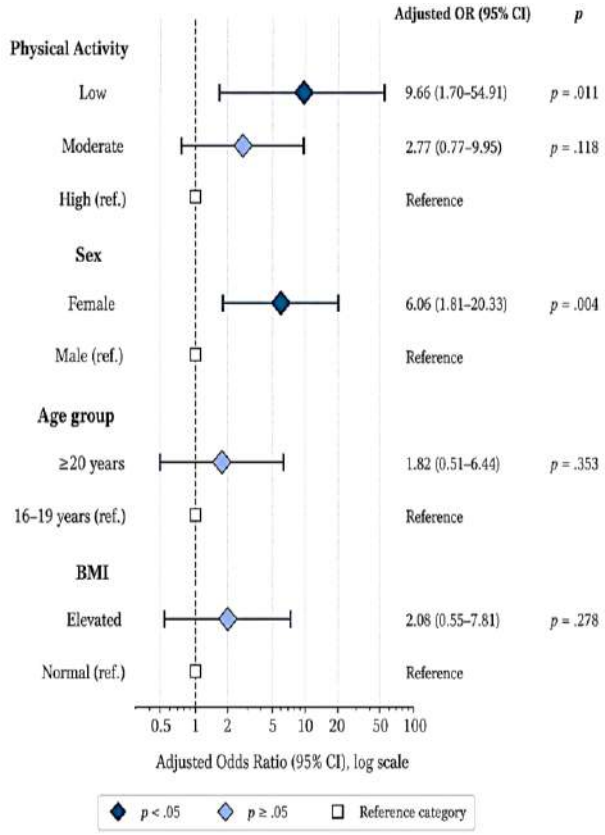


Figure 1. Adjusted odds ratios for reduced cardiorespiratory fitness (multivariable logistic regression, n = 92).

Bivariate and multivariable analysis of physical activity, sex, age group, body mass index, and cardiorespiratory fitness

Bivariate analysis showed that low levels of physical activity, as well as female sex, were significantly associated with a higher likelihood of reduced cardiorespiratory fitness (CRF) (Table 2). Moderate PA was

not significantly associated with reduced CRF in either the crude or adjusted models. The association for low PA remained significant after multivariable adjustment (Table 3), although the wide confidence interval indicates limited precision. No significant associations were found for body mass index (BMI) or age group. Adjusted odds ratios with 95% confidence intervals are summarized graphically in Figure 1.

DISCUSSION

The main finding of this cross-sectional study is a statistically significant association between low self-reported PA and reduced CRF among Peruvian medical students, with an adjusted OR of 9.66 (95% CI: 1.70–54.91). The confidence interval remains wide, reflecting limited precision given the sample size, although substantially narrower than in preliminary analyses following correction of a physical activity classification error identified during data verification. This association should therefore be interpreted with caution. Comparisons with previous studies in other countries (Franklin & Jae, 2024; Tatius et al., 2024) are limited by differences in design, population, and cardiorespiratory fitness assessment methods, including the use of different protocols and prediction equations. Given the small number of participants in the high-activity category and the high prevalence of reduced CRF, the logistic regression estimates are likely unstable. Therefore, the observed effect size should be interpreted as an exploratory signal rather than a precise quantification of the association.

The observed association is biologically plausible. Regular PA induces well-documented cardiovascular adaptations, including improved endothelial function and increased stroke volume (Nystoriak & Bhatnagar, 2018). Conversely, chronic stress, common in medical training, may activate the hypothalamic-pituitary-adrenal axis and potentially counteract some exercise-induced benefits (Hackney, 2006). However, our cross-sectional design cannot establish whether the association is mediated by these pathways. Recent systematic reviews have confirmed the positive association between physical activity and cardiorespiratory fitness in young populations (Peralta et al., 2020).

The practical implications of these findings are particularly relevant for the design of educational and health policies. The curricular integration of physical activity, the improvement of sports infrastructure, and the implementation of active breaks during academic schedules emerge as priority strategies (Kapoor et al., 2022; Zyriax & Windler, 2023). Likewise, regular monitoring of cardiorespiratory fitness using standardized protocols could serve as an early indicator of cardiovascular risk in this population.

Regarding physical activity levels, 33.7% of students were found to have low PA levels, 39.1% moderate PA levels, and 27.2% high PA levels. This finding is consistent with the World Health Organization's Global Action Plan on Physical Activity 2018–2030, which indicates that approximately one in five adults and four in five adolescents worldwide have insufficient levels of physical activity (WHO, 2018). Previous research has identified multiple barriers to PA among university students, including lack of time, academic stress, and limited access to facilities (Ferreira Silva et al., 2022). Although we did not measure barriers directly, these factors may contribute to the low PA levels observed in our sample.

On the other hand, 78.3% of students presented reduced cardiorespiratory fitness. This finding is consistent with studies conducted in different parts of the world. For instance, a systematic review indicates that, over recent decades, CRF has significantly declined among adolescents globally (Fühner et al., 2021). Various factors that may influence CRF in medical students have been identified. These include widely recognized non-modifiable factors, such as age, sex, and race or ethnicity (Howard et al., 2013), as well as modifiable factors, including physical activity, dietary patterns (Júdice et al., 2017), obesity (Mendelson et al., 2016),

 © 2026 ARD Asociación Española

sedentary behavior (Santos et al., 2014), and socioeconomic status (Ombrellaro et al., 2018). In adults, for example, VO_{2max} has been observed to be higher in Caucasians compared to African Americans (Swift et al., 2017). Young individuals with obesity who are less physically active tend to have lower VO_{2max} (mL/kg/min) compared to their normal-weight peers (Pate et al., 2006). These findings suggest that medical students with low levels of physical activity and reduced CRF may have a higher risk of developing cardiometabolic diseases in the future.

In our study, 62% of the evaluated students were female. This distribution reflects a trend observed in our country over recent decades, where a predominance of women in medical careers has been reported. This trend has also been documented globally, with survey analyses by field and country showing a female predominance across all categories (Herreros-Irarrázabal et al., 2024). Our results confirm that female sex is associated with lower CRF, with a 6.06-fold higher likelihood of presenting reduced CRF. This sex difference is well-documented in normative CRF data; for example, sex differences in VO_{2max} of approximately 15–20% persist even when values are normalized for body mass (Ogawa et al., 1992). Our finding of a 6.06-fold higher odds of reduced CRF in women is consistent with these physiological differences. However, because we did not adjust for fat-free mass, we cannot determine whether this association reflects true sex differences in cardiorespiratory capacity or differences in body composition. Residual confounding by unmeasured variables cannot be excluded.

The present study has certain limitations that should be considered when interpreting the results. The assessment of physical activity through self-administered questionnaires, although methodologically valid, introduces potential biases such as social desirability and limitations in recall accuracy. The cross-sectional design does not allow for the establishment of definitive causal relationships between the analyzed variables. Additionally, the use of a sample from a single university limits the generalizability of the findings. The sample is relatively small and drawn from a single private university in Lima; thus, the findings should not be extrapolated directly to all medical students in Peru or other countries, but rather viewed as a context-specific snapshot that requires confirmation in larger, more diverse cohorts. Furthermore, although all eligible students enrolled during the study period were invited to participate, the exact number of students approached and the corresponding response rate were not formally recorded, which precludes a precise assessment of potential non-participation bias. Uncontrolled variables such as sleep patterns and diet, which are known to influence cardiorespiratory capacity, may have affected the results. Finally, the post-pandemic context in which the data were collected may have influenced the physical activity patterns reported by participants.

Another limitation relates to the operational definition of reduced cardiorespiratory fitness (CRF). Although we used a MET-based cutoff (<8 METs) to define reduced CRF—a pragmatic choice informed by the exercise-capacity categories described by Myers et al. (2002) and the AHA's emphasis on CRF as a clinical vital sign (Ross et al., 2016)—we acknowledge that percentile-based norms specific for age and sex (e.g., FRIEND registry; Kaminsky et al., 2015) would provide greater precision. However, the absence of validated percentile tables for Peruvian young adults and the sample size constraints prevented us from applying this approach. We therefore emphasize that our definition of reduced CRF is an operational categorization for this study, not a clinical diagnostic standard.

Additionally, we did not measure several potential confounders, including sleep duration, dietary patterns, stress levels, smoking, alcohol and other substance use, and screen time. These lifestyle factors are known to influence both PA and CRF in young adult populations, and their omission may have resulted in residual confounding.

The use of a self-reported PA questionnaire (IPAQ short version) is susceptible to recall bias and social desirability bias, which typically lead to overestimation of PA levels. This misclassification could have attenuated or inflated the observed associations.

CONCLUSION

In this cross-sectional study of medical students in Lima, Peru, low self-reported physical activity was associated with higher odds of reduced cardiorespiratory fitness. Female sex was also independently associated with markedly higher odds of reduced CRF, a secondary finding that warrants further investigation given its precision relative to the primary exposure. However, the wide confidence intervals and the observational design preclude strong causal inferences and precise effect estimation. Residual confounding by unmeasured lifestyle factors (e.g., sleep, diet, stress) and the use of a self-reported PA questionnaire further limit the findings.

These results highlight the need for prospective studies with objective measurements of both physical activity (e.g., accelerometry) and cardiorespiratory fitness (e.g., direct gas analysis), as well as larger, multicentric samples. Interventions to promote active lifestyles during medical training should be evaluated in randomized controlled trials before widespread implementation.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Pedro Juan Cazorla Salinas, Carlos Eduardo Alvarado Ortiz Ureta. Methodology: Felipe León Ignacio Cconchoy, Patrick Sebastian Cazorla Saravia, Vicente Aleixandre Benites Zapata, Wilver Omero Rodriguez López. Formal analysis: Felipe León Ignacio Cconchoy, Patrick Sebastian Cazorla Saravia, Vicente Aleixandre Benites Zapata, Wilver Omero Rodriguez López. Investigation: Pedro Juan Cazorla Salinas, María Mercedes Saravia Bartra. Data curation: Felipe León Ignacio Cconchoy, Patrick Sebastian Cazorla Saravia. Writing – original draft: Felipe León Ignacio Cconchoy, Pedro Juan Cazorla Salinas, María Mercedes Saravia Bartra, Carlos Eduardo Alvarado Ortiz Ureta. Writing – review & editing: Felipe León Ignacio Cconchoy, Pedro Juan Cazorla Salinas, María Mercedes Saravia Bartra, Vicente Aleixandre Benites Zapata. Supervision: Pedro Juan Cazorla Salinas, María Mercedes Saravia Bartra.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

 © 2026 ARD Asociación Española

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Bhatti, S., Leidi, A., Leake, D., & Li, J.-M. (2020). Studying biological science does not lead to adoption of a healthy lifestyle. *Perspectives in Public Health, 140*(4), 232–239. https://doi.org/10.1177/1757913919890889

Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J. F., & Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity. *Medicine & Science in Sports & Exercise, 35*(8), 1381–1395. https://doi.org/10.1249/01.MSS.0000078924.61453.FB

DeFina, L. F., Haskell, W. L., Willis, B. L., Barlow, C. E., Finley, C. E., Levine, B. D., & Cooper, K. H. (2015). Physical activity versus cardiorespiratory fitness: Two (partly) distinct components of cardiovascular health? *Progress in Cardiovascular Diseases, 57*(4), 324–329. https://doi.org/10.1016/j.pcad.2014.09.008

Fan, L. M., Collins, A., Geng, L., & Li, J.-M. (2020). Impact of unhealthy lifestyle on cardiorespiratory fitness and heart rate recovery of medical science students. *BMC Public Health, 20*(1), 1012. https://doi.org/10.1186/s12889-020-09154-x

Ferreira Silva, R. M., Mendonça, C. R., Azevedo, V. D., Raoof Memon, A., Noll, P. R. E. S., & Noll, M. (2022). Barriers to high school and university students' physical activity: A systematic review. *PLOS ONE, 17*(4), e0265913. https://doi.org/10.1371/journal.pone.0265913

Foster, C., Jackson, A. S., Pollock, M. L., Taylor, M. M., Hare, J., Sennett, S. M., Rod, J. L., Sarwar, M., & Schmidt, D. H. (1984). Generalized equations for predicting functional capacity from treadmill performance. *American Heart Journal, 107*(6), 1229–1234. https://doi.org/10.1016/0002-8703(84)90282-5

Franklin, B. A., & Jae, S. Y. (2024). Physical activity, cardiorespiratory fitness and atherosclerotic cardiovascular disease: Part 1. *Pulse, 12*(1), 113–125. https://doi.org/10.1159/000541165

Hackney, A. C. (2006). Stress and the neuroendocrine system: The role of exercise as a stressor and modifier of stress. *Expert Review of Endocrinology & Metabolism, 1*(6), 783–792. https://doi.org/10.1586/17446651.1.6.783

Herreros-Irarrázabal, D., González-López, M. F., Nuche-Salgado, R., de Souza-Lima, J., & Mahecha-Matsudo, S. (2024). Physical activity levels and sedentary behaviour according to sex, age, BMI, academic year, and country among medical students in Latin America. *BMC Public Health, 24*(1), 1699. https://doi.org/10.1186/s12889-024-19133-1

Howard, E. N., Frierson, G. M., Willis, B. L., Haskell, W. L., Powell-Wiley, T. M., & DeFina, L. F. (2013). The impact of race and higher socioeconomic status on cardiorespiratory fitness. *Medicine & Science in Sports & Exercise, 45*(12), 2286–2291. https://doi.org/10.1249/MSS.0b013e31829c2f4f

Júdice, P. B., Silva, A. M., Berria, J., Petroski, E. L., Ekelund, U., & Sardinha, L. B. (2017). Sedentary patterns, physical activity and health-related physical fitness in youth: A cross-sectional study. *International Journal of Behavioral Nutrition and Physical Activity, 14*(1), 25. https://doi.org/10.1186/s12966-017-0481-3

Kaminsky, L. A., Arena, R., Beckie, T. M., Brubaker, P. H., Church, T. S., Forman, D. E., Franklin, B. A., Gulati, M., Lavie, C. J., Myers, J., Patel, M. J., Piña, I. L., Weintraub, W. S., & Williams, M. A. (2013). The importance of cardiorespiratory fitness in the United States: The need for a national registry: A policy statement from the American Heart Association. *Circulation, 127*(5), 652–662. https://doi.org/10.1161/CIR.0b013e31827ee100

Kaminsky, L. A., Arena, R., & Myers, J. (2015). Reference standards for cardiorespiratory fitness measured with cardiopulmonary exercise testing: Data from the Fitness Registry and the Importance of Exercise National Database (FRIEND). *Mayo Clinic Proceedings, 90*(11), 1515–1523. https://doi.org/10.1016/j.mayocp.2015.07.026

Kapoor, G., Chauhan, P., Singh, G., Malhotra, N., & Chahal, A. (2022). Physical activity for health and fitness: Past, present and future. *Journal of Lifestyle Medicine, 12*(1), 9–14. https://doi.org/10.15280/jlm.2022.12.1.9

Kodama, S., Saito, K., Tanaka, S., Maki, M., Yachi, Y., Asumi, M., Sugawara, A., Totsuka, K., Shimano, H., Ohashi, Y., Yamada, N., & Sone, H. (2009). Cardiorespiratory fitness as a quantitative predictor of all-cause mortality and cardiovascular events in healthy men and women: A meta-analysis. *JAMA, 301*(19), 2024–2035. https://doi.org/10.1001/jama.2009.681

Lee, I. M., Shiroma, E. J., Lobelo, F., Puska, P., Blair, S. N., & Katzmarzyk, P. T. (2012). Effect of physical inactivity on major non-communicable diseases worldwide: An analysis of burden of disease and life expectancy. *The Lancet, 380*(9838), 219–229. https://doi.org/10.1016/S0140-6736(12)61031-9

Lubans, D., Richards, J., Hillman, C., Faulkner, G., Beauchamp, M., Nilsson, M., Kelly, P., Smith, J., Raine, L., & Biddle, S. (2016). Physical activity for cognitive and mental health in youth: A systematic review of mechanisms. *Pediatrics, 138*(3), e20161642. https://doi.org/10.1542/peds.2016-1642

Mantilla Toloza, S. C., & Gómez-Conesa, A. (2007). El Cuestionario Internacional de Actividad Física: Un instrumento adecuado en el seguimiento de la actividad física poblacional. *Revista Iberoamericana de Fisioterapia y Kinesiología, 10*(1), 48–52. https://doi.org/10.1016/S1138-6045(07)73665-1

Mendelson, M., Michallet, A.-S., Tonini, J., Favre-Juvin, A., Guinot, M., Wuyam, B., & Flore, P. (2016). Low cardiorespiratory fitness is partially linked to ventilatory factors in obese adolescents. *Pediatric Exercise Science, 28*(1), 87–97. https://doi.org/10.1123/pes.2013-0151

Myers, J., Prakash, M., Froelicher, V., Do, D., Partington, S., & Atwood, J. E. (2002). Exercise capacity and mortality among men referred for exercise testing. *The New England Journal of Medicine, 346*(11), 793–801. https://doi.org/10.1056/NEJMoa011858

Nystoriak, M. A., & Bhatnagar, A. (2018). Cardiovascular effects and benefits of exercise. *Frontiers in Cardiovascular Medicine, 5*, 135. https://doi.org/10.3389/fcvm.2018.00135

Ogawa, T., Spina, R. J., Martin, W. H., 3rd, Kohrt, W. M., Schechtman, K. B., Holloszy, J. O., & Ehsani, A. A. (1992). Effects of aging, sex, and physical training on cardiovascular responses to exercise. *Circulation, 86*(2), 494–503. https://doi.org/10.1161/01.CIR.86.2.494

Ombrellaro, K. J., Perumal, N., Zeiher, J., Hoebel, J., Ittermann, T., Ewert, R., Dörr, M., Keil, T., Mensink, G. B. M., & Finger, J. D. (2018). Socioeconomic correlates and determinants of cardiorespiratory fitness in the general adult population: A systematic review and meta-analysis. *Sports Medicine - Open, 4*(1), 25. https://doi.org/10.1186/s40798-018-0137-0

Pate, R. R., Wang, C.-Y., Dowda, M., Farrell, S. W., & O'Neill, J. R. (2006). Cardiorespiratory fitness levels among US youth 12 to 19 years of age. *Archives of Pediatrics & Adolescent Medicine, 160*(10), 1005–1012. https://doi.org/10.1001/archpedi.160.10.1005

Peralta, M., Henriques-Neto, D., Gouveia, É. R., Sardinha, L. B., & Marques, A. (2020). Promoting health-related cardiorespiratory fitness in physical education: A systematic review. *PLOS ONE, 15*(8), e0237019. https://doi.org/10.1371/journal.pone.0237019

 © 2026 ARD Asociación Española

Pollock, M. L., Foster, C., Schmidt, D., Hellman, C., Linnerud, A. C., & Ward, A. (1982). Comparative analysis of physiologic responses to three different maximal graded exercise test protocols in healthy women. *American Heart Journal, 103*(3), 363–373. https://doi.org/10.1016/0002-8703(82)90275-7

Prieto-Benavides, D. H., García-Hermoso, A., Izquierdo, M., Alonso-Martínez, A. M., Agostinis-Sobrinho, C., Correa-Bautista, J. E., & Ramírez-Vélez, R. (2019). Cardiorespiratory fitness cut-points are related to body adiposity parameters in Latin American adolescents. *Medicina, 55*(9), 508. https://doi.org/10.3390/medicina55090508

Raghuveer, G., Hartz, J., Lubans, D. R., Takken, T., Wiltz, J. L., Mietus-Snyder, M., Perak, A. M., Baker-Smith, C., Pietris, N., & Edwards, N. M. (2020). Cardiorespiratory fitness in youth: An important marker of health: A scientific statement from the American Heart Association. *Circulation, 142*(7), e101–e118. https://doi.org/10.1161/CIR.0000000000000866

Ross, R., Blair, S. N., Arena, R., Church, T. S., Després, J. P., Franklin, B. A., Haskell, W. L., Kaminsky, L. A., Levine, B. D., Lavie, C. J., Myers, J., Niebauer, J., Sallis, R., Sawada, S. S., Sui, X., & Wisløff, U. (2016). Importance of assessing cardiorespiratory fitness in clinical practice: A case for fitness as a clinical vital sign: A scientific statement from the American Heart Association. *Circulation, 134*(24), e653–e699. https://doi.org/10.1161/CIR.0000000000000461

Santos, R., Mota, J., Okely, A. D., Pratt, M., Moreira, C., Coelho-e-Silva, M. J., Vale, S., & Sardinha, L. B. (2014). The independent associations of sedentary behaviour and physical activity on cardiorespiratory fitness. *British Journal of Sports Medicine, 48*(20), 1508–1512. https://doi.org/10.1136/bjsports-2012-091610

Swift, D. L., Johannsen, N. M., Earnest, C. P., Newton, R. L., McGee, J. E., & Church, T. S. (2017). Cardiorespiratory fitness and exercise training in African Americans. *Progress in Cardiovascular Diseases, 60*(1), 96–102. https://doi.org/10.1016/j.pcad.2017.06.001

Tatius, B., Hajar, N., Tursinawati, Y., Romadhoni, R., Baihaqi, M. H., Muhammad, K., Akmal, M. I., & Ja'far, I. M. (2024). Factors affecting cardiorespiratory fitness among medical students: A cross-sectional study. *Universal Journal of Public Health, 12*(5), 820–827. https://doi.org/10.13189/ujph.2024.120504

Tomkinson, G. R., Lang, J. J., & Tremblay, M. S. (2019). Temporal trends in the cardiorespiratory fitness of children and adolescents representing 19 high-income and upper middle-income countries between 1981 and 2014. *British Journal of Sports Medicine, 53*(8), 478–486. https://doi.org/10.1136/bjsports-2017-097982

von Elm, E., Altman, D. G., Egger, M., Pocock, S. J., Gøtzsche, P. C., & Vandenbroucke, J. P. (2007). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: Guidelines for reporting observational studies. *The Lancet, 370*(9596), 1453–1457. https://doi.org/10.1016/S0140-6736(07)61602-X

World Health Organization. (2000). *Obesity: Preventing and managing the global epidemic: Report of a WHO consultation* (WHO Technical Report Series No. 894).

World Health Organization. (2018). *Global action plan on physical activity 2018–2030: More active people for a healthier world*. World Health Organization.

Zyriax, B.-C., & Windler, E. (2023). Lifestyle changes to prevent cardio- and cerebrovascular disease at midlife: A systematic review. *Maturitas, 167*, 60–65. https://doi.org/10.1016/j.maturitas.2022.09.003

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

APPENDIX 1

Supplementary Table 1. STROBE Statement—Checklist of items that should be included in reports of cross-sectional studies.

	Item No	Recommendation	Page No
Title and abstract	1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	1
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	1
Objectives	3	State specific objectives, including any prespecified hypotheses	2
Methods			
Study design	4	Present key elements of study design early in the paper	2
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	2
Participants	6	(a) Give the eligibility criteria, and the sources and methods of selection of participants	2
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	3-4
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	3-4
Bias	9	Describe any efforts to address potential sources of bias	5
Study size	10	Explain how the study size was arrived at	5
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	2-4
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	5-6
		(b) Describe any methods used to examine subgroups and interactions	N/A
		(c) Explain how missing data were addressed	2
		(d) If applicable, describe analytical methods taking account of sampling strategy	N/A
		(e) Describe any sensitivity analyses	N/A
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	2 (partial — see limitation, p.9)
		(b) Give reasons for non-participation at each stage	9-10
		(c) Consider use of a flow diagram	N/A
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	6
		(b) Indicate number of participants with missing data for each variable of interest	6
Outcome data	15*	Report numbers of outcome events or summary measures	6
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	6-7
		(b) Report category boundaries when continuous variables were categorized	3-4
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	N/A
Discussion			
Key results	18	Summarise key results with reference to study objectives	7
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	9–10
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	7–10
Generalisability	21	Discuss the generalisability (external validity) of the study results	9
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	11

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

Solid as a rock? Psychological skills, mood states and mental health indicators in young rugby players

Verónica Gómez-Espejo. *Department of Personality, Evaluation and Psychological Treatment. Human Movement and Sports Science Research Group (HUMSE). CEIR Campus Mare Nostrum (CMN). University of Murcia. Murcia, Spain.*

Antonio Núñez-Prats. *Department of Psychology. GICAFE (Research Group of Sports Sciences). University of the Balearic Islands. Mallorca, Spain.*

Laura Gil-Caselles. *Faculty of Sports Sciences. Human Movement and Sports Science Research Group (HUMSE). University of Murcia. San Javier, Murcia, Spain.*

Paula Ortiz-Márholz. *Faculty of Education and Humanities. Institute of Sport and Wellbeing. Andres Bello University. Las Condes, Chile.*

Alejandro García-Mas. *Department of Psychology. University of the Balearic Islands. Mallorca, Spain.*

Aurelio Olmedilla. *Department of Personality, Evaluation and Psychological Treatment. Human Movement and Sports Science Research Group (HUMSE). CEIR Campus Mare Nostrum (CMN). University of Murcia. Murcia, Spain.*

ABSTRACT

Rugby is a high-contact team sport involving substantial physical, emotional and social demands. This study examined the associations between psychological skills related to sport performance and mental health indicators, including sleep quality, fatigue, mood states and injury history, in young rugby players. An empirical, cross-sectional and associative study was conducted with 27 regional under-16 and under-18 rugby players aged 14–17 years. Participants completed an ad hoc questionnaire on sociodemographic, sport-related and injury variables, together with the Psychological Characteristics Related to Sports Performance Questionnaire, the Profile of Mood States and the Pittsburgh Sleep Quality Index. Non-parametric analyses were performed. Players generally reported adequate perceived sleep quality, low negative mood states, moderate tension and preserved vigour. Stress control was positively associated with the influence of performance evaluation and motivation, while motivation was related to team cohesion. Higher influence of performance evaluation was associated with lower tension. Players with previous injuries showed higher mental skills and cohesion. Cluster analysis identified a profile characterized by better psychological skills, higher motivation and lower tension. These findings suggest that psychological skills, cohesion, sleep perception and mood states may be relevant dimensions for understanding well-being in youth rugby.

Keywords: youth sport; team sports; psychological well-being; sleep quality; fatigue; injury history.

Cite this article as:
Gómez-Espejo, V., Núñez-Prats, A., Gil-Caselles, L., Ortiz-Márholz, P., García-Mas, A., & Olmedilla, A. (2026). Solid as a rock? Psychological skills, mood states and mental health indicators in young rugby players. *Journal of Human Sport and Exercise, 21*(4), 1635-1651. https://doi.org/10.55860/cnyqrq66

Corresponding author. *Human Movement and Sports Science (HUMSE). University of Murcia. CEIR Campus Mare Nostrum (CMN), C/ Argentina, s/n, Campus de San Javier, 30720 Santiago de la Ribera, Murcia, Spain.*
E-mail: laura.gilc@um.es

Submitted for publication June 23, 2026.
Accepted for publication August 06, 2026.
Published September 30, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.

©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.

doi: https://doi.org/10.55860/cnyqrq66

INTRODUCTION

In recent decades, sport psychology has shown increasing interest in understanding the psychological characteristics associated with participation in different sports. Early research attempted to determine whether athletes' personality traits could explain their preference for particular sport disciplines, although the evidence has often been inconsistent and sometimes contradictory (Allen et al., 2013). More recent approaches have shifted the focus from the idea that certain personality profiles predispose individuals to choose specific sports towards a more dynamic perspective, in which sport participation itself may contribute to the development, modification, or reinforcement of psychological characteristics over time (Allen et al., 2021; Thornton et al., 2024; White et al., 2024).

This perspective is particularly relevant in youth sport, where athletes are still developing their psychological, emotional, and social resources. During adolescence, competitive sport may act both as a demanding context and as a formative environment in which young athletes learn to cope with pressure, fatigue, performance evaluation, team demands, and injury-related experiences. These factors are closely linked to mental health, understood not only as the absence of psychological symptoms, but also as the presence of adaptive functioning, emotional regulation, perceived competence, social support, and well-being.

Rugby represents a particularly relevant context for studying these processes. It is a high-contact team sport characterized by intense physical demands, repeated exposure to collisions, tolerance to discomfort and pain, and a strong emphasis on cooperation, collective identity, and commitment. Previous work on sport commitment, including research conducted with elite rugby players such as the New Zealand All Blacks, has highlighted rugby as a useful setting for understanding adherence, motivation, and persistence under demanding practice conditions (Scanlan et al., 2003, 2016). In addition, recent consensus work on elite youth athletes has emphasized that demanding sport environments may provide developmental, psychological, and social benefits, but may also involve threats to health and well-being when training, competition, recovery, and psychosocial support are not adequately managed (Bergeron et al., 2024). In this sense, rugby may provide a unique framework for analysing how young athletes manage emotional activation, fatigue, sleep routines, perceived evaluation, injury-related experiences, and team belonging.

Among the psychological variables involved in sport performance and mental health, mood states, fatigue, sleep quality, and injury history deserve particular attention. Mood states are relevant because they reflect athletes' emotional responses to training and competition and may be associated with both performance and psychological well-being (Brandt et al., 2017; Campo et al., 2019; Fullagar et al., 2015; Nédélec et al., 2012; Shearer et al., 2015). Fatigue, in turn, is a common consequence of demanding training loads and may influence recovery, emotional regulation, perceived stress, and readiness to perform. Sleep quality is also a central indicator of recovery and mental health, particularly in adolescent athletes, as insufficient or poor-quality sleep may affect mood, attention, physical recovery, injury risk, and vulnerability to psychological distress (Charest & Grandner, 2020).

Injury history is another important dimension when analysing athletes' psychological functioning. Sports injuries are not only physical events; they may also involve emotional, cognitive, and social consequences. Previous research has shown that injury experiences can be associated with anxiety, mood disturbances, perfectionistic tendencies, coping processes, and broader indicators of mental health in athletes (Gil-Caselles et al., 2023, 2025). Moreover, recent consensus work on the psychology of sport injury has highlighted the need to consider psychological factors across the whole injury process, including injury risk, rehabilitation, return to sport, and long-term adjustment (Tranaeus et al., 2024). However, injury may also become a context

 © 2026 ARD Asociación Española

for psychological learning when athletes receive appropriate support during recovery and return to play. In this regard, the relationship between injury, psychological skills, and mental health should be understood in a nuanced way, considering both vulnerability and adaptation.

Psychological skills related to sport performance, such as stress control, motivation, mental skills, mental toughness, and team cohesion, may play a protective role in demanding sport environments. These skills can help athletes interpret external evaluation, physical demands, fatigue, and competitive pressure as manageable challenges rather than as overwhelming threats. In team sports, cohesion and cooperation may be especially relevant, as the perception of belonging and shared effort can buffer the negative impact of stress and contribute to more adaptive emotional functioning. Regarding the conceptual issue at hand, previous systematic review and meta-analytic evidence has shown that the most adequate theoretical frameworks for to explain and put together these variables is twofold. On one hand, there are the concept of mental toughness, which we know is positively associated with athletic performance (Hsieh et al., 2024). Mental toughness may mediate athletes' responses to demanding or adverse sporting situations by helping them remain determined, focused, confident, and emotionally composed. This psychological capacity allows athletes to sustain, or even enhance, their performance despite pressure, setbacks, and fatigue (Hsieh et al., 2024). It supports effective skill execution and decision-making under high-stakes conditions, promotes recovery from injury, failure, or poor performance by transforming adversity into a learning opportunity, and may protect against burnout. Indeed, athletes with greater mental toughness tend to report lower emotional exhaustion and sport devaluation (Poulus et al., 2024). Importantly, mental toughness is not necessarily a fixed attribute, as it can be strengthened through psychological skills training in sport (Pocius & Malinauskas, 2024).

On the other hand, there are the psychological wellbeing (Peris-Delcampo et al., 2024), intrinsically related with the mental health, which provides knowledge about the way -for the athletes- to perform exigent sports without breaking psychologically. This combination of psychological concepts, with its derived variables, is particularly important in rugby, where collective effort and exposure to demanding physical situations are central elements of the sport culture. In line with recent evidence, psychological skills training and other psychological interventions may contribute to athletes' mental well-being, although more robust research designs are still needed to clarify their effectiveness across different sport populations (Wang et al., 2025).

Despite the growing interest in athlete mental health and their psychological wellbeing, there is still limited evidence on how psychological skills, sleep quality, fatigue, mood states, and injury history are related in young rugby players. Most research has focused on adult or elite athletes, whereas adolescent players in regional development contexts have received less attention. Studying these populations is important because early identification of adaptive and maladaptive psychological profiles may help to design preventive interventions aimed at promoting mental health, recovery, emotional regulation, and positive sport development.

Therefore, the aim of this study was to examine the associations between psychological skills related to sport performance and mental health indicators, including sleep quality, fatigue, mood states, and injury history, in young rugby players from regional under-16 and under-18 teams. Based on previous literature, it was expected that higher psychological skills, particularly stress control, motivation, and cohesion, would be associated with more adaptive mood profiles and better indicators of psychological well-being.

MATERIAL AND METHODS

Study design

This study followed an empirical, observational, cross-sectional, and associative design (Ato et al., 2013). Its aim was to examine the relationships between psychological skills related to sport performance and several mental health indicators, including sleep quality, fatigue, mood states, and injury history, in young rugby players. No experimental manipulation was conducted, and all variables were assessed in the participants' natural sport context during a training period.

Participants

Twenty-seven rugby players from regional under-16 and under-18 teams participated in the study. Participants were recruited through convenience sampling from a regional rugby development context. The sample was distributed across two age categories: under-16 (n = 14; 11 males and 3 females) and under-18 (n = 13; 11 males and 2 females). Overall, 81.5% of the participants were male and 18.5% were female, with ages ranging from 14 to 17 years.

The under-16 group had a mean age of 14.50 ± 0.67 years, had spent an average of 1.08 ± 0.29 years in the category, and had been registered with the federation for 5.58 ± 3.00 years. The under-18 group had a mean age of 16.55 ± 0.52 years, had spent 1.73 ± 0.47 years in the category, and had been registered with the federation for 4.82 ± 2.60 years. All participants were actively involved in federated rugby at the time of data collection.

Measures

Sociodemographic and sport-related information was collected using an ad hoc questionnaire designed for this study. The questionnaire included age, sex, competitive category, number of years practicing sport at the highest competitive level, number of years of continuous federated sport participation, weekly training frequency, and daily training duration.

Current and previous injury history was assessed using an ad hoc injury questionnaire. This questionnaire recorded the presence or absence of current injury, type of injury, injury severity, and the number of sport injuries sustained during the previous two seasons. Injury type included muscle injury, fracture, tendinopathy, contusion, sprain, and other injuries. Injury severity was categorised according to the number of days of sport absence. Mild injuries were defined as those involving one day without training; moderate injuries as those involving at least six days without training; severe injuries as those involving one to three months of sport absence; and very severe injuries as those involving more than four months of sport absence.

Psychological characteristics related to sport performance were assessed using the Psychological Characteristics Related to Sport Performance Questionnaire, known by its Spanish acronym CPRD, developed by Gimeno et al. (2001). The CPRD is based on the Psychological Skills Inventory for Sports developed by Mahoney et al. (1987) and consists of 55 items rated on a five-point Likert scale ranging from strongly disagree to strongly agree. It includes five subscales: Stress Control, Influence of Performance Evaluation, Motivation, Team Cohesion, and Mental Skills. Higher scores indicate higher levels of the corresponding psychological characteristic. Previous studies have reported acceptable internal consistency for the total scale, $\alpha = 0.85$, and for most subscales: Stress Control, $\alpha = 0.88$; Influence of Performance Evaluation, $\alpha = 0.72$; Motivation, $\alpha = 0.67$; Team Cohesion, $\alpha = 0.78$; and Mental Skills, $\alpha = 0.34$. According to Gimeno and Pérez-Llantada (2010), the low internal consistency of the Mental Skills subscale may be explained by the fact that this dimension includes a broad range of different psychological skills.

 © 2026 ARD Asociación Española

Nevertheless, the subscale was retained due to the factorial loadings of its items, which were above 0.30. Similar psychometric considerations have also been reported in previous research using the original Psychological Skills Inventory for Sports (Chartrand et al., 1992).

Mood states were assessed using the Spanish-adapted and validated short version of the Profile of Mood States, developed by Fuentes et al. (1995) from the original Profile of Mood States by McNair et al. (1971). This version includes 29 items rated on a five-point scale ranging from 0, not at all, to 4, very much. The questionnaire assesses five mood states: Tension, Depression, Anger, Vigour, and Fatigue. Previous studies have reported satisfactory Cronbach's alpha values for the five dimensions: Tension, $\alpha = 0.83$; Anger, $\alpha = 0.85$; Vigor, $\alpha = 0.83$; Fatigue, $\alpha = 0.82$; and Depression, $\alpha = 0.78$. Higher scores indicate higher levels of each mood state.

Sleep quality was assessed using the Spanish-language version of the Pittsburgh Sleep Quality Index (Escobar-Córdoba & Eslava-Schmalbach, 2005), a widely used self-report instrument for assessing perceived sleep quality (Smyth, 1999). Previous validation studies have reported adequate convergent and divergent validity and moderate reliability, with a Cronbach's alpha of .72 (Escobar-Córdoba & Eslava-Schmalbach, 2005). For the purposes of this study, two sleep-related indicators were analysed: sleep latency and perceived sleep quality.

Procedure

Participants were recruited from regional under-16 and under-18 rugby teams during three training camps held at a High-Performance Sports Centre in the final quarter of the season, between April and June.

The research project and data collection requirements were first explained to the federation representative. The representative then informed the coaches and players, and permission was obtained to conduct the study. All players were informed about the aims of the study, the voluntary nature of participation, and the confidentiality and anonymity of their data. Written informed consent was obtained from all participants and, in the case of minors, written authorization was also obtained from their parents or legal guardians. The study was approved by the Ethics Committee of the University of Murcia, Spain (reference: ID 4734/2023), and was conducted in accordance with the principles of the Declaration of Helsinki for research involving human participants (World Medical Association, 2025).

Data collection was conducted at three time points, corresponding to the three training camp periods at the High-Performance Sports Centre. In each session, the POMS and fatigue assessment were administered to the players. In the first session, participants also completed the sociodemographic, sport-related, and injury history questionnaires, which collected information on the number of injuries sustained during the previous two seasons, injury type and severity, years of federation membership, and time spent in their current competitive category.

Statistical analysis

Data distribution was examined using the Shapiro–Wilk test (Shapiro & Wilk, 1965). The CPRD factors met the assumption of normality, except for Mental Skills, which showed a non-normal distribution. Regarding the POMS, only Tension and Vigor met the assumption of normality. None of the PSQI variables analysed met the assumption of normality. Given the small sample size and the distribution of the study variables, non-parametric analyses were performed.

For the PSQI, only two variables were included in the analyses: sleep latency and perceived sleep quality. Descriptive statistics were calculated for all study variables. Means and standard deviations were reported for continuous variables, whereas frequencies and percentages were reported for categorical variables. Spearman's rank correlation coefficients were used to examine associations between CPRD dimensions, mood states, and sleep-related variables. Between-group comparisons were performed using the Mann–Whitney U test for two-group comparisons and the Kruskal–Wallis test for comparisons involving more than two groups. A hierarchical cluster analysis was conducted to identify psychological profiles based on CPRD dimensions and POMS tension scores. All variables were standardized prior to analysis (transformation to Z-scores). Clustering was performed using Ward's hierarchical clustering method (ward.D2 algorithm) with Euclidean distance metrics. A two-cluster solution was established to classify athletes into distinct psychological profiles, based on theoretical interpretability and separation between groups. The statistical significance level for descriptive comparisons between clusters was set at $p < .05$.

RESULTS

Reliability testing

The CPRD and POMS questionnaires showed Cronbach's alpha values above .80, indicating good reliability. The PSQI showed a Cronbach's alpha value above .73, indicating acceptable reliability.

Descriptive analysis

As shown in Table 1, the mean and standard deviation values of the rugby players placed them within the medium percentiles of the CPRD scale: Stress Control, 50th percentile; Influence of Performance Evaluation, 80th percentile; Motivation, 65th percentile; Mental Skills, 55th percentile; and Cohesion, 55th percentile. It should also be noted that higher scores on Influence of Performance Evaluation indicate greater control over the impact of external evaluation on one's own performance.

Furthermore, the scores for the POMS factors placed the players within the low percentiles of the POMS scale: Tension, 38th percentile; Depression, 40th percentile; Anger, 37th percentile; Vigor, 52nd percentile; and Fatigue, 43rd percentile.

Table 1. Descriptive statistics for CPRD and POMS factors.

	Stress control	Influence of evaluation	Motivation	Mental skills	Cohesion	Tension	Depression	Anger	Vigour	Fatigue
$\bar{x}$	54.7	31.7	21.2	20.9	19.3	7.73	2.05	2.41	16.2	5.50
SD	10.5	7.13	4.40	4.68	2.27	3.83	2.54	3.02	3.35	2.89

Table 2. Descriptive statistics for sleep latency and perceived sleep quality.

Category	Frequency	%
Minutes to fall asleep		
Less than 15 minutes	14	60.9
Between 16 and 30 minutes	6	26.1
Between 31 and 45 minutes	2	8.7
More than 60 minutes	1	4.3
Perceived sleep quality		
Very poor	1	4.3
Fairly poor	5	21.7
Fairly good	13	56.5
Very good	4	17.4

 © 2026 ARD Asociación Española

Regarding sleep routines, as shown in Table 2, 87.0% of the sample reported falling asleep within 30 minutes, after combining the categories "*less than 15 minutes*" and "*between 16 and 30 minutes*". Similarly, 73.9% of the sample reported good perceived sleep quality, after combining the categories "*fairly good*" and "*very good*". No correlations were found between the PSQI variables and the CPRD or POMS factors. Likewise, no differences were observed in the CPRD or POMS factors according to the sleep latency and perceived sleep quality categories.

The relationships between the study variables were examined using Spearman's correlation matrix, as shown in Table 3. Significant positive correlations were observed between Stress Control and Influence of Performance Evaluation, and between Stress Control and Motivation. In addition, Motivation was positively correlated with Cohesion.

Table 3. Spearman's correlation matrix for CPRD and POMS factors.

Variable	Stress control	Influence of evaluation	Motivation	Mental skills	Cohesion	Tension	Depression	Anger	Vigour	Fatigue
Stress control	—									
Influence of Evaluation	.563**	—								
Motivation	.576**	.199	—							
Mental skills	.168	-.154	-.056	—						
Cohesion	-.099	-.224	.433*	.016	—					
Tension	-.220	-.479*	.081	-.095	.225	—				
Depression	.149	.029	.313	.182	.010	.403	—			
Anger	.228	-.028	.079	.286	-.056	.320	.623**	—		
Vigour	.072	-.251	.300	.080	.366	.280	.184	.247	—	
Fatigue	-.247	-.377	.031	-.037	.522*	.108	-.134	.053	.374	—

*Note. * = p < .05, ** = p < .01, *** = p < .001.*

The analysis of the correlations between the CPRD and POMS factors revealed a significant negative correlation between Influence of Performance Evaluation and Tension, indicating that higher scores in Influence of Performance Evaluation were associated with lower levels of tension. A significant positive correlation was also observed between Cohesion and Fatigue. Finally, within the POMS factors, Depression and Anger were positively correlated.

Group comparisons

A Mann–Whitney U test was conducted to compare CPRD dimensions between categories (under-16 vs. under-18). The results showed that the under-18 group scored significantly higher on Mental Skills (p = .015). No significant differences were observed for the remaining variables: Stress Control, Influence of Performance Evaluation, Motivation, and Cohesion.

Additional differences were found when comparing CPRD factors according to the number of injuries using the Kruskal–Wallis test. Significant differences were observed for Mental Skills (p = .048) and Cohesion (p = .028).

To further examine the relationship between injury history and CPRD factors, and based on these findings, the categories of one and two injuries were combined, resulting in two groups: "*Yes*", including athletes who had sustained at least one injury, and "*No*", including athletes who had never sustained an injury. The Mann–Whitney U test revealed that athletes who had sustained one or more injuries scored significantly higher on Mental Skills (p = .009) and Cohesion (p = .006).

Although significant differences were observed only for Mental Skills and Cohesion, a tendency towards higher scores in Stress Control and Motivation was also evident among athletes who had sustained injuries (Table 4).

Table 4. Descriptive statistics for CPRD factors according to injury history (Yes/No).

CPRD Factor	Injury history	Mean	SD
Influence of evaluation	Yes	31.3	6.24
	No	32.2	8.28
Motivation	Yes	21.8	4.47
	No	20.6	4.46
Mental skills	Yes	23.0	3.28
	No	18.6	5.05
Cohesion	Yes	20.5	1.51
	No	18.0	2.28
Stress control	Yes	55.3	8.61
	No	54.0	12.71

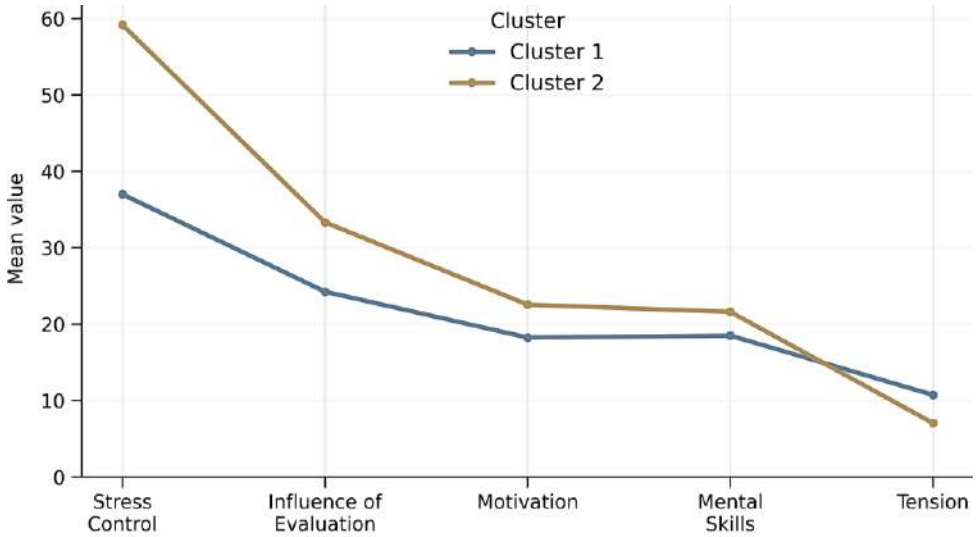
When comparing athletes reporting fatigue with those who did not report fatigue, athletes with fatigue showed significantly higher scores on the Tension factor (p = .012). Furthermore, athletes with higher Cohesion scores also reported higher levels of Fatigue (p = .003). Significant differences in Fatigue were also observed between the under-16 and under-18 groups (p = .019).

Profiles of psychological skills

A hierarchical cluster analysis identified two profiles of rugby players based on psychological skills, assessed through the CPRD, and Tension, assessed through the POMS.

Table 5. Centroids of the hierarchical cluster analysis.

Cluster	Stress control	Influence of evaluation	Motivation	Mental skills	Tension
1	37.000	24.250	18.250	18.500	10.750
2	59.167	33.333	22.556	21.611	7.056



Note. Cluster 1 = lower psychological skills and higher tension profile; Cluster 2 = higher psychological skills and lower tension profile. CPRD = Psychological Characteristics Related to Sport Performance Questionnaire; POMS = Profile of Mood States.

Figure 1. Mean values across the psychological profiles identified through hierarchical cluster analysis.

 © 2026 ARD Asociación Española

As shown in Table 5, Profile 2 was characterized by higher scores in Stress Control, Influence of Performance Evaluation, Motivation, and Mental Skills, together with lower scores in Tension. In contrast, Profile 1 showed lower scores in the CPRD dimensions and higher scores in Tension. These findings suggest that higher psychological skill scores were associated with lower tension levels, as shown in Figure 1.

DISCUSSION

The results of this study suggest that young rugby players may present a psychological profile compatible with adaptive functioning and favourable indicators of psychological well-being, despite being exposed to a demanding sport environment. Overall, participants reported adequate perceived sleep quality, low levels of negative mood states, moderate Tension, and preserved Vigour. In addition, psychological skills related to sport performance, particularly Stress Control, Influence of Performance Evaluation, Motivation, Mental Skills, and Cohesion, showed meaningful associations with mood-related variables and injury history. From a mental health perspective, understood not only as the absence of psychological symptoms but also as the presence of psychological resources, emotional regulation, and adaptive functioning, these findings contribute to a better understanding of well-being in young athletes exposed to demanding training contexts (Ryff, 1989; White et al., 2024).

Viewed within contemporary mental-health frameworks, these findings should not be interpreted solely as isolated questionnaire scores, but as a multidimensional pattern of psychological functioning. The combination of low negative mood states, preserved Vigour, adequate perceived sleep quality, team cohesion, and psychological skills may be considered compatible with psychological well-being and adaptive functioning in this specific group of young rugby players. From a positive youth development perspective, these personal and social resources may help athletes manage the demands associated with training, performance evaluation, fatigue, and injury-related experiences (Bergeron et al., 2024; Núñez et al., 2025; Ryff, 1989; White et al., 2024). Nevertheless, given the cross-sectional design, these findings should not be interpreted as evidence that rugby participation directly promotes resilience, flourishing, or psychological development.

Therefore, the higher scores observed in mental skills and cohesion among athletes with a history of injury may reflect processes of psychological growth stemming from adversity, rather than mere recovery. Thus, the experience of a physical injury acts as a catalyst, prompting athletes to develop coping mechanisms and emotional self-regulation skills, as well as to seek support within their social environment (Roy-Davis et al., 2017).

Perceived sleep quality is a relevant factor for understanding sport performance, recovery, and psychological adjustment, although it is not always systematically analysed in young athletes (García-Mas et al., 2003). In the present study, most players reported low sleep latency and good perceived sleep quality. Moreover, no significant correlations were found between the sleep-related variables analysed and the CPRD or POMS factors. These findings suggest that, in this sample, perceived sleep was not negatively associated with psychological skills or mood states. This result should be interpreted in light of the assessment context, as data were collected during a preparation and training period rather than during competition. Therefore, sleep patterns may have been more closely related to training routines and recovery demands than to competition-related anxiety or emotional dysregulation (Sargent et al., 2014).

Previous research has shown that sleep quality may influence physical performance, mental performance, injury risk, recovery, medical health, and mental health in athletes (Charest & Grandner, 2020). However, the

relationship between sport participation and sleep is complex. Some systematic evidence suggests that elite sport may be associated with poorer sleep quality, including insomnia symptoms and sleep fragmentation (Gupta et al., 2017), whereas other studies indicate that many athletes maintain adequate sleep quality, particularly when appropriate recovery routines are present (Brandt et al., 2017; Leeder et al., 2012). This is especially relevant in team sports, where training load, recovery routines, travel, competition schedules, and accumulated fatigue may influence both sleep and perceived readiness to perform (Fullagar et al., 2015; Nédélec et al., 2012; Sargent et al., 2014). In the present study, the absence of significant associations between perceived sleep and psychological variables may therefore suggest that sleep quality was relatively preserved during the assessment period, possibly because data were collected in a preparation and training context rather than during competition. In this regard, the findings support the idea that demanding sport participation, by itself, is not necessarily associated with poorer perceived sleep or worse psychological well-being indicators in young athletes, particularly when training demands are accompanied by adequate recovery routines.

The mood profile observed in this sample also points towards adaptive functioning. The players showed low levels of Depression and Anger, moderate levels of Tension, and relatively preserved Vigor. This pattern may be interpreted as compatible with functional activation rather than psychological distress. Previous research has shown that mood states are sensitive to training and competitive demands and may provide useful information about athletes' recovery, readiness, and psychological adjustment (Brandt et al., 2017; Campo et al., 2019; Shearer et al., 2015). In rugby, emotional activation may be particularly relevant because the sport involves repeated physical contact, collective effort, tactical decision-making, and exposure to demanding performance situations (Campo et al., 2019; Shearer et al., 2015). Therefore, moderate Tension and Fatigue should not necessarily be interpreted as maladaptive when they are not accompanied by high Depression or Anger. In the present study, the coexistence of moderate activation, preserved Vigor, and low negative mood states suggests a mood pattern closer to adaptive sport involvement than to emotional maladjustment.

Regarding psychological skills, the descriptive results showed medium scores in most CPRD dimensions, with a particularly high score in Influence of Performance Evaluation. This dimension was positively associated with Stress Control and negatively associated with Tension. These findings are coherent with the conceptual basis of the CPRD, which assesses psychological characteristics related to sport performance, including the athlete's ability to manage stress, external evaluation, motivation, cohesion, and mental skills (Gimeno et al., 2001; Gimeno & Pérez-Llantada, 2010). From this perspective, players who report greater control over the influence of performance evaluation may be better able to interpret coaches' feedback, peer comparison, selection processes, and competitive demands as manageable aspects of sport participation rather than as threatening experiences. This interpretation is also consistent with previous research highlighting the relevance of psychological skills for sport performance and adaptation to demanding contexts (Chartrand et al., 1992; Hsieh et al., 2024; Mahoney et al., 1987). In youth sport contexts, perceived evaluation from coaches, peers, and competitive environments can be a relevant source of psychological pressure. However, when athletes develop better stress regulation skills, external evaluation may become integrated into the learning and performance process rather than being experienced as a source of maladaptive tension.

Motivation was positively associated with Stress Control and Cohesion, which reinforces the importance of the team environment in rugby. Rugby is characterized by high physical contact, shared effort, tactical cooperation, and collective identity. In this context, cohesion may contribute to the regulation of demanding experiences by strengthening belonging, perceived support, and commitment to the group. Previous research

 © 2026 ARD Asociación Española

has highlighted the role of team belonging and group processes in sport environments (Davis et al., 2022; Gu et al., 2022), and the present findings are consistent with this perspective.

An interesting result was the positive association between Cohesion and Fatigue. Although fatigue is usually considered a potential risk factor when it accumulates or is poorly managed, in this study it was not associated with higher Depression or Anger. This may indicate that fatigue was experienced as part of a shared training process rather than as an isolated or aversive experience. In team sports, demanding training contexts may contribute to group cohesion when athletes perceive that effort, tiredness, and commitment are shared among teammates. In this sense, fatigue may have represented a normative adaptive load within a structured training environment rather than a marker of psychological maladjustment, particularly when shared effort is accompanied by cohesion, belonging, and perceived group support (Davis et al., 2022; Gu et al., 2022). This interpretation is also consistent with research on rugby teams showing that social identity and cohesion may be linked to perceptions of group functioning and performance (Coffey, 2023).

The differences observed according to age category also deserve attention. Under-18 players showed higher Mental Skills than under-16 players, suggesting that psychological skills may develop progressively alongside sport experience, technical learning, tactical understanding, and exposure to competitive demands. This finding should be interpreted cautiously due to the small sample size, but it is consistent with the idea that youth sport can provide a context for the development of self-regulation, coping strategies, and performance-related psychological resources.

Injury history was also associated with psychological variables. Players who had sustained one or more injuries reported higher Mental Skills and Cohesion, with non-significant tendencies towards higher Stress Control and Motivation. Although sports injuries are commonly associated with negative emotional, cognitive, and behavioural consequences, they may also become opportunities for psychological learning when athletes receive adequate support during recovery and return to play. These findings are consistent with the global psychological model of sport injuries (Olmedilla & García-Mas, 2009) and with previous work suggesting that sport injury may be followed by positive psychological changes once recovery and return to sport have been achieved (Haugen, 2022). In this sample, previous injury may have contributed to the development of psychological skills and team belonging, although longitudinal studies are needed to clarify this interpretation.

The cluster analysis reinforced the relationship between psychological skills and mood states. One profile was characterized by higher Stress Control, Influence of Performance Evaluation, Motivation, and Mental Skills, together with lower Tension. In contrast, the second profile showed lower psychological skill scores and higher Tension. These findings suggest that psychological skills may be relevant for understanding how young rugby players manage sport demands. From a well-being perspective, this pattern is consistent with eudaimonic approaches that emphasize personal growth, environmental mastery, and self-regulation as central dimensions of psychological adjustment (Ryff, 1989). Similarly, Núñez et al. (2025) suggest that the progressive development of psychological skills may help athletes interpret environmental demands as manageable challenges rather than as threats.

The identification of these profiles may provide sports psychologists with a useful tool for early detection. Cluster-based characterization may help professionals identify athlete profiles that could be more vulnerable to burnout or psychological distress during periods of high demand, thereby facilitating the implementation of targeted preventive interventions. Nevertheless, these findings should be interpreted with caution because of the relatively small sample size. Future studies using larger longitudinal samples and cross-validation

procedures are needed to determine whether this two-cluster configuration can be replicated across different competitive levels and sporting contexts.

Consistent with this perspective, evidence suggests an association between psychological skills, flow states, and athlete wellbeing. Flow may mediate the relationship between psychological skills and athlete wellbeing. Skills such as attentional control, emotional regulation, goal setting, and self-confidence create favourable conditions for flow by helping athletes remain focused and balance perceived challenges with their abilities. In turn, the absorption, enjoyment, and fulfilment associated with flow may enhance both hedonic and eudaimonic wellbeing (Isham & Jackson, 2022).

Overall, the findings indicate that poorer psychological well-being was not observed in this specific sample of young rugby players despite the demands of their sport context. Rather, the results describe a multidimensional profile in which situational activation, fatigue, and perceived evaluation coexist with stress regulation, team cohesion, preserved sleep perception, and low negative mood states. These characteristics may be understood as personal and social resources compatible with adaptive functioning in youth sport environments. However, longitudinal research is required to determine whether sport participation contributes to the development of these resources over time.

Limitations and future research

This study has several limitations that should be considered when interpreting the findings. First, the sample size was small and drawn from a specific context, namely regional under-16 and under-18 rugby teams, which limits the generalizability of the results to other competitive levels, cultural contexts, and sport modalities. In addition, the sample showed a clear male predominance, preventing comparative analyses by sex and limiting the extrapolation of the findings to female athletes.

Second, the cross-sectional design does not allow causal relationships to be established between the variables analysed. Although associations were observed between psychological skills, mood states, fatigue, cohesion, sleep perception, and injury history, it is not possible to determine the directionality of these relationships or their evolution over time.

Third, a further limitation concerns the exclusive use of self-report questionnaires to assess all study variables. Although the instruments employed are well validated and widely used in sport psychology research and are particularly appropriate for capturing athletes' subjective perceptions and experiences, reliance solely on self-report measures may increase the risk of common-method variance and social desirability bias. Furthermore, the absence of complementary objective indicators, such as actigraphy to assess sleep, training load metrics, or physiological markers of recovery, limits data triangulation and the validation of the observed associations.

Finally, data were collected during preparation and training period rather than during competition, which may have influenced the reported levels of tension, fatigue, mood states, and sleep perception. Future studies should include larger and more balanced samples, longitudinal designs, and assessments conducted at different phases of the competitive season. Moreover, combining validated self-report questionnaires with objective measures of sleep, training load, and recovery would provide a more comprehensive understanding of the relationships among psychological skills, sleep, performance demands, injury history, and mental health indicators in young athletes.

 © 2026 ARD Asociación Española

Practical applications

From an applied perspective, the findings support the inclusion of psychological well-being and recovery as routine components of youth rugby development. Coaches and sport psychology professionals could implement brief, periodic monitoring of tension, fatigue, mood states, perceived recovery, and sleep-related difficulties at relevant points of the season, particularly during demanding training periods, competition phases, and return-to-play processes. Rather than interpreting isolated scores, practitioners should monitor changes over time and use them to initiate conversations with athletes, adapt training or recovery demands when necessary, and facilitate referral to qualified mental-health professionals when persistent difficulties are detected.

The results also suggest several specific areas for intervention. Psychological-skills programs could include stress regulation, coping with performance evaluation, goal setting, attentional control, and strategies for managing competitive demands. Given the associations involving Cohesion, teams could reinforce belonging and perceived support through shared goal setting, structured team discussions, peer-support initiatives, and the active involvement of athletes in team decision-making. These strategies may be especially relevant during injury rehabilitation, when maintaining contact with teammates, providing regular psychological support, and progressively preparing athletes for return to play may help reduce isolation and support adaptive recovery.

At an organizational level, rugby federations and youth development programs could incorporate psychological well-being, team climate, recovery, and injury-related support into their quality standards. This may include coach education in adolescent mental health, clearly defined referral pathways, access to sport psychology services, and coordinated monitoring involving coaches, medical staff, psychologists, athletes, and families. Given the cross-sectional nature and small sample of the present study, these recommendations should be regarded as applied directions to be evaluated in future longitudinal and intervention-based research.

CONCLUSIONS

This study suggests that young rugby players may present a psychological profile compatible with adaptive functioning and favourable indicators of psychological well-being, despite exposure to a demanding training environment. In this sample, players reported generally adequate perceived sleep quality, low negative mood states, moderate tension, and preserved vigour.

The findings also suggest that psychological skills, particularly Stress Control, Mental Skills, Motivation, and Cohesion, may play an important role in how young rugby players adapt to fatigue, perceived evaluation, and injury-related experiences. Previous injury was associated with higher Mental Skills and Cohesion, which may indicate that, when appropriately supported, the injury and return-to-play process can become a context for psychological learning, coping development, and strengthening of team belonging.

Taken together, these results support the idea that youth rugby may provide valuable context for the development of psychological resources and the promotion of psychological well-being, provided that training environments combine performance demands with adequate recovery, social support, and attention to athletes' emotional and psychological needs.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Verónica Gómez-Espejo, Antonio Núñez. Methodology: Verónica Gómez-Espejo, Antonio Núñez, Laura Gil-Caselles. Formal analysis: Laura Gil-Caselles. Investigation: Verónica Gómez-Espejo, Antonio Núñez, Laura Gil-Caselles, Paula Ortiz-Márholz. Data curation: Laura Gil-Caselles, Paula Ortiz-Márholz. Writing – original draft: Verónica Gómez-Espejo, Antonio Núñez. Writing – review & editing: Verónica Gómez-Espejo, Antonio Núñez, Alejandro García-Mas, Aurelio Olmedilla. Supervision: Verónica Gómez-Espejo, Antonio Núñez. Project administration: Aurelio Olmedilla. Manuscript adaptation to journal requirements: Aurelio Olmedilla.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This study was partially supported by the Psychology Program of the High-Performance Sports Centre CAR Infanta Cristina, Los Alcázares, Murcia, Spain (Grant No. UMU31047-GINVEST10294).

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was conducted in accordance with the principles of the Declaration of Helsinki for research involving human participants. The protocol was approved by the Ethics Committee of the University of Murcia, Spain (reference ID 4734/2023). All participants provided written informed consent. In the case of minor participants, written authorisation was also obtained from their parents or legal guardians.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

 © 2026 ARD Asociación Española

ACKNOWLEDGEMENTS

The authors would like to thank the federation representatives, coaches, and players who participated in this study.

REFERENCES

Allen, M. S., Greenlees, I., & Jones, M. V. (2013). Personality in sport: A comprehensive review. *International Review of Sport and Exercise Psychology*, *6*(1), 184–208. https://doi.org/10.1080/1750984X.2013.769614

Allen, M. S., Laborde, S., & Walter, E. E. (2021). Extraversion development in childhood, adolescence and adulthood: Testing the role of sport participation in three nationally representative samples. *Journal of Sports Sciences*, *39*(19), 2255–2263. https://doi.org/10.1080/02640414.2021.1930672

Ato, M., López-García, J. J., & Benavente, A. (2013). Un sistema de clasificación de los diseños de investigación en psicología. *Anales de Psicología*, *29*(3), 1038–1059. https://doi.org/10.6018/analesps.29.3.178511

Bergeron, M. F., Côté, J., Cumming, S. P., Purcell, R., Armstrong, N., Basilico, L., Burrows, K., Charrin, J.-B., Felix, A., Groesswang, H., Iwasaki, Y., Kocher, M., Martowicz, M., McConnell, K., Moran, J., Holm-Moseid, C., Mountjoy, M., Soligard, T., Tetelbaum, E., … Erdener, U. (2024). IOC consensus statement on elite youth athletes competing at the Olympic Games: Essentials to a healthy, safe and sustainable paradigm. *British Journal of Sports Medicine*, *58*(17), 946–965. https://doi.org/10.1136/bjsports-2024-108186

Brandt, R., Bevilacqua, G. G., & Andrade, A. (2017). Perceived sleep quality, mood states, and their relationship with performance among Brazilian elite athletes during a competitive period. *Journal of Strength and Conditioning Research*, *31*(4), 1033–1039. https://doi.org/10.1519/JSC.0000000000001551

Campo, M., Champely, S., Lane, A. M., Rosnet, E., Ferrand, C., & Louvet, B. (2019). Emotions and performance in rugby. *Journal of Sport and Health Science*, *8*(6), 595–600. https://doi.org/10.1016/j.jshs.2016.05.007

Charest, J., & Grandner, M. A. (2020). Sleep and athletic performance: Impacts on physical performance, mental performance, injury risk and recovery, medical health, and mental health. *Sleep Medicine Clinics*, *15*(1), 41–57. https://doi.org/10.1016/j.jsmc.2019.11.005

Chartrand, J. M., Jowdy, D. P., & Danish, S. J. (1992). The Psychological skills inventory for sports: Psychometric characteristics and applied implications. *Journal of Sport and Exercise Psychology*, *14*(4), 405–413. https://doi.org/10.1123/jsep.14.4.405

Coffey, M. (2023). *Athletes' intrateam social identities and perceptions of performance, group cohesion, and group membership in female rugby teams* [Master's thesis, University of Calgary]. PRISM Repository. https://ucalgary.scholaris.ca/items/fec39a65-31bb-48f5-902d-1a9b0a601806

Davis, A. S., Kafka, A. M., González-Morales, M. G., & Feitosa, J. (2022). Team belonging: Integrating teamwork and diversity training through emotions. *Small Group Research*, *53*(1), 88–127. https://doi.org/10.1177/10464964211044813

Escobar-Córdoba, F., & Eslava-Schmalbach, J. (2005). Validación colombiana del índice de calidad de sueño de Pittsburgh. *Revista de Neurología*, *40*(3), 150–155. https://doi.org/10.33588/rn.4003.2004320

Fuentes, I., Balaguer, I., Meliá, J. L., & García-Merita, M. L. (1995). *Forma abreviada del Perfil de los Estados de Ánimo (POMS)*. In Actas del V Congreso Nacional de Psicología de la Actividad Física y el Deporte (pp. 29–39).

Fullagar, H. H. K., Duffield, R., Skorski, S., Coutts, A. J., Julian, R., & Meyer, T. (2015). Sleep and recovery in team sport: Current sleep-related issues facing professional team-sport athletes. *International Journal of Sports Physiology and Performance*, *10*(8), 950–957. https://doi.org/10.1123/ijspp.2014-0565

García-Mas, A., Aguado, F. J., Cuartero, J., Calabria, E., Jiménez, R., & Pérez, R. (2003). Sueño, descanso y rendimiento en jóvenes deportistas de competición. *Revista de Psicología del Deporte*, *12*(2), 181–195.

Gil-Caselles, L., Martínez-López, M., González-Hernández, J., & Olmedilla-Zafra, A. (2023). Historia de lesiones, perfeccionismo, catastrofismo y vulnerabilidad a la ansiedad en triatletas. *Cuadernos de Psicología del Deporte*, *23*(3). https://doi.org/10.6018/cpd.550281

Gil-Caselles, L., Ruiz-Barquín, R. R., Giménez-Egido, J. M., García-Naveira, A., & Olmedilla, A. (2025). Perfectionism, mental health and vulnerability to injury in triathletes. *Frontiers in Psychology*, *16*, 1561432. https://doi.org/10.3389/fpsyg.2025.1561432

Gimeno, F., Buceta, J. M., & Pérez-Llantada, M. C. (2001). El cuestionario «Características Psicológicas Relacionadas con el Rendimiento Deportivo» (CPRD): Características psicométricas. *Análisis de Psicología*, *19*(1), 93–113.

Gimeno, F., & Pérez-Llantada, M. C. (2010). *Características psicométricas del cuestionario CPRD*. In F. Gimeno & J. M. Buceta (Eds.), Evaluación psicológica en el deporte. El cuestionario CPRD (pp. 81-124). Dykinson.

Gu, S., Bi, S., Guan, Z., Fang, X., & Jiang, X. (2022). Relationships among sports group cohesion, passion, and mental toughness in Chinese team sports athletes. *International Journal of Environmental Research and Public Health*, *19*(22), 15209. https://doi.org/10.3390/ijerph192215209

Gupta, L., Morgan, K., & Gilchrist, S. (2017). Does elite sport degrade sleep quality? A systematic review. *Sports Medicine*, *47*(7), 1317–1333. https://doi.org/10.1007/s40279-016-0650-6

Haugen, E. (2022). Athlete mental health and psychological impact of sport injury. *Operative Techniques in Sports Medicine*, *30*(1), 150898. https://doi.org/10.1016/j.otsm.2022.150898

Hsieh, Y. C., Lu, F. J. H., Gill, D. L., Hsu, Y. W., Wong, T. L., & Kuan, G. (2024). Effects of mental toughness on athletic performance: A systematic review and meta-analysis. *International Journal of Sport and Exercise Psychology*, *22*(6), 1317–1338. https://doi.org/10.1080/1612197X.2023.2204312

Isham, A., & Jackson, T. (2022). Finding flow: Exploring the potential for sustainable fulfilment. *The Lancet Planetary Health*, *6*(1), e66–e74. https://doi.org/10.1016/S2542-5196(21)00286-2

Leeder, J., Glaister, M., Pizzoferro, K., Dawson, J., & Pedlar, C. (2012). Sleep duration and quality in elite athletes measured using wristwatch actigraphy. *Journal of Sports Sciences*, *30*(6), 541–545. https://doi.org/10.1080/02640414.2012.660188

Mahoney, M. J., Gabriel, T. J., & Perkins, T. S. (1987). Psychological skills and exceptional athletic performance. *The Sport Psychologist*, *1*(3), 181–199. https://doi.org/10.1123/tsp.1.3.181

McNair, D. M., Lorr, M., & Droppleman, L. F. (1971). *Manual for the Profile of Mood States*. Educational and Industrial Testing Service.

Nédélec, M., McCall, A., Carling, C., Le Gall, F., Berthoin, S., & Dupont, G. (2012). Recovery in soccer: Part I—Post-match fatigue and time course of recovery. *Sports Medicine*, *42*(12), 997–1015. https://doi.org/10.2165/11635270-000000000-00000

Núñez, A., Peris-Delcampo, D., Ortiz-Marholz, P., & García-Mas, A. (2025). El escudo de la salud: Relaciones entre la actividad física y el bienestar psicológico. *Retos*, *71*, 412–428. https://doi.org/10.47197/retos.v71.115757

Olmedilla, A., & García-Mas, A. (2009). El modelo global psicológico de las lesiones deportivas. *Acción Psicológica*, *6*(2), 77–91. https://doi.org/10.5944/ap.6.2.223

Peris-Delcampo, D., Núñez, A., Ortiz-Marholz, P., Olmedilla, A., Cantón, E., Ponseti, J., & García-Mas, A. (2024). The bright side of sports: A systematic review on well-being, positive emotions and performance. *BMC Psychology*, *12*(1), 284. https://doi.org/10.1186/s40359-024-01769-8

Pocius, E., & Malinauskas, R. (2024). Development of mental toughness among basketball sports school students. *Behavioral Sciences*, *14*(4), 314. https://doi.org/10.3390/bs14040314

Poulus, D. R., Sargeant, J., Zarate, D., Griffiths, M. D., & Stavropoulos, V. (2024). Burnout profiles among esports players: Associations with mental toughness and resilience. *Journal of Sports Sciences*, *42*(18), 1685–1694. https://doi.org/10.1080/02640414.2024.2405794

Roy-Davis, K., Wadey, R., & Evans, L. (2017). A grounded theory of sport injury-related growth. *Sport, Exercise, and Performance Psychology*, *6*(1), 35–52. https://doi.org/10.1037/spy0000080

 © 2026 ARD Asociación Española

Ryff, C. D. (1989). Happiness is everything, or is it? Explorations on the meaning of psychological well-being. *Journal of Personality and Social Psychology*, *57*(6), 1069–1081. https://doi.org/10.1037/0022-3514.57.6.1069

Sargent, C., Lastella, M., Halson, S. L., & Roach, G. D. (2014). The impact of training schedules on the sleep and fatigue of elite athletes. *Chronobiology International*, *31*(10), 1160–1168. https://doi.org/10.3109/07420528.2014.957306

Scanlan, T. K., Chow, G. M., Sousa, C., Scanlan, L. A., & Knifsend, C. A. (2016). The development of the Sport Commitment Questionnaire-2 (SCQ-2). *Psychology of Sport and Exercise*, *22*, 233–246. https://doi.org/10.1016/j.psychsport.2015.08.002

Scanlan, T. K., Russell, D. G., Wilson, N. C., & Scanlan, L. A. (2003). Project on elite athlete commitment (PEAK): I. Introduction and methodology. *Journal of Sport and Exercise Psychology*, *25*(3), 360–376. https://doi.org/10.1123/jsep.25.3.360

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality: Complete samples. *Biometrika*, *52*(3–4), 591–611. https://doi.org/10.1093/biomet/52.3-4.591

Shearer, D. A., Kilduff, L. P., Finn, C., Jones, R. M., Bracken, R. M., Mellalieu, S. D., Owen, N., Crewther, B. T., & Cook, C. J. (2015). Measuring recovery in elite rugby players: The brief assessment of mood, endocrine changes, and power. *Research Quarterly for Exercise and Sport*, *86*(4), 379–386. https://doi.org/10.1080/02701367.2015.1066927

Smyth, C. (1999). The Pittsburgh Sleep Quality Index (PSQI). *Journal of Gerontological Nursing*, *25*(12), 10–11. https://doi.org/10.3928/0098-9134-19991201-10

Thornton, C., Baird, A., & Sheffield, D. (2024). Athletes and experimental pain: A systematic review and meta-analysis. *The Journal of Pain*, *25*(6), 104450. https://doi.org/10.1016/j.jpain.2023.12.007

Tranaeus, U., Gledhill, A., Johnson, U., Podlog, L., Wadey, R., Wiese Bjornstal, D., & Ivarsson, A. (2024). 50 years of research on the psychology of sport injury: A consensus statement. *Sports Medicine*, *54*(7), 1733–1748. https://doi.org/10.1007/s40279-024-02045-w

Wang, W., Schweickle, M. J., Arnold, E. R., & Vella, S. A. (2025). Psychological interventions to improve elite athlete mental wellbeing: A systematic review and meta-analysis. *Sports Medicine*, *55*(4), 877–897. https://doi.org/10.1007/s40279-024-02173-3

White, R. L., Vella, S., Biddle, S., Sutcliffe, J., Guagliano, J. M., Uddin, R., Burgin, A., Apostolopoulos, M., Nguyen, T., Young, C., Taylor, N., Lilley, S., & Teychenne, M. (2024). Physical activity and mental health: A systematic review and best-evidence synthesis of mediation and moderation studies. *International Journal of Behavioral Nutrition and Physical Activity*, *21*(1), 134. https://doi.org/10.1186/s12966-024-01676-6

World Medical Association. (2025). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human participants. *JAMA*, *333*(1), 71–74. https://doi.org/10.1001/jama.2024.21972

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

A pedagogical model for learning to teach wheeled sports: Perspectives from students on the Bachelor's degree in Sport

Diana Andrea Vera Rivera . *Faculty of Education. National Pedagogical University. Bogotá, Colombia.*
Luz Amelia Hoyos Cuartas. *Faculty of Physical Education. National Pedagogical University. Bogotá, Colombia.*

ABSTRACT

Introduction: This study integrated methodological theories derived from general and sports pedagogy, focusing on the training process for future physical education teachers. Objective: To analyse the perceptions of students in the Bachelor of Sports Science program at the National Pedagogical University (UPN) regarding the implementation of the "*Wheel of knowledge*" teaching model. Methodology: This project employed a qualitative approach with a hermeneutic design, allowing for the understanding and interpretation of the categories of the didactic model and the process of learning to teach the sports of roller skating, figure skating, skateboarding, and inline hockey. The study was conducted using convenience sampling, with the participation of 50 third-semester students from the Sports Program at the National Pedagogical University (UPN). Instrument: An ad hoc questionnaire was designed and administered, consisting of 20 open-ended questions organized into two categories: a) teaching model and b) "*Learning to teach wheeled sports*." The instrument was assessed using expert judgment and analysed using Kendall's coefficient ($W = .78$, $p < .05$), revealing significant consensus and strong expert agreement. Results: The analysis revealed that teacher candidates view the "*Wheel of knowledge*" instructional model as a pedagogical alternative for structuring instructional mediation in wheeled sports. The discourse analysis identifies the dimension of teaching action and implementation as the transformative axis of pedagogical practice, where traditional methodologies can be combined through strategies mediated by creativity and the specific reconfiguration of teaching.

Keywords: physical education; teaching methods; pedagogy; student perception; teacher training; wheeled sports.

Cite this article as:
Vera Rivera, D. A., & Hoyos Cuartas, L. A. (2026). A pedagogical model for learning to teach wheeled sports: Perspectives from students on the Bachelor's degree in Sport. *Journal of Human Sport and Exercise, 21*(4), 1652-1666. https://doi.org/10.55860/95767542

Corresponding author. *Facultad de Ciencias de la Educación. Universidad Pedagógica Nacional. Bogotá, Colombia.*
E-mail: daverar@pedagogica.edu.co
Submitted for publication July 19, 2026.
Accepted for publication August 31, 2026.
Published September 30, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/95767542

© 2026 ARD Asociación Española

INTRODUCTION

When we consider a pedagogical model as a space for ongoing reflection and inquiry into the process of learning to teach sports, this is where the theoretical contribution of the present study becomes significant, drawing on the perspectives of various authors, general pedagogy, and the field of sports. Midoul et al. (2026) and Hernández et al. (2019) emphasize that the process of learning to teach does not focus solely on teacher-directed content but is also nourished by shared experiences, enabling students to discover ways to transform the studied content and apply it to a specific context. Hoyos (2024) proposes transforming knowledge acquisition based on the concept of pedagogy, stating that pedagogy is the tool that addresses not only how to teach but also what to teach.

Martin et al. (2026) and Juvera et al. (2021), based on physical education teachers' perceptions, determined the importance of implementing new teaching methods tailored to the specific needs of sports and physical education. Hoyos (2022) highlights the constant interaction between what teachers think, what students want to learn, and the content deemed necessary. In the specific case of students in sports education, they must be attuned to selecting and implementing decisions in their learning processes that allow them to transform their role as teachers from a perspective of analysis and interaction with the subject matter.

Chang et al. (2026) and Morón et al. (2024) address the need to identify a more effective instructional planning process that enhances students' holistic education. The specific objective was to assess learning preferences according to the four quadrants (assimilative, divergent, convergent, and accumulative) and based on this, to design personalized strategies to optimize teaching. Luna (2019) describes a study on the formative assessment of a university educational model. By combining various methodological techniques, administering large-scale questionnaires, and focusing on identifying critical elements, this makes it an essential tool for managing educational quality and relevance in the university setting.

In their study, Brasó et al. (2023) analyse the impact of a course and propose a training model based on perceptions of competencies and teaching strategies. Medina et al. (2020) propose developing tools to evaluate the teaching process; the purpose of the text revolves around validating a scale that allows for reflection on the peer teaching-learning process in the technical and tactical models of sport. For their part, Cisternas et al. (2023) note that physical education teacher training should focus on the fields of didactics, pedagogy, and the specific practices of various sports disciplines.

From this perspective, López (2025) establishes a teaching system with a greater theoretical and less practical component for the various aspects of sports. Olvera and Fernández-Morales (2021) emphasize that, for teaching sports, traditional teaching models can be used more frequently than approaches based on meaningful learning and shared classrooms. For their part, Pizarro et al. (2024) established a program based on the comprehensive teaching model to improve the motivation of hockey players, while the study by Brasó et al. (2023) focused on developing teaching units for physical education teacher training, based on the experiences of students guided by educational research.

Amorim and Ribeiro-Silva (2022) reflect on teacher training in physical education, defining a desirable teacher profile for their professional work. Similarly, López et al. (2020) designed a new method for evaluating content through an approach that incorporates teamwork and the actual implementation of a teaching practice. Following this approach, Manso et al. (2021) developed a proposal based on Goubak, which refers to the integration of alternative sports. This study invites the identification of new methodologies for integrating the teaching and learning processes specific to physical education and sports.

Findings from studies related to didactic models as a means of learning to teach sports provide a starting point for generating proposals in the field of wheeled sports, specifically in the training of future graduates, equipping them with the skills and abilities to adapt relevant knowledge to different sports contexts. This leads to the central objective of this research: to analyse the perceptions of students in the Bachelor's Degree in Sports regarding the implementation of the teaching model, "*Wheel of knowledge*."

METHODOLOGY

This qualitative study, based on a hermeneutic design, included 50 undergraduate students in the Sports Studies program at the National Pedagogical University: 15 women between the ages of 18 and 19, and 35 men between the ages of 19 and 21. The sampling method was purposive, as the participants were already enrolled in the academic program. The study adheres to the ethical principles set forth in UPN Resolution 1642 of 2018 and the UNESCO Declaration on Bioethics and Human Rights; thus, this research complied with the principles of human dignity and human rights, posed no harm to the participants, who agreed to participate, and signed an informed consent form that informed the participant of all procedures and the use of data solely for academic purposes.

Instrument

An ad hoc questionnaire consisting of 20 open-ended questions was designed and administered. These questions were strategically grouped into two key categories: a) teaching model, which addressed aspects such as pedagogy and the implementation of the model; and b) learning to teach wheeled sports, which focused on the dimensions of creativity, transformation, and support.

Validation was conducted through systematic evaluation by a panel of 15 experts, 8 of whom held a Ph.D. in Education or Physical Activity and Sports Sciences, 6 held a master's degree in Didactics, Pedagogy, or Sports Sciences, and 1 was a national-level skating coach.

The validation criteria used by the experts included: relevance of the categories, conceptual clarity, pedagogical coherence, adequacy of items, and alignment with the research objectives. The Content Validity Index (CVI) analysis was performed using the ja.Moví software, version 2.7, to measure the degree of agreement among the 15 experts regarding the relevance of the items.

The structure of the questionnaire (20 items) was analysed. The I-CVI indicated that 95% of the items obtained a value of 1.0, reflecting unanimous agreement among the 15 experts regarding their clarity and relevance. The remaining items reached an index of .93, and the scale-level content validity index met the .95 criterion, indicating strong content validity for measuring perceptions regarding the implementation of the "*Wheel of knowledge*" model. Kendall's W concordance analysis was used to assess the degree of agreement among experts in their ratings. The resulting W value was .78, indicating strong expert agreement.

To ensure transparency, scientific replicability, and open access, the final version of the questionnaire and its corresponding application guide are available in the institutional repository of Cuauhtémoc University under the title of the doctoral dissertation (Perception of a Didactic Model for Teaching Wheeled Sports) or by sending a request to the authors' email addresses.

Structure of the "Wheel of knowledge" teaching model

The "*Wheel of knowledge*" teaching model is the result of the doctoral dissertation mentioned above. It integrates teaching theories, pedagogical principles of sport, and strategies designed to facilitate the learning

 © 2026 ARD Asociación Española

of content specific to wheeled sports, such as roller hockey, skateboarding, and roller skating. This framework is detailed in Table 1.

Table 1. Structure of the instructional model (Wheel of Knowledge).

Component	**Characterization (M.D.)**	**Interaction (M.IN.)**	**Implementation (M.IP.)**	**Transformation (M.T.) and Assessment (M.E.)**
General Instructional Models	Active, Socratic	Integrative, Collaborative	Mastery Learning, Technological Perspective	Communicative-Interactive
Teaching Models and Principles (Sports)	Personal and Social Responsibility	Collaborative Learning and Adaptation	Skill-Based Instruction, Progression	Comprehensive Education, Conscious Participation
Learning Theories and Teaching Styles	Cognitive; Task Assignment	Constructivist; Guided Discovery	Comprehensive; Problem-Solving	Comprehensive; Metacognition
Phase Explanation	Setup Phase In this phase, the student-teacher becomes familiar with sports that share the use of the wheel. Sessions are structured around guiding questions following the Socratic model and focus on creating initial learning scenarios that foster trust and interaction. Students participate in instructor-guided exercises, identifying key instructional elements such as postural alignment, falling techniques, movement execution without and with equipment, use of the stick, and unstable bases. Video analysis activities are also conducted to promote reflection on movement execution and learning processes.	Introductory Phase Students begin learning how to teach through the exploration of wheeled sports. Research activities and collaborative discussions encourage them to analyse the evolution of these sports and identify appropriate teaching elements. Through integrative and collaborative models, students design artifacts such as functional skateboard prototypes and develop teaching strategies based on collaborative learning, teamwork, and adaptation.	Foundation Phase In this phase, students consolidate teaching processes through comprehensive learning. They study the technical fundamentals of various wheeled sports, including figure skating, skateboarding, and hockey. Theoretical content is examined before practical application, enabling students to identify and understand each technical element through skill-based instruction and progressive learning.	Specialization Phase The student-teacher applies the knowledge acquired throughout the program, focusing on the process of learning to teach. Communication strategies, comprehensive instruction, experiential learning, lesson planning, content organization, and sports festival management are integrated into practice. The emphasis is placed on demonstrating the ability to teach wheeled sports effectively while promoting active student participation and reflective learning.

The "*Wheel of knowledge*" instructional model is designed to structure the process of learning to teach wheeled sports by recognizing teaching as a continuous cycle. Its elements are not treated in isolation; rather, each component contributes to linking experiences that reflect the progression of learning. The conceptual foundation of the model was established based on the methodological work of Olguín et al. (2025) on how to implement teaching strategies in educational settings.

The "*Wheel of knowledge*" model differs from other proposals for sports instruction in that it integrates the teaching of technical elements with the creation of supportive learning environments, achieved by identifying students' prior knowledge with the aim of consolidating and transforming it (Rodríguez et al., 2023). The

"*Rueda el saber*" model posits that the teaching-and-learning process involves giving pre-service teachers the opportunity to become agents who constantly analyse and reflect on their role as future educators, transforming their motor experiences into a setting for constructing meaningful learning relevant to their role as teachers (Hoyos, 2024).

Table 2. Comparison of the "*Wheel of knowledge*" model vs. instructional models.

Teaching/Instructional model	**Main approach**	**Teacher´s role**	**Future Teacher´s role**	**Similarities and differences with the "*Wheel of knowledge*"**
Global / Analytical (Hoyos, 2012)	Repetition of analytical technical movements and automation of sports techniques.	Direct instruction, demonstration of the technique, and correction of errors.	Future teachers practise technical skills and progressively master the sport's techniques.	Difference: The analytical model requires a progression from basic movement patterns to more complex technical execution. "*Wheel of knowledge*" uses the technique as a means of constructing an analysis and teaching the athletic movement.
Comprehensive / TgfU (Harvey, 2006; Pizarro et al., 2024)	Tactical understanding and decision-making through simplified game situations.	Tactical problem facilitator and Socratic questioner.	An active contributor to solving tactical problems in the game.	Similarity: Both use guided discovery. Difference: TGfU focuses on game tactics. The "*Wheel of knowledge*" model focuses on learning to teach by understanding the physical, technical, and tactical aspects of wheeled sports.
Physical Education (MED) (Siedentop, 1994)	Experiencing different roles in sports (referee, coach, captain) during actual seasons.	Organizer, guide, and environmental manager.	An active role assigned within a sports team.	Similarity: Collaborative work and hands-on experience with the competency-based system through festivals. Difference: MED focuses on general sports culture; "*Rueda el saber*" develops teachers' instructional competencies.
Personal and Social Responsibility. (TPSR) (Hellison, 1983)	Development of social-emotional values, autonomy, and behavioural self-regulation.	An ethical guide who fosters opportunities for reflection and autonomy.	An individual who is self-regulated and shares responsibility for their environment.	Similarity: Training in values and assertive communication. Difference: TPSR prioritizes social behaviour; "*Wheel of knowledge*" balances human values and sports education.
"*Wheel of knowledge*" (Vera-Rivera, 2026)	Learn how to teach wheeled sports by integrating general and sports-specific teaching methods.	Mediator, collaborator, and facilitator of knowledge.	A builder of knowledge, a creator of resources, and a mentor to learners.	Holistic Integration: It synthesizes the best of each approach and introduces the transformation of knowledge through performance.

The "*Wheel of knowledge*" model offers a continuous learning process organized into four stages: Assessment: This stage identifies students' strengths and weaknesses in relation to wheeled sports. It aims to build confidence through activities with a Socratic approach (questions and assessment worksheets) and basic motor exploration (sensory activities). Students' prior knowledge is assessed to help them progress from simple to complex concepts. Next comes the Interaction phase: this promotes collaborative work and

 © 2026 ARD Asociación Española

inquiry, based on guided discovery to understand the dynamics of wheeled sports and facilitate motor adaptation to each sport. Implementation: Focused on learning through problem-solving. It uses comprehensive instruction and active feedback to consolidate technique through methodological progressions. Transformation: This represents the culmination of the model's metacognitive process. The teacher-in-training transfers and transforms knowledge into their actual practice as an instructor, consolidating their professional identity; reflection on their role is expected. This approach proposes recognizing errors or doubts as inputs for learning, stimulates the capacity for innovation in the design of teaching environments, and promotes the transfer of teaching competencies to real-world educational settings in the field of teaching wheeled sports.

The "*Wheel of knowledge*" model contributes to the training of future physical education teachers through an ongoing learning environment where the future educator and the model's facilitator continuously analyse interaction and reflection. The model seeks to go beyond the learning of technical elements of roller skating, skateboarding, and inline hockey by fostering critical thinking, self-assessment, and pedagogical application. This dynamic fosters what Sánchez et al. (2022) define as learning experiences generated through emotions and interactions with the environment, allowing the future graduate to question their theoretical preconceptions, identify flaws in verbal and nonverbal communication, and independently restructure their lesson plans. Consequently, the teacher in training develops a professional profile characterized by empathy and methodological flexibility in the face of error or doubt.

Table 3. Transferring the "*Wheel of knowledge*" model to other sports and paralympic contexts.

Context / Sports setting	Purposes of the model	Characteristics of the model
Conventional Sports on Wheels (Skating, Skateboarding, Hockey)	Postural control on unstable surfaces (tubes, bottles, canes, mats, boxes, cushions, balls), techniques for falling while in motion, propulsion and braking using specific equipment, and the use of a stick and a board.	sequential progression, from setting the stage to specialization, self-creation of teaching materials, video analysis of postural movements, and socio-emotional mediation.
Ball Sports	Use of movement analysis for technical correction, based on the Socratic method, and the development of tactics in real game situations.	Structure based on instructional moments (MD, MIN, MIP, MT, ME), use of Comenius's triad (Teacher-Student-Content), and formative and shared assessment.
Paralympic Wheeled Sports (Wheelchair Basketball, Rugby, Tennis, Wheelchair Track and Field, Para cycling).	Controlling the centre of gravity in a sports wheelchair, propulsion techniques, emergency braking, manoeuvrability, and leaning with the wheelchair, understanding each player's role based on the nature of the sport.	Adaptation of the familiarization phase to facilitate interaction with the chair as an extension of the body, balance awareness, and educational principles of responsibility and conscious participation.

RESULTS AND DISCUSSION

The analysis process was guided by a hermeneutic design for interpreting students' perceptions, following a sequence of defined stages outlined by López (2002), which includes the selection of units of analysis, the coding of information, categorization according to dimensions, and finally the interpretation of the results of participants' perceptions in light of the implementation of the "*Wheel of knowledge*" teaching model.

Figure 1 illustrates the transition from the preliminary understanding of perceptions to the explicit articulation of emerging categories, resulting from the analysis and interpretation of participating students' assessments of the "*Wheel of knowledge*" model.

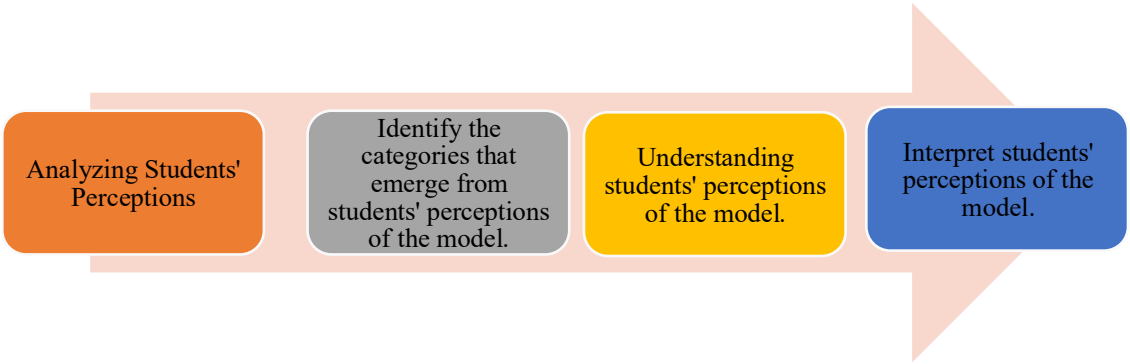


Figure 1. Hermeneutic design phase.

To comply with the interpretive scope, as explained in Figure 1, the process included the selection of units of analysis, the coding of information, categorization according to dimensions, and finally the interpretation of the results regarding perceptions of the implementation of the "*Wheel of knowledge*" teaching model. The following sections present the steps carried out using the hermeneutic technique developed in the following stages:

a) Pattern identification: This involves tracking information related to the subject of study, counting the selected responses in relation to the categories, and then identifying the code.
b) Coding: The categories of analysis identified in the students' responses were assigned specific colours to guide the identification of codes generated with Atlas.ti 24.
c) Comprehension: This involves synthesizing the category analysis, followed by determining the participating students' perceptions of the model and what it contributes to the process of learning to teach wheeled sports.
d) Interpretation: At this stage, the participants' perceptions are interpreted using the interpretive exercise provided by Atlas.ti 24, followed by the connections between each of the students' responses and the categories "*didactic model*" and "*learning to teach wheeled sports*."

Coding procedures

The qualitative analysis was conducted using Atlas.ti 24 software through a three-phase hermeneutic process: a) selection of units of analysis from the ad hoc questionnaire and document matrix; b) deductive and deductive-emergent coding, assigning codes to the central categories: Didactic Model (Code MED) and Learning to Teach (Code PAAE); and c) axial categorization, establishing semantic networks of density and interconnection among dimensions (Didactics, Implementation, Learning, Teaching) and subdimensions (Creativity, Transformation, Support).

Information triangulation

A triangulation of sources and methods was applied, comparing: a) the discursive perceptions of the 50 student teachers collected via the questionnaire; b) the document analysis matrix; and c) the practical teaching evaluations and field observation protocols recorded in session logs and photographic/videographic evidence.

To ensure the rigor of the qualitative research, care was taken to ensure that: a) the implementation of the model with participants in the field over 16 weeks and 32 sessions was carried out directly by one of the researchers; b) the credibility of the findings was supported through expert review and the use of representative verbatim quotes; c) a meticulous record was kept in the field journal; and d) data were stored in coded folders to preserve the participants' identities.

 © 2026 ARD Asociación Española

Results for the "teaching model" category

This section presents an analysis of perceptions regarding the "*Teaching model*" category, based on student responses. The semantic network visualizes the most significant relationships that emerge from student discourse regarding the elements that compose and structure the teaching model discussed during the course. Using Atlas.ti 24, thematic clusters, recurring phrases, and significant links were identified, reflecting how students understand, interpret, and internalize the fundamentals of the proposed model for teaching wheeled sports.

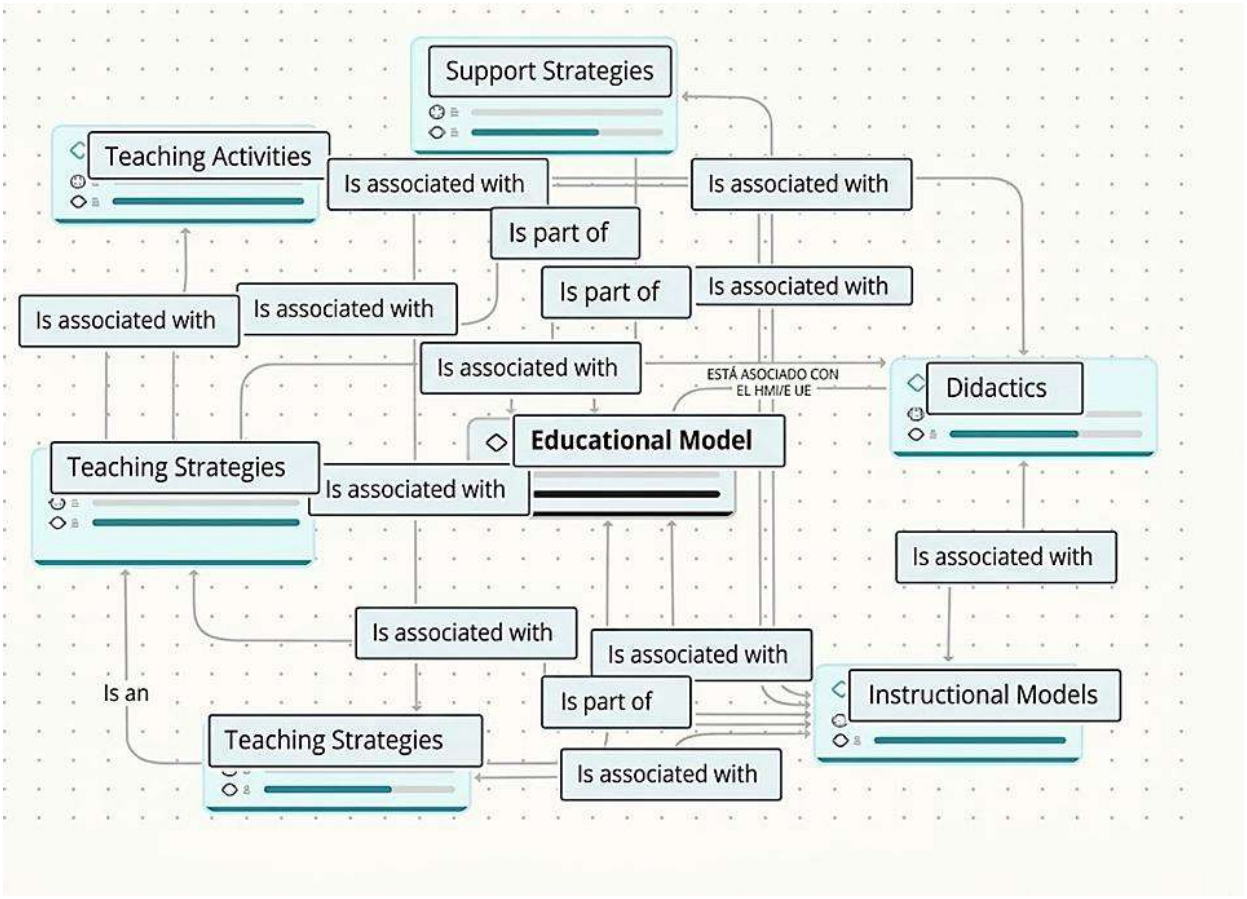


Figure 2. Analysis of perceptions regarding instructional models.

Figure 2 highlights the detailed relationships within the network of dimensions generated using Atlas.ti 24. It demonstrates how teaching strategies emerge in close connection with support strategies, forming a conceptual framework in which teaching practice and the instructional model are integrated as elements for the development of meaningful teaching learning experiences. The category "*teaching model,*" in conjunction with the dimensions of model implementation and teaching practice, reflects how these aspects do not operate in isolation but rather through constant dialogue and joint construction. According to the perception of the student teachers, they recognize the implementation of the "*Wheel of knowledge*" teaching model as an organized, coherent, and relevant framework for approaching the teaching of wheeled sports.

The implementation of the "*Wheel of knowledge*" model requires not only a clear conceptual structure but also intentional teaching practice that combines creative strategies with appropriate didactic principles, adapted to the specific characteristics of the sports being studied. Figure 2 illustrates how the students

participating in the study directly associate teaching methods with the implementation of the "*Wheel of knowledge*" teaching model. This association is reflected in the connection that emerges between the methodological strategies used in class and the proposed teaching models, where a close relationship is perceived between teaching practice and instructional strategies, including those oriented toward formative support. Thus, the teacher's pedagogical practice is understood as a systematic construction that incorporates relevant resources, clear timelines, and opportunities for constant feedback.

The category "*teaching model*" detailed in Figure 2 is understood by students as a process that integrates practical and recreational activities with support strategies, enabling an experiential approach to disciplines such as hockey, skateboarding, and roller skating. Participants highlight the importance of class organization, content distribution, the pedagogical intent of each activity, and the active role they play in the process. This semantic network thus demonstrates that students not only recognize the components of the model but also interpret its application as a coherent, effective educational experience centred on the development of their competencies as future physical education teachers.

To support the analysis, direct quotations taken from the statements of the 50 UPN students (Students 1 through 50) were included and organized according to the analytical categories and dimensions listed below. Some of the perceptions are presented as follows:

Category 1: Teaching Model (Dimensions: Pedagogy, Teaching Practice, Student Support)

- Quote 1.1 (Student 5): "*First of all, the class provided a foundation for sports practice with teaching tools that made learning easy... The professor uses various teaching methods, such as ball games and circuit training, to encourage active participation from the group*."
- Quote 1.2 (Student 1): "*I liked the way she used teaching methods to spark our creativity and employed various strategies to show us, for example, the correct way to teach hockey... In class, I really liked the explanation of each exercise*."
- Quote 1.3 (Student 8): "*The teacher is always respectful both inside and outside the classroom. She guides and directs each process; in my case, she always supported me with the equipment (skates) since it made me afraid, providing active feedback*."
- Quote 1.4 (Student 50): "*I feel that the class gave me much more than I expected—not just materials, strategies, lesson plans, and pedagogy… but it also enriched me emotionally, in my soul, and in my heart*."

Results for the category "learning to teach wheeled sports"

The "*learning to teach wheeled sports*" category focuses on the relationships revealed by the network of dimensions generated using Atlas.ti 24. It shows how the dimension of creativity is directly associated with the teaching phases proposed within the didactic model, highlighting that such creativity becomes a fundamental alternative for stimulating the process of learning to teach wheeled sports. This finding is illustrated in Figure 3, showing that the "*Wheel of knowledge*" didactic model not only generates a content structure but also stimulates the development of innovative teaching proposals by students.

In this regard, the category "*the process of learning to teach wheeled sports*" highlights how future teachers recognize and value their training experience within the framework of the implemented model. Finally, it is acknowledged that the training process is not limited to the acquisition of technical knowledge, but also involves a connection to the student's attitude, commitment, and willingness to participate in the environments proposed by the model. This leads to the conclusion that teacher training within the "*Wheel of knowledge*"

 © 2026 ARD Asociación Española

model is oriented toward the reflective, participatory, and creative construction of pedagogical knowledge in sports.

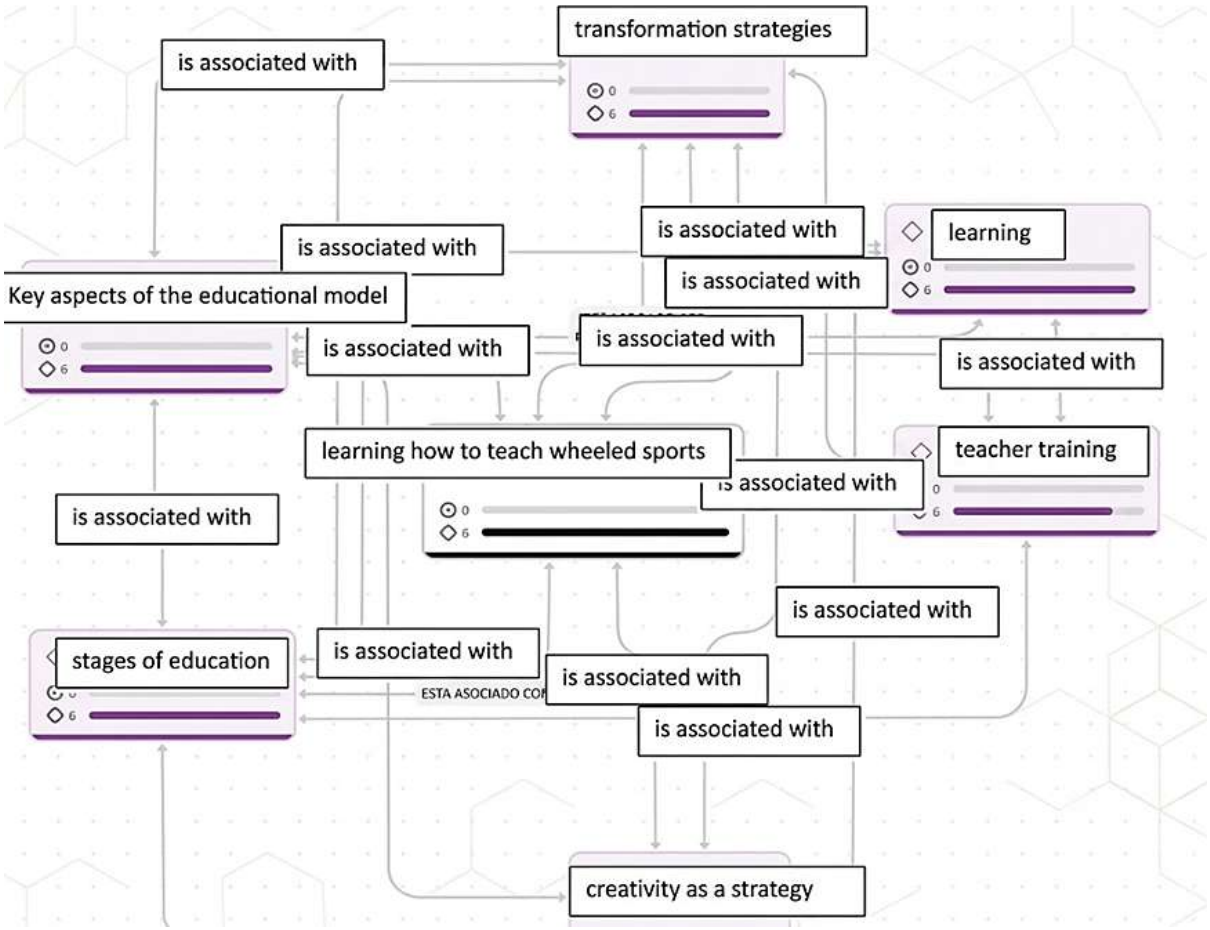


Figure 3. Analysis of perceptions regarding the "*learn to teach wheel sports*" model.

The process of learning to teach is understood as an intentional and structured scenario that enables the progressive development of skills aimed at transmitting and mediating specific content or topics. Thus, the interaction between teaching methods and practical classroom scenarios fosters a broader understanding of the content and allows future sports education graduates to integrate knowledge, values, and skills to build their role as teachers. From the students' perspective, there is a connection that helps identify the process of learning to teach wheeled sports through methodologies and activities that involve teaching from the simplest to the most complex, integrating specific knowledge from each of the sports disciplines: skating, hockey, and skateboarding. Broadly speaking, there is evidence of a shared understanding of the teaching process as a transformative and enriching space, both conceptually and experientially.

Figure 3 illustrates how students are able to establish meaningful connections between the process of learning to teach wheeled sports and various elements related to creativity, understood as a key strategy for facilitating learning while simultaneously laying a solid foundation for the transformation of acquired knowledge. Based on the analysis conducted, it is highlighted that students not only recognize the content of the implemented educational model but also identify that its structure incorporates the instructional moments

defined in the model and aligns with the phases of sports instruction, encouraging them to create and apply teaching methodologies appropriate to a given context.

Below are some of the insights from: Category 2: Learning to Teach Wheeled Sports (Dimensions: Learning, Transformation, Creativity).

- Quote 2.1 (Student 6): "*It was very interesting that we, as teachers in our academic settings, were encouraged to seek out this creative alternative so we could develop our own materials (making skates and sticks).*"
- Quote 2.2 (Student 14): "*I feel that from the very first day, the instructor was charismatic and respectful of our different backgrounds… She takes the time to observe each of us individually to teach us the importance of personal growth, focusing more on technique*."
- Quote 2.3 (Student 18): "*In this age of technology, learning to conduct observational work using technological tools (such as recording one's posture on a cell phone) is a necessary skill that this course provided*."
- Quote 2.4 (Student 1): "*This teaching model applied by the teacher not only successfully taught us how to use or put these tools into practice but also allowed us to absorb her knowledge so that we could learn to teach our own students*."

To complement the triangulation process, this study combined student perceptions with three practical field assessment instruments:

1. Postural and video observation protocols:
During the Diagnostic and Interaction Sessions, biomechanical observation templates were used to assess the students' performance. Analysis using mobile devices allowed for a comparison of the student's self-perception with the observed technical execution, regarding qualitative improvements in each movement, the identification of starting posture, gliding, and the stability of the centre of gravity on wheels.

2. Practical assessments based on teaching competencies (experiential classes):
In the Specialization Phase, each teacher in training enrolled in the Bachelor of Sports Science program completed the process of learning to teach wheeled sports by conducting an actual teaching session with an assigned learner. The future teacher's performance was evaluated using a matrix of pedagogical competencies: a) mastery of technical and didactic language; b) management of the learner's physical and emotional safety; c) methodological progression from simple to complex tasks; and d) warmth and empathy in formative feedback.

3. Integrated triangulation matrix:
The findings showed convergence between the prospective teachers' self-reported confidence in the questionnaire and the pedagogical effectiveness observed in the teaching practicum. Those who reported a high impact in the creativity dimension also designed notable teaching variations during the performance at the "*Rueda el saber*" Festival, suggesting that the model helped transform theory into professional practice.

This establishes a link to the study by Olvera and Fernández-Morales (2021). Their findings reveal the persistence of traditional teaching models and, to a lesser extent, the implementation of innovative approaches such as meaningful learning and shared classrooms. Both studies agree on the importance of reforming teacher-training processes to meet contemporary educational demands. A significant dialogue was found with the research by Moreno et al. (2024), who analysed teachers' conceptions of physical education oriented toward the student's holistic development. Both studies agree on the importance of rethinking

 © 2026 ARD Asociación Española

teacher training, not only from a technical perspective but also from a human, affective, formative, and ongoing support perspective. This study incorporates a complementary perspective from Saraví (2019) research, which examines the construction of professional and academic identity in skateboarding. Although focused on a specific sport, the study provides key insights into the role of professional training in emerging and alternative disciplines, highlighting the need to strengthen the competencies of those who take on roles as coaches or trainers. This line of analysis aligns with the findings of this research, as it proposes a pedagogical model that focuses not only on the technical instruction of roller sports but also on the development of a teaching profile with a professional, pedagogical, and social vision.

Cisternas et al. (2023), who, through a review, identified key elements in the development of physical educators' professional identity. While this research proposes a training framework based on pedagogical practice and the use of teaching strategies applied to wheeled sports, the study emphasizes that teaching identity is progressively shaped through meaningful training experiences. Both studies agree that pedagogical practices are fundamental to consolidating the role of the future teacher, not only in terms of technical knowledge but also in terms of their social, personal, and professional dimensions. A point of convergence is established with the study by González and Abad (2023), who examine artistic-visual and digital learning in figure skating within higher education. Both works, although from different perspectives, agree on the need to integrate new methodological strategies that enrich the training of sports professionals. While this study proposes a pedagogical model with a specific focus on developing teaching competencies in roller sports, it highlights the importance of incorporating digital, visual, and artistic elements into instruction, aiming for a more comprehensive education. Last but not least, the research by Manso et al. (2021), who developed an innovative proposal based on the alternative sport Goubak as a collaborative strategy in the initial training of physical education teachers. This convergence demonstrates that the use of teaching models centred on practical and collaborative experiences not only improves teaching performance but also addresses contemporary challenges in physical education, broadening the methodological and pedagogical scope of future professionals.

CONCLUSIONS

Through an analysis of the implementation of the "*Wheel of knowledge*" teaching model, it became evident how pedagogical practice can be adapted and enriched by designing learning environments that foster active participation and the acquisition of knowledge through experience. This research promotes the development of specific knowledge related to sports instruction, with an emphasis on the disciplines of roller skating, skateboarding, and inline hockey, approached not only from a technical perspective but also from a didactic and formative one.

Looking ahead to future work, we propose conducting a systematic follow-up on the implementation of the "*Wheel of knowledge*" teaching model, with the aim of formally integrating it as a curricular strategy within the curriculum for training future physical education teachers. This integration would help consolidate pedagogical processes that are more relevant and better adapted to the realities of today's sports environment. From there, this research opens the door to developing new lines of inquiry in university settings, school environments, and the field of sports training.

Another line of research emerging from this study focuses on evaluating the transfer of the didactic principles and strategies of the "*Wheel of knowledge*" teaching model to other sports contexts that share similar functional characteristics, such as Paralympic sports, which are also played on wheels. This proposal would allow for an analysis of how the model's methodological foundations can be adapted to specific scenarios,

opening the door to the possibility of conducting comparative studies that contrast the application of the teaching model with other content areas.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Diana Andrea Vera Rivera. Methodology: Luz Amelia Hoyos Cuartas, Diana Andrea Vera Rivera. Formal analysis: Diana Andrea Vera Rivera, Luz Amelia Hoyos Cuartas. Investigation: Diana Andrea Vera Rivera, Luz Amelia Hoyos Cuartas. Data curation: Diana Andrea Vera Rivera, Luz Amelia Hoyos Cuartas. Writing – original draft: Diana Andrea Vera Rivera, Luz Amelia Hoyos Cuartas. Writing – review & editing: Diana Andrea Vera Rivera, Luz Amelia Hoyos Cuartas. Supervision: Diana Andrea Vera Rivera, Luz Amelia Hoyos Cuartas.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

ACKNOWLEDGMENTS

The researchers would like to thank the students in the Bachelor of Sports Science program at the National Pedagogical University who participated in this study.

REFERENCES

Amorim, C., & Ribeiro-Silva, E. (2022). Professional identity in physical education: A review of the literature. *Retos: New Trends in Physical Education, Sport, and Recreation*, (46), 774–788. https://doi.org/10.47197/retos.v46.94479

 © 2026 ARD Asociación Española

Brasó, J., Pérez-González, M., Arderiu-Antonell, M., & Rillo-Albert, A. (2023). Teacher training in physical education: Creation of a repository of teaching units. *Retos: New Trends in Physical Education, Sport, and Recreation*, (49), 414–426. https://doi.org/10.47197/retos.v49.98114

Cisternas, C., Batista, P., Merellano-Navarro, E., & Ribeiro-Silva, E. (2023). Professional identity of physical education teachers: An integrative literature review. *Ebalonmano.com*, 19(3), 276–290. https://doi.org/10.17398/1885-7019.19.276

Chang, T., Ma, H., Chen, H., Yan, Z., & Cao, M. (2026). Beyond physical effort: Adolescent well-being and school belonging to school sports participation under the Chinese "double reduction" policy. *Journal of Human Sport and Exercise*, 21(3), 1144–1153. https://doi.org/10.55860/9b157f33

Díez García, R., & Márquez, I. (2015). La cultura skate en las sociedades contemporáneas: una aproximación etnográfica a la ciudad de Madrid. *Empiria. Revista de Metodología de Ciencias Sociales*, (30), 133–158. https://doi.org/10.5944/empiria.30.2015.13888

Espejo, R., Infantes-Rojas, B., Moya-Medina, M. A., & Morente-Oria, H. (2022). ICT as teaching tools for physical education teachers in formal training using the flipped classroom model. *PORT TK-EuroAmerican Journal of Sport Sciences*, 10(1), 1–10.

Gómez, J. L., Monroy-Bermúdez, L. de J., & Bonilla-Torres, C. A. (2019). Characterization of pedagogical models and their relevance to critical accounting education. *Entramado*, 15(1), 164–189. https://doi.org/10.18041/1900-3803/entramado.1.5428

González, M., & Abad-Segura, E. (2023). Approaches to artistic-visual and digital learning in higher education. *Maskana*, 14(1), 66–77. https://doi.org/10.18537/mskn.14.01.05

Guamangallo Naula, G. M. (2024). Gamification in the teaching-learning process of university students of physical activity and sports: Systematic review. *MENTOR Revista de Investigación Educativa y Deportiva*, 3(9), 1325–1347. https://doi.org/10.56200/mried.v3i9.8559

Guerrero, C., Correal-Cuervo, R., Bohórquez-Olaya, C., Burgos-Díaz, C., Jaimes-Bernal, C., & Montañez-Torres, C. (2023). Educational model, pedagogical practices, and faculty evaluations in higher education. *Education and Humanism*, 25(45), 205–226. https://doi.org/10.17081/eduhum.25.45.6594

Harvey, D. (2006). The STEM model as a didactic methodological resource for building critical scientific knowledge among physics students. *Revista de Educación y Ciencias, 10*(2), 45-60.

Hellison, D. (2003). *Teaching responsibility through physical activity* (2ª ed.). Champaign, IL: Human Kinetics.

Hernández, C. (2019). The process of teaching and learning: An inquiry from the educational context. *Scientific Journal*, 4(12), 254–274. https://doi.org/10.29394/Scientific.issn.2542-2987.2019.4.12.13.254-274

Hoyos, L. (2012). *Characterization of school sports programs in Bogotá: analysis of didactic models used for their teaching* [Doctoral research, University of León]. University of León Institutional Repository (BULERIA). https://buleria.unileon.es/handle/10612/2361

Hoyos, L. A. (2022). Comenius's influence on teaching models for contemporary school sports education. In M. Prada & D. Rubio (Eds.), *Comenius, 350 years later* (pp. 289–308). National Pedagogical University.

Hoyos, L. A. (2024). Sport as a scientific discipline and its teachability. In D. Parga, P. Zapata, & R. Tuay-Sigua (Eds.), *Science and mathematics education: Contexts, challenges, and opportunities* (pp. 423–438). National Pedagogical University.

Juvera, J. L., Ceballos-Gurrola, O., Zamarripa-Rivera, J. I., Rodríguez, J. R., & Fernández-Barradas, E. Y. (2021). Physical education teachers' perceptions of the new educational model in Mexico. *Retos*, (42), 916–923. https://doi.org/10.47197/retos.v43i0.88188

López, F. (2002). Content analysis as a research method. *Revista de Educación*, (4), 167–180.

López, R. (2025). Best practices in the training of skating coaches. University of Flores; Argentine Skating Confederation. https://doi.org/10.63790/b99jbd66

López-Pastor, V. M., Molina-Soria, M., Pascual-Arias, C., & Manrique-Arribas, J. C. (2020). La importancia de utilizar la evaluación formativa y compartida en la formación inicial del profesorado de educación física: los proyectos de aprendizaje tutorado como ejemplo de buena práctica. *Retos*, (37), 620–627. https://doi.org/10.47197/retos.v37i37.74193

Luna, E. (2019). Formative assessment of the educational model in higher education institutions in Mexico. *Mexican Journal of Educational Research*, 24(83), 997–1026.

Manso-Lorenzo, V., Fraile-García, J., González-Víllora, S., Evangelio, C., & Ibaibarriaga-Toset, Á. (2021). Innovating in the initial training of physical education teachers: Goubak as a collaborative proposal between teachers and students. *Spanish Journal of Physical Education and Sports*, (434), 55–64.

Martin-Aleman, W. F., Tovar Quintero, A. C., Pardo Daza, Y. R., Rodriguez, J. F., Tellez, L. A., & Peña, J. C. (2026). Relationship between neuromuscular performance and academic performance in university sports training students. *Journal of Human Sport and Exercise*, 21(3), 926–935. https://doi.org/10.55860/8dq1ap63

Medina Rivilla, A., & Salvador Mata, F. (Coords.). (2009). *Didáctica general* (2nd ed.). Pearson Educación; Universidad Nacional de Educación a Distancia.

Midoul, K., El Mohajir, B. E., El Hichami, O., & Souri, A. (2026). Methodological trends in machine learning for sports: A systematic and quantitative review (2020–2026). *Journal of Human Sport and Exercise, 21*(3), 978–993. https://doi.org/10.55860/6ff7nv62

Moreno, M. J., Escobar-de-Murzi, F., Porras-Ramírez, K. A., & Bolívar-Silva, O. D. (2024). Teachers' conceptions of physical education for the holistic development of students. *Perspectivas Magazine*, 9(S1), 160–171. https://doi.org/10.22463/25909215.4771

Morón, E. D. J. (2024). A teaching model based on learning styles for the holistic education of students. *Delectus*, 7(1), 52–62. https://doi.org/10.36996/delectus.v7i1.243

Olguín-Martínez, C. M., Martínez-García, V. M., Chávez-Hernández, A., & De la Paz, M. T. D. J. (2025). Contemporary pedagogical models in Mexican higher education. *Journal of Social Sciences*, XXXI(2), 139–153.

Olvera González, M., & Fernández Morales, K. (2021). Innovación educativa en la práctica docente en educación superior: revisión sistemática de la literatura. *Innovación Educativa (México, DF)*, 21(85), 31–51.

Pizarro, D., Cosín, J., González-Cutre, D., González-Fernández, F. T., & Práxedes, A. (2024). Influence of the ludo-technical model and teaching games for understanding on roller hockey player motivation. *Apunts Educación Física y Deportes*, 157, 31–39. https://doi.org/10.5672/apunts.2014-0983.es.(2024/3).157.04

Ríos, C. (2016). Figure skating: A medium for arts education. *Apunts Educación Física y Deportes, 15*, 37–59.

Rodríguez-Ortiz, A. M., Hernández-Rodríguez, J. C., López-Rúa, A. M., & Cadavid-Alzate, V. (2023). Analysis, classification, and philosophical foundations of critical thinking models. *Sophia, Philosophy of Education Collection, 35*, 211-248.https://doi.org/10.17163/soph.n35.2023.07

Saraví, J. (2023). Skateboarding y deporte : un análisis desde las voces de los y las jóvenes practicantes del Gran La Plata. Revista da Alesde 15(2), 161-174. https://www.memoria.fahce.unlp.edu.ar/art_revistas/pr.18774/pr.18774.pdf

Shaheen, M., Pradhan, S., & Ranajee, R. (2019). Sampling in qualitative research. In S. Pradhan (Ed.), *Qualitative techniques for workplace data analysis* (pp. 25–51). IGI Global. https://doi.org/10.4018/978-1-5225-5366-3.ch002

Siedentop, E. (1994). Learning to Teach. *Editorial Española. 157*, 41-69.

Sánchez Suricalday, A., García Varel, A. B., & Castro Martín, B. (2022). Development of an educational research model based on Constructivist Grounded Theory. *Márgenes: Revista de Educación de la Universidad de Málaga, 3*(2), 117-136. https://doi.org/10.24310/mgnmar.v3i2.13082

Vera- Rivera, D. (2026). *Percepción de un modelo didáctico para la enseñanza de los deportes sobre ruedas*. [Tesis de Doctorado, Universidad Cuauhtémoc México].

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

ORIGINAL ARTICLE

60-m sprint time and late-segment stride measures during horizontal plyometric training in youth athletes: A single-group field study

Carlos Francisco Hernández García. *University Institute of Physical Education and Sport. University of Antioquia (UdeA). Medellín, Colombia.*

Wilder Geovanny Valencia-Sánchez . *University Institute of Physical Education and Sport. University of Antioquia (UdeA). Medellín, Colombia.*

Samuel José Gaviria-Alzate. *Faculty of Education and Social Sciences. Antioquia Institute of Technology – University Institution (TdeA). Medellín, Colombia.*

ABSTRACT

This exploratory single-group study examined changes in 60-m sprint time and late-segment stride measures during six weeks of horizontal plyometric training. Nine male track-and-field athletes aged 12-13 years were assessed before and after a programme of 12 planned sessions. Sprint time was recorded with a smartphone application, and stride length, stride time and ground contact time were assessed from 120-Hz video over 40-48 m. Pre-test-post-test changes were analysed at the athlete level. Mean 60-m sprint time decreased from 10.46 ± 0.39 to 10.18 ± 0.28 s (mean change −0.282 s, 95% CI −0.479 to −0.085 s; p = .011; d_z = −1.10). Changes in stride length, stride time and ground contact time within the 40-48-m segment were inconclusive, with all confidence intervals including zero. Lower whole-sprint time was therefore accompanied by uncertain late-segment estimates, leaving the phase and mechanical basis of the change unresolved. The uncontrolled design and measurement uncertainty preclude attribution to the training programme. For youth sprint monitoring, total timing, phase-specific assessment and mechanical analysis provide complementary information; a change in overall performance does not, by itself, establish where or how that change occurred.

Keywords: biomechanics; measurement uncertainty; adolescence; field assessment; kinematics.

Cite this article as:
Hernández García, C. F., Valencia-Sánchez, W. G., & Gaviria-Alzate, S. J. (2026). 60-m sprint time and late-segment stride measures during horizontal plyometric training in youth athletes: A single-group field study. *Journal of Human Sport and Exercise, 21*(4), 1667-1678. https://doi.org/10.55860/j1eya459

Corresponding author. *Instituto Universitario de Educación Física y Deporte, Universidad de Antioquia (UdeA), Calle 70 No. 52-21, Medellín, Colombia.*
E-mail: Wilder.valencia@udea.edu.co
Submitted for publication August 12, 2026.
Accepted for publication September 21, 2026.
Published September 30, 2026.
Journal of Human Sport and Exercise. ISSN 1988-5202.
©Asociación Española de Análisis del Rendimiento Deportivo. Alicante. Spain.
doi: https://doi.org/10.55860/j1eya459

INTRODUCTION

Sprint performance is an important component of youth track-and-field and contributes to performance across many sports. Sprint velocity emerges from the interaction between stride length and stride frequency, which in turn reflects the magnitude, orientation, and timing of force application during ground contact (Buchheit et al., 2014; Haugen et al., 2019; Hunter et al., 2004; Morin et al., 2012). However, sprinting is not mechanically uniform across the race. Early acceleration depends strongly on the ability to produce and orient force horizontally, whereas maximum-velocity running requires high force production within progressively shorter ground-contact times (Buchheit et al., 2014; Haugen et al., 2019; Morin et al., 2012). Consequently, an improvement in total sprint time does not necessarily indicate that acceleration and maximum-velocity mechanics changed to the same extent.

Plyometric training uses rapid stretch-shortening-cycle actions to develop neuromuscular power and can improve sprint and jump performance (Cormie et al., 2011; Markovic & Mikulic, 2010; Sáez de Villarreal et al., 2012). When progressively prescribed and appropriately supervised, plyometric training is considered suitable for children and adolescents (Lloyd & Oliver, 2012; Lloyd et al., 2016; Ramirez-Campillo et al., 2023). Evidence from young athletes indicates that sprint adaptations may depend on age, maturation status, training dose, and exercise orientation (Norgeot & Fouré, 2024; Ramírez-Campillo et al., 2015; Ramirez-Campillo et al., 2023; Tottori & Fujita, 2019). In pre-adolescent boys, plyometric training has been associated with improvements in sprint velocity and step length during the maximum-velocity phase (Tottori & Fujita, 2019). Moreover, horizontally oriented plyometric exercises may have particular relevance to sprint acceleration because of the importance of horizontally directed force production during the early stages of sprinting (Kossow et al., 2018; Loturco et al., 2015; Moran et al., 2021; Samozino et al., 2022). Nevertheless, comparisons of vertical, horizontal, and combined plyometric programmes suggest that transfer is outcome-specific rather than determined solely by exercise direction (Moran et al., 2021; Norgeot & Fouré, 2024; Ramírez-Campillo et al., 2015).

Biological maturation is an additional consideration in youth training research. Athletes of the same chronological age may differ substantially in growth and maturational status, which can influence physical performance and responsiveness to training (Lloyd et al., 2016; Malina et al., 2015). This is especially relevant in athletes aged 12-13 years, who may be positioned before, near, or after peak height velocity. Studies comparing maturity groups indicate that sprint and jump adaptations to plyometric or combined training may differ between pre- and post-peak-height-velocity athletes (Lloyd et al., 2016). Therefore, findings from small chronological-age groups should be interpreted cautiously when biological maturation has not been assessed.

For coaches, an important question is whether a change in total sprint time is accompanied by a change in the running pattern being monitored. Total time integrates performance across the entire distance, whereas video from one segment describes only the strides sampled there. The two measurements are complementary, but neither identifies the information supplied by the other. Their interpretation is especially consequential in small youth squads, where accessible equipment may provide whole-sprint timing and a limited view of stride mechanics without a continuous velocity profile.

This study examined paired changes in 60-m sprint time and stride measures from the 40-48-m segment during a six-week period of training that included horizontal plyometrics. The aim was to describe whole-sprint and late-segment changes together, without assuming that a change in total time identified its location

 © 2026 ARD Asociación Española

or mechanism. The analysis was exploratory, with 60-m sprint time as the principal outcome and stride length, stride time and ground contact time as secondary outcomes.

MATERIAL AND METHODS

Participants

Nine male track-and-field athletes aged 12-13 years from a municipal squad in the Urabá subregion of Antioquia, Colombia, were included in the analysis. All nine had paired pre-test and post-test values for the four outcomes. Eligibility required at least two months of athletics practice. Biological maturation was not assessed, and individual anthropometric data and detailed training histories were unavailable.

Study design

The study used a single-group pre-test-post-test design within the squad's regular training programme. The investigator was the athletes' usual coach, and the plyometric sessions and sprint/video assessments took place during scheduled club training, without additional study-specific visits. There was no control group or random allocation.

Measures

60-m sprint assessment

Athletes performed three maximal 60-m sprints at each assessment, with approximately five minutes of recovery between attempts. They started without blocks, from a semi-erect position with one foot advanced and the opposite hand on the ground.

Sprint time was recorded using the Photo Finish application on a Xiaomi Mi 10 Pro smartphone. Timing began with an acoustic start signal, and the camera identified the finish. The same device and procedure were used at both assessments, and times were transferred to a spreadsheet.

Photo Finish has been evaluated against photocells over shorter sprint protocols (Marco-Contreras et al., 2024). This evidence does not provide a protocol-specific typical error or smallest detectable change for the present 60-m assessment in early-adolescent athletes.

Video recording and stride analysis

Sagittal-plane video was recorded at 1920 × 1080 pixels and 120 frames·s^{-1} using a Xiaomi Mi 10 Pro smartphone. The camera was mounted on a tripod approximately 7 m perpendicular to the running lane, at around half the athlete's standing height and centred on the 40–48-m analysis zone. This zone was treated as a late-sprint segment because individual maximum velocity within it was not verified.

Videos were analysed in Kinovea version 0.9.5. Spatial calibration used each athlete's greater-trochanter-to-lateral-femoral-condyle distance when the runner was perpendicular to the camera. The calibration was not validated against a fixed reference in the movement plane. Original calibration images were unavailable, preventing assessment of landmark visibility, plane alignment and perspective error.

A stride was defined as one complete cycle of the same limb. Stride length was the horizontal displacement between successive ground contacts of that limb; ground contact time was the interval from initial contact to toe-off; and stride time was the interval between successive initial contacts. The recording frequency corresponded to 8.33 ms between frames. Temporal summaries are presented to whole milliseconds for readability.

One complete stride of the self-reported dominant limb was assessed in each of the three runs by the same analyst. Independent verification and intra- and inter-rater reliability were not established for the video-derived measures; analyst blinding could not be confirmed.

Validation studies of smartphone-based running and sprint measurements demonstrate the importance of evaluating a specific recording and analysis procedure (Balsalobre-Fernández et al., 2017; Romero-Franco et al., 2017). The present combination of camera placement, anatomical calibration and temporal extraction was not validated against a criterion system.

Procedures

Both assessments were conducted on the same outdoor athletics track in the Urabá subregion of north-western Colombia, an area characterised by a warm, humid tropical climate.

The warm-up comprised general activation, general and exercise-specific dynamic stretching, and short runs. Its duration and repetition counts were not recorded.

Plyometric training programme

The programme prescribed two horizontal-jumping sessions per week for six weeks, on Tuesdays and Thursdays at approximately 15:00, with around 48 h between sessions. The 12 sessions were scheduled within regular club training on a concrete athletics surface.

Sessions 1-6 prescribed bilateral jumps and sessions 7-12 unilateral jumps. The planned volume was 1,209 jump repetitions, comprising 420 bilateral and 789 unilateral repetitions. Target distances were expressed as percentages of each athlete's baseline maximum horizontal jump distance and marked with cones. Approximately 15 s separated repetitions, with 100 m of walking recovery between series. Higher distance targets involved fewer consecutive jumps and lower targets more consecutive jumps; the exact allocation into sets and repetitions was unavailable. The percentages describe distance targets rather than measured mechanical intensity. Table 1 presents the session plan.

Table 1. Six-week horizontal plyometric training plan.

Session	Planned jump repetitions	Target distance (% MHJD)	Orientation
1	50	100	Bilateral
2	50	100	Bilateral
3	70	90	Bilateral
4	70	90	Bilateral
5	90	80	Bilateral
6	90	80	Bilateral
7	110	70	Unilateral
8	110	70	Unilateral
9	160	80	Unilateral
10	160	80	Unilateral
11	120	90	Unilateral
12	129	90	Unilateral
Total	1,209	-	420 bilateral; 789 unilateral

Note. MHJD = baseline maximum horizontal jump distance. Counts denote jump repetitions, not individually verified foot contacts. The planned total is 1,209 repetitions: 420 bilateral and 789 unilateral. Distance targets were marked with cones; the documented recovery was approximately 15 s between repetitions and 100 m of walking between series. Exact sets achieved target distances, attendance, limb allocation, completed dose and adverse events were not recoverable. The plan is a historical exposure description, not a validated safe or effective prescription.

 © 2026 ARD Asociación Española

An attendance criterion of at least 80% was specified in the programme. Session-level attendance, completed repetitions, limb allocation, achieved distances, technical quality, concurrent training and exertion ratings were unavailable. Pain, injury and other adverse-event records were also unavailable; actual exposure, adherence and safety could therefore not be evaluated.

Ethical safeguards

Field activities and data collection were completed in 2022 within the athletes' regular club training programme. The project was subsequently reviewed and approved by the Research Ethics Committee of Tecnológico de Antioquia - Institución Universitaria, Medellín, Colombia, on 27 May 2026 (Acta No. 04, semester 2026-01), which classified the reviewed project as research without risk under Article 11 of Colombian Resolution 8430 of 1993. Because the review occurred after completion of the field activities, it was retrospective and did not constitute prospective ethical oversight of the 2022 data collection. Because the participants were minors, the surviving consent documentation and its limitations are reported explicitly under Consent to participate. The present report is restricted to retrospective analysis of pre-existing, de-identified records; no additional participant contact, intervention or data collection was undertaken for this analysis, and no directly identifying information is reported.

Analysis

The original analyses were conducted in IBM SPSS Statistics version 25; the reported calculations were reproduced in Python.

The athlete was the unit of analysis. For each outcome, one pre-test and one post-test athlete-level value were included in the paired analyses. Three attempts were completed at each assessment, although separately identifiable trial-level values were not retained in the archived dataset. No imputation was performed, and change was calculated as post-test minus pre-test.

Sprint split times and adverse events were listed in the retrospective registry. Horizontal-jump outcomes were excluded from inferential analysis because paired values were available for only three athletes. Means and standard deviations summarised each assessment. Two-sided paired-samples t tests were used for sprint time, stride length and stride time. Ground contact time was analysed using an exact Wilcoxon signed-rank test, excluding zero differences and assigning mid-ranks to tied absolute differences. The exact probability was obtained by enumerating the possible sign allocations of the non-zero pairs.

For each outcome, the 95% confidence interval (CI) for mean paired change was calculated as the mean difference ± t(0.975, 8) × SD of the differences/√9. The ground-contact-time interval was descriptive and t-based, rather than derived from the signed-rank test. Cohen's d_z was calculated as the mean paired difference divided by its standard deviation. Rank-biserial correlation (r_{rb}) for ground contact time used non-zero pairs only. Relative change was 100 × mean paired change/group pre-test mean; the same scaling was applied to the confidence limits. These intervals describe sampling uncertainty conditional on the analysed values and do not account for their provenance or measurement error.

Sprint time was the principal descriptive outcome and the stride measures were exploratory. No adjustment for multiple comparisons was applied. Interpretation prioritised the direction, magnitude and confidence interval of each estimate over statistical significance alone. Sample size was determined by the availability of paired data for nine athletes, without a prospective sample-size calculation. No equivalence margin or threshold for a practically meaningful individual change was specified.

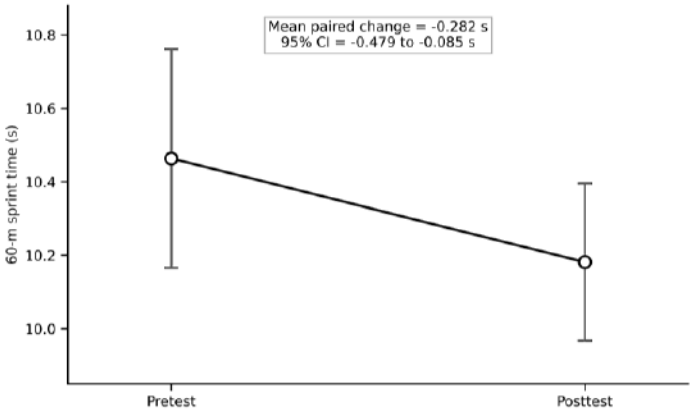
RESULTS

Table 2 presents the pre-test and post-test values and paired changes for the nine athletes. Figure 1 shows the group sprint-time means, and Figure 2 places relative changes across the four outcomes on a common scale.

Table 2. Paired changes in 60-m sprint time and late-segment stride measures (nine archived pairs).

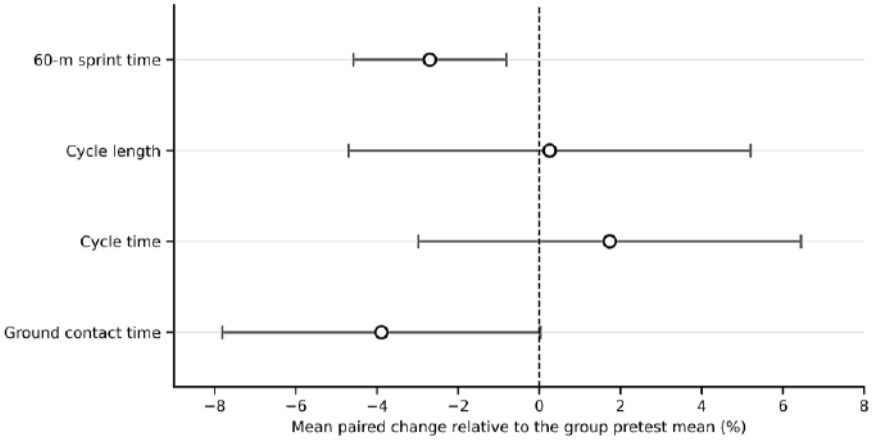
Outcome	Pre, M ± SD	Post, M ± SD	Mean paired change [95% CI]	Test statistic; *p*	Standardised change
60-m sprint time (s)	10.46 ± 0.39	10.18 ± 0.28	−0.282 [−0.479, −0.085]	t(8) = −3.30; *p* = .011	dz = −1.10
Stride length (cm)	381.6 ± 21.4	382.6 ± 30.8	+1.0 [−17.9, +19.9]	t(8) = 0.12; *p* = .909	dz = 0.04
Stride time (ms)	519 ± 33	528 ± 47	+9 [−15, +33]	t(8) = 0.85; *p* = .421	dz = 0.28
Ground contact time (ms)	140 ± 14	134 ± 16	−5 [−11, 0][1]	W = 0; *p* = .125[2]	rrb = −1.00[2]

Note. Analyses use one retained entry per athlete, outcome and occasion (n = 9), not verified three-attempt means. Changes are post-test minus pre-test. Confidence intervals condition on the retained entries and do not include measurement or source-record uncertainty. [1] Temporal summaries are rounded to whole milliseconds; acquisition was specified at 120 Hz (8.33 ms per frame). The contact-time interval is descriptive and t-based, rather than an inversion of the signed-rank test; its upper bound is slightly positive before rounding. [2] The exact signed-rank test excludes five zero differences and enumerates the 16 possible sign allocations of the four non-zero mid-ranks. The rank-biserial coefficient applies only to those four pairs. d_z = Cohen's standardised paired change; r_{rb} = rank-biserial correlation.



Note. Values are means with 95% confidence intervals for each occasion mean (n = 9).

Figure 1. Recorded sprint time across the training period.



Note. Points are mean paired changes and horizontal bars are 95% confidence intervals (n = 9).

Figure 2. Whole-sprint and late-segment changes.

 © 2026 ARD Asociación Española

Mean 60-m sprint time decreased from 10.46 ± 0.39 s to 10.18 ± 0.28 s. The mean paired change was −0.282 s (95% CI −0.479 to −0.085), equivalent to −2.7% ($t(8) = -3.30$, $p = .011$, $d_z = -1.10$). All nine athletes had lower post-test values; individual changes ranged from −0.86 to −0.02 s.

Mean stride length was 381.6 ± 21.4 cm at pre-test and 382.6 ± 30.8 cm at post-test, a paired change of +1.0 cm (95% CI −17.9 to +19.9), or approximately +0.3% ($t(8) = 0.12$, $p = .909$, $d_z = 0.04$).

Mean stride time was 519 ± 33 ms at pre-test and 528 ± 47 ms at post-test, a paired change of +9 ms (95% CI −15 to +33), or approximately +1.7% ($t(8) = 0.85$, $p = .421$, $d_z = 0.28$).

Mean ground contact time was 140 ± 14 ms at pre-test and 134 ± 16 ms at post-test. The mean paired change was approximately −5 ms (−3.9%), with a descriptive 95% CI of approximately −11 to 0 ms; the unrounded upper limit was slightly positive. Five athletes had identical pre-test and post-test values and four had lower post-test values. The exact signed-rank test gave $W = 0$ and $p = .125$; $r_{rb} = -1.00$ among the four non-zero pairs.

DISCUSSION

Mean 60-m sprint time was approximately 0.28 s lower at the end of the training period, while estimates of change in the 40-48-m stride measures remained imprecise. The central finding is therefore a difference in whole-sprint time with inconclusive information about the accompanying late-segment running pattern. Total sprint time and measurements from one short segment describe different aspects of performance; interpreting them together requires distinguishing the magnitude of a change from its location and mechanical basis.

The direction of the sprint-time change is consistent with reports of improved sprint performance following plyometric training (Cormie et al., 2011; Lloyd & Oliver, 2012; Lloyd et al., 2016; Markovic & Mikulic, 2010; Ramirez-Campillo et al., 2023; Sáez de Villarreal et al., 2012). Horizontally directed exercises provide a plausible stimulus for the force-production demands of sprint acceleration (Kossow et al., 2018; Loturco et al., 2015, 2018; Moran et al., 2021; Samozino et al., 2022), but comparisons of exercise orientations indicate that transfer depends on the performance outcome and training context (Moran et al., 2021, 2024; Norgeot & Fouré, 2024; Ramírez-Campillo et al., 2015). The present study adds an exploratory description from a municipal youth squad, rather than evidence that horizontal exercises are superior or that they caused the difference in sprint time.

Interpreting the late-segment measures

Stride length and stride time must be interpreted jointly; a longer stride does not by itself imply greater running speed if its duration also increases. Their mean changes were approximately +0.3% and +1.7%, respectively, but both confidence intervals included changes in either direction. These estimates are insufficient to establish a change in segment velocity, which was not measured directly. Equally, they do not establish that mechanics were unchanged. A contrast between the statistical results for total sprint time and a stride measure is not evidence of a physiological dissociation.

An earlier-phase change is one hypothesis that could explain lower total time without a clear difference in the sampled strides. It remains untested here because sprint splits, continuous velocity, acceleration kinematics and force measurements were unavailable. Cross-sectional evidence also indicates age-related differences in sprint-phase distribution (Bleeker & Siener, 2025), cautioning against assigning the same 40–48-m zone

to every athlete's maximum-velocity phase. Validated split timing at 5, 10, 20, 30, 40 and 60 m, or continuous velocity measurement, would distinguish a change in acceleration from one later in the sprint.

Ground contact time showed a different descriptive pattern: five athletes had identical recorded values across assessments and four had reductions. The rank-biserial coefficient of −1.00 reflects the consistent direction of only those four non-zero differences, not a uniformly large response across the group. Its magnitude must therefore be read alongside the small number of contributing pairs, the descriptive confidence interval and the temporal resolution. Similarly, variation in sprint-time changes does not separate training responsiveness from ordinary fluctuation or measurement error; responder classifications are not supported.

Training exposure and monitoring

The programme combined an individualised distance prescription with a bilateral-to-unilateral progression. Controlled research in youth athletes has examined the consequences of different plyometric volumes (Aztarain-Cardiel et al., 2024). In the present study, however, 1,209 repetitions describe the prescription, not the dose completed. The relationship between exposure and performance change cannot be estimated without attendance, completed work and concurrent-training records. The programme, including its concrete-surface setting, should therefore be understood as the training context rather than a validated prescription or evidence of safety.

A practical monitoring strategy should begin with the coaching question (Table 3). Whole-sprint timing describes total performance; split timing or continuous velocity locates changes within the sprint; calibrated video characterises selected stride measures; and suitable mechanical profiling addresses force–velocity determinants. These are complementary levels of assessment, not interchangeable indicators. The framework is a proposal for organising measurements, not a validated tool from this study. In resource-limited programmes, the priority is a small, reproducible set of measures that answers the intended question, with preserved trial records and an established error range.

Table 3. A question-led monitoring framework for resource-limited youth programmes.

Question	Minimum measurement layer	Record and quality check to preserve	Inference not supported by that layer alone
Did recorded whole-sprint performance change?	Standardised total sprint timing with clearly defined start and finish.	Original time-stamped export or video; authentic repeated attempts; aggregation rule; device, start protocol, recovery and testing conditions; exact-protocol test–retest error.	Causation by the training block, location of a phase change, or an individual response beyond error.
Where within the sprint did a difference occur?	Validated split timing or a suitable continuous velocity measure.	Segment distances; synchronisation and event definitions; segment-specific reliability. Future studies may use 5-, 10-, 20-, 30-, 40- and 60-m splits.	Which force or stride mechanism produced the segment difference.
Which segment-specific stride quantity differed?	Video with an appropriate frame rate, fixed spatial calibration and operational event definitions.	Original recordings; frame indices for contact and toe-off; calibration in the movement plane; repeated digitisation and, where feasible, blinded independent analysis.	A validated maximum-velocity phase without individual verification, whole-race mechanics, or direct force measurement.
Which mechanical determinant is implicated?	Appropriate validated velocity-based modelling or direct force instrumentation.	Model inputs, equations and assumptions; reference validation; uncertainty estimates; separation of model-derived quantities from directly measured forces.	A force-velocity profile from a single total time, a stride length or exercise orientation alone.

Note. This proposed framework was not tested or validated in the present study. Each approach requires protocol-specific validation, preserved source records and appropriate research oversight, consent and data governance when used for research.

 © 2026 ARD Asociación Española

Limitations and future research

Measurement error is particularly important when interpreting a change of approximately 0.28 s in total time or approximately 5 ms in ground contact time. External Photo Finish validation (Marco-Contreras et al., 2024) does not establish test–retest error for the present 60-m procedure, so the sprint-time difference cannot be compared with a protocol-specific detectable-change threshold. At 120 Hz, the interval between frames is 8.33 ms. Averaging can yield a mean change smaller than one frame but cannot improve the acquisition resolution. Missing event annotations and the unvalidated anatomical calibration further limit confidence in the temporal and spatial estimates.

The small male sample from a single squad limits precision and generalisability. Incomplete recruitment records prevent reconstruction of the full enrolment process and assessment of selection into the analytical sample. Without a comparison group, the sprint-time change remains compatible with familiarisation, regular training, maturation, motivation, environmental variation, regression to the mean and measurement error. The unavailable trial-level records and aggregation rule also prevent independent verification of the analysed values. Biological maturation was not assessed, so developmental status could not be considered when interpreting group or individual changes. Training exposure, adherence and safety could not be quantified, and protocol-specific timing and analyst reliability were not established.

Future studies should use randomised or appropriately matched comparisons with equivalent usual-training exposure and a sample size justified by a practically meaningful change and measurement error. Developmental assessment should use repeated anthropometry or another suitable maturation measure (Malina et al., 2015). Comparison with electronic timing gates and between-day repeat assessments in similar youth athletes would establish protocol-specific validity and reliability. Video analysis should include a fixed calibration reference and repeat or blinded independent digitisation. Session records should capture completed work, technical quality, pain and adverse events alongside concurrent training. These measures would allow performance change, developmental variation and measurement uncertainty to be considered separately.

CONCLUSION

The six-week training period coincided with lower recorded 60-m sprint time, while changes in late-segment stride measures remained uncertain. The study does not establish a plyometric training effect or identify the phase or mechanism of the total-time difference. For coaches, the main implication is to match the measurement to the question: total timing describes performance, whereas phase localisation and mechanical explanation require additional, appropriately validated assessments.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Carlos Francisco Hernández García. Methodology: Carlos Francisco Hernández García. Formal analysis: Samuel José Gaviria-Alzate. Investigation: Carlos Francisco Hernández García. Data curation: Carlos Francisco Hernández García. Writing – original draft: Carlos Francisco Hernández García. Writing – review & editing: Wilder Geovanny Valencia-Sánchez, Samuel José Gaviria-Alzate. Supervision: Wilder Geovanny Valencia-Sánchez.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

ETHICS APPROVAL

Field activities and data collection were completed in 2022. The project was subsequently reviewed and approved by the Research Ethics Committee of Tecnológico de Antioquia - Institución Universitaria, Medellín, Colombia, on 27 May 2026 (Acta No. 04, semester 2026-01), which classified the reviewed project as research without risk under Article 11 of Colombian Resolution 8430 of 1993. Because this review occurred after data collection, the approval was retrospective and did not constitute prospective ethical oversight of the 2022 field activities.

CONSENT TO PARTICIPATE

The original 2022 academic project included a research-specific informed-consent form describing the study, its procedures, voluntary participation, use of participant data and the right to withdraw, with separate signature fields for a parent or legal guardian and the athlete. Completed signed forms are not available in the surviving project archive; therefore, research-specific parental consent and participant assent cannot now be retrospectively verified, and the authors do not claim otherwise. Parents or legal guardians had authorised participation in the athletes' regular club training programme and associated assessments. The present secondary analysis is limited to pre-existing, de-identified records. The subsequent institutional review classified the project as research without risk under Article 11 of Colombian Resolution 8430 of 1993; no waiver of consent or prospective ethical oversight is claimed. No participant re-contact was undertaken and no directly identifying information is reported.

DATA AVAILABILITY

Aggregate outputs and de-identified analytical materials that do not permit participant identification are available from the corresponding author upon reasonable request, subject to appropriate confidentiality safeguards. Original source records and participant-level materials are not publicly available.

TRIAL REGISTRATION

The study was retrospectively registered at ClinicalTrials.gov in 2026 (NCT07571083).

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, ChatGPT assisted with language editing, source checking, statistical verification through code preparation and execution, and

 © 2026 ARD Asociación Española

revision of methodological and interpretative text. Claude also assisted with manuscript preparation. The authors critically reviewed and verified all AI-assisted material, made the final decisions concerning the study design, analysis, interpretation and conclusions, and retain full responsibility for the originality, integrity and accuracy of the manuscript.

REFERENCES

Aztarain-Cardiel, K., Garatachea, N., & Pareja-Blanco, F. (2024). Effects of plyometric training volume on physical performance in youth basketball players. *Journal of Strength and Conditioning Research*, *38*(7), 1275–1279. https://doi.org/10.1519/JSC.0000000000004779

Balsalobre-Fernández, C., Agopyan, H., & Morin, J.-B. (2017). The validity and reliability of an iPhone app for measuring running mechanics. *Journal of Applied Biomechanics*, *33*(3), 222–226. https://doi.org/10.1123/jab.2016-0104

Bleeker, S., & Siener, M. (2025). Development of juvenile sprint performance in boys: Analysis of speed phases—A cross-sectional study by age. *Frontiers in Sports and Active Living*, *7*, Article 1701476. https://doi.org/10.3389/fspor.2025.1701476

Buchheit, M., Samozino, P., Glynn, J. A., Michael, B. S., Al Haddad, H., Mendez-Villanueva, A., & Morin, J.-B. (2014). Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *Journal of Sports Sciences*, *32*(20), 1906–1913. https://doi.org/10.1080/02640414.2014.965191

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: Part 2—Training considerations for improving maximal power production. *Sports Medicine*, *41*(2), 125–146. https://doi.org/10.2165/11538500-000000000-00000

Haugen, T., Seiler, S., Sandbakk, Ø., & Tønnessen, E. (2019). The training and development of elite sprint performance: An integration of scientific and best practice literature. *Sports Medicine - Open*, *5*, Article 44. https://doi.org/10.1186/s40798-019-0221-0

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length and step rate during sprint running. *Medicine & Science in Sports & Exercise*, *36*(2), 261–271. https://doi.org/10.1249/01.MSS.0000113664.15777.53

Kossow, A. J., & Ebben, W. P. (2018). Kinetic analysis of horizontal plyometric exercise intensity. *Journal of Strength and Conditioning Research*, *32*(5), 1222–1229. https://doi.org/10.1519/JSC.0000000000002096

Lloyd, R. S., & Oliver, J. L. (2012). The youth physical development model: A new approach to long-term athletic development. *Strength and Conditioning Journal*, *34*(3), 61–72. https://doi.org/10.1519/SSC.0b013e31825760ea

Lloyd, R. S., Radnor, J. M., De Ste Croix, M. B. A., Cronin, J. B., & Oliver, J. L. (2016). Changes in sprint and jump performances after traditional, plyometric, and combined resistance training in male youth pre- and post-peak height velocity. *Journal of Strength and Conditioning Research*, *30*(5), 1239–1247. https://doi.org/10.1519/JSC.0000000000001216

Loturco, I., Contreras, B., Kobal, R., Fernandes, V., Moura, N., Siqueira, F., Winckler, C., Suchomel, T., & Pereira, L. A. (2018). Vertically and horizontally directed muscle power exercises: Relationships with top-level sprint performance. *PLOS ONE*, *13*(7), Article e0201475. https://doi.org/10.1371/journal.pone.0201475

Loturco, I., Pereira, L. A., Kobal, R., Zanetti, V., Kitamura, K., Abad, C. C. C., & Nakamura, F. Y. (2015). Transference effect of vertical and horizontal plyometrics on sprint performance of high-level U-20 soccer players. *Journal of Sports Sciences*, *33*(20), 2182–2191. https://doi.org/10.1080/02640414.2015.1081394

Malina, R. M., Rogol, A. D., Cumming, S. P., Coelho e Silva, M. J., & Figueiredo, A. J. (2015). Biological maturation of youth athletes: Assessment and implications. *British Journal of Sports Medicine*, *49*(13), 852–859. https://doi.org/10.1136/bjsports-2015-094623

Marco-Contreras, L. A., Bataller-Cervero, A. V., Gutiérrez, H., Sánchez-Sabaté, J., & Berzosa, C. (2024). Analysis of the validity and reliability of the Photo Finish® smartphone app to measure sprint time. *Sensors*, *24*(20), Article 6719. https://doi.org/10.3390/s24206719

Markovic, G., & Mikulic, P. (2010). Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Medicine*, *40*(10), 859–895. https://doi.org/10.2165/11318370-000000000-00000

Moran, J., Ramirez-Campillo, R., Liew, B., Chaabene, H., Behm, D. G., García-Hermoso, A., Izquierdo, M., & Granacher, U. (2021). Effects of vertically and horizontally orientated plyometric training on physical performance: A meta-analytical comparison. *Sports Medicine*, *51*(1), 65–79. https://doi.org/10.1007/s40279-020-01340-6

Moran, J., Vali, N., Sand, A., Beato, M., Hammami, R., Ramirez-Campillo, R., Chaabene, H., & Sandercock, G. (2024). Effect of vertical, horizontal, and combined plyometric training on jump, sprint and change of direction performance in male soccer players. *PLOS ONE*, *19*(5), Article e0295786. https://doi.org/10.1371/journal.pone.0295786

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J.-R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, *112*(11), 3921–3930. https://doi.org/10.1007/s00421-012-2379-8

Norgeot, F., & Fouré, A. (2024). Effects of vertical and horizontal plyometric training on jump performances and sprint force-velocity profile in young elite soccer players. *European Journal of Applied Physiology*, *124*(9), 2591–2601. https://doi.org/10.1007/s00421-024-05477-4

Ramírez-Campillo, R., Gallardo, F., Henriquez-Olguín, C., Meylan, C. M. P., Martínez, C., Álvarez, C., Caniuqueo, A., Cadore, E. L., & Izquierdo, M. (2015). Effect of vertical, horizontal, and combined plyometric training on explosive, balance, and endurance performance of young soccer players. *Journal of Strength and Conditioning Research*, *29*(7), 1784–1795. https://doi.org/10.1519/JSC.0000000000000827

Ramirez-Campillo, R., Sortwell, A., Moran, J., Afonso, J., Clemente, F. M., Lloyd, R. S., Oliver, J. L., Pedley, J., & Granacher, U. (2023). Plyometric-jump training effects on physical fitness and sport-specific performance according to maturity: A systematic review with meta-analysis. *Sports Medicine - Open*, *9*(1), Article 23. https://doi.org/10.1186/s40798-023-00568-6

Romero-Franco, N., Jiménez-Reyes, P., Castaño-Zambudio, A., Capelo-Ramírez, F., Rodríguez-Juan, J. J., González-Hernández, J., Toscano-Bendala, F. J., Cuadrado-Peñafiel, V., & Balsalobre-Fernández, C. (2017). Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods. *European Journal of Sport Science*, *17*(4), 386–392. https://doi.org/10.1080/17461391.2016.1249031

Sáez de Villarreal, E., Requena, B., & Cronin, J. B. (2012). The effects of plyometric training on sprint performance: A meta-analysis. *Journal of Strength and Conditioning Research*, *26*(2), 575–584. https://doi.org/10.1519/JSC.0b013e318220fd03

Samozino, P., Peyrot, N., Edouard, P., Nagahara, R., Jimenez-Reyes, P., Vanwanseele, B., & Morin, J.-B. (2022). Optimal mechanical force-velocity profile for sprint acceleration performance. *Scandinavian Journal of Medicine & Science in Sports*, *32*(3), 559–575. https://doi.org/10.1111/sms.14097

Tottori, N., & Fujita, S. (2019). Effects of plyometric training on sprint running performance in boys aged 9–12 years. *Sports*, *7*(10), Article 219. https://doi.org/10.3390/sports7100219

This work is licensed under a Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0 DEED).

 © 2026 ARD Asociación Española