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Influence of a 12-week bodily-kinesthetic intelligence-oriented teaching approach on fundamental movement skill development in children

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ABSTRACT

Early childhood developmental fundamental movement competence is one of the most important predictors of physical literacy and the conscientious retention of physical activity in the future. Current physical education curriculums, however, tend to poorly incorporate cognitive and kinaesthetic learning activities which help develop a comprehensive motor sense. This study was done to discuss the influence of a 12 weeks bodily-kinaesthetic intelligence (BKI)-based physical education intervention on the fundamental movement skills of the early school-aged children. A randomized pre-test- post-test control-group study was conducted in a sample of 100 children with ages between 6 and 8 years where half ($n = 50$) was experimental (BKI-based programme) and the other half ($n = 50$) was control (traditional physical education). The intervention was provided three times a week and lasted 45 minutes in 12 weeks. The Test of Gross Motor Development-Second Edition (TGMD-2) was used to determine locomotor and object-control skills. Data analysis entailed paired and independent t-tests and analysis of covariance (ANCOVA), and the effect size of paired and independent t-tests were calculated by use of Cohen d . The findings showed a statistically significant change in the experimental group as compared to the control group ($p < .001$) in locomotor skills and ANCOVA supported the fact that the intervention has a significant effect after adjusting the baseline performance. Object-control skills showed no significant differences between groups anyway. These results suggest greater efficiency of the incorporation of the bodily-kinaesthetic intelligence principles into early-stage physical education to facilitate the locomotor movement competency and promote the developmentally suitable and cognitively interested motor-learning milieu at schools.

Keywords: Physical education, Fundamental movement skills, Bodily-kinaesthetic intelligence, Physical literacy, Motor development, School-aged children.

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INTRODUCTION

The basis of physical developments in children involves basic movement skills (FMS) which form the basis of lifetime participation in the activities of physical activity, sporting roles and health. Such skills as locomotor, object-control, and stability movements facilitate the interaction system among children with the environment and become the foundations of physical literacy, meaning the motivation, confidence, physical ability, knowledge, and comprehension necessary to appreciate and take ownership of involvement in physical activity throughout life (Bailey, 2020; Newell, 2020). It is proven continuously that children with adequate competency in movement in early school ages are more capable to remain physically and cognitively and psychosocially active throughout their growth (Bremer and Cairney, 2018; Wick et al., 2017).

However, despite the common understanding of the significance of FMS, the studies reveal that most of the modern-day physical education (PE) programmes fail to assist in the systematic development of the latter, especially in the early childhood stage (Brian, 2021; Martínez-Bello & Estevan, 2021). The conventional PE classes usually depend on free play or sport related exercises that focus on either the number of participants, or the results of their performance, rather than on the qualitative learning of movement patterns. Although these methods help to encourage fun, they do not always advance sticky, versatile, and relocatable motor capabilities (Cocker, 2018). As a result, a significant part of children approaches adolescence's stage in the form of incompetency in movement, which was reconciled to diminished physical activity, diminished fitness, and enhanced sedentary behaviour in the next phase of life (Adank et al., 2018; Praxades et al., 2024).

The recent pedagogical changes have portrayed approaches based on physical literacy that involve an integration of motor learning into the process of cognitive and affective processes (Bailey, 2020). In that context, one of the fundamental abilities of human beings, as a theory by Gardner, is bodily-kinaesthetic intelligence (BKI) that refers to the efficient application of the body in purposeful movement, solving problems, and being in action (Gardner, 2011; Macedonia, 2019). Movement is a natural way that children learn, explore, and communicate, implying that PE programmes that are based on BKI principles could offer an appropriate pathway of developmentally relevant and cognitively interesting ways to acquire motor skills (Nista-Piccolo, 2020; Li and Siriphan, 2023). The implementation of BKI into PE can promote the feeling of going beyond the repeated practice of mechanical skills and promote the awareness of the body, spatial orientation, rhythmic coordination, and mindful movement practice (Light and Clarke, 2021; León et al., 2024).

Early school age is a vulnerable stage of motorization and neural, musculoskeletal, and perceptual systems show increased plasticity (Martínez-Bello and Estevan, 2021). The motor mastery that children get at this age is deeply predictive of physical involvement later in life and participation in sports (Hands, 2008). By contrast, a lack of exposure to structured and developmentally sequenced motor learning experiences could be one of the factors involved in the chronic movement deficits (Neville et al., 2019). These disparities are accelerated by socioeconomic and contextual factors, and the interventions based on inclusion and implemented at the school level can be introduced (Matarma et al., 2020).

The practical activities are supported using empirical evidence that shows the efficacy of structured motor programmes compared with unstructured activity in enhancing movement competency in children. The interventions based on the progressive difficulty of the tasks and variability of the movements and object-control challenges proved to have better outcome in the area of coordination, balance, or object-control skills than the traditional PE methods (Jahagirdar et al., 2017; Kouli et al., 2024). Nonetheless, most of the current programmes widely focus on the physical realm of motor learning, frequently neglecting the mental and emotional aspects that contribute to the ways children experience, control and store learning about

movement (He et al., 2023; Akil et al., 2024). Through the instruction based on BKI, the pedagogical framework combines these domains, according to which it is possible to place the movement as a physical as well as a cognitive learning process (Moreau, 2015; Pereira et al., 2024).

The evaluation of movement competency among children is typically based on specific validated tools, including the Test of Gross Motor Development, Second Edition (TGMD-2), which is able to give individual and valid results on locomotor and object-control skills (Field et al., 2020; Palmer et al., 2021). The TGMD-2 has been extensively utilized in the field of intervention research, having been used to assess change in motor performance in those populations considered to be at suitable ages (Todd et al., 2003). The objective comparison of instructional strategies and evidence-based assessment of curriculum performance can be achieved through its application (Staples et al., 2021). Even though theoretical and empirical evidence has been published to associate the applicability of bodily-kinaesthetic intelligence to motor learning, there are a few studies that have been experimental and analysed structured BKI-based interventions in school PE programs (Michelaki and Bournelli, 2022; Yudanto, 2023). Specifically, controlled research studies that explore the possibility of obtaining any positive result into the application of fundamental movement skills with the application of BKI principles into the regular PE classes instead of the conventional ones need to be conducted. Thus, the aim of the current research was to study the outcomes of 12 weeks bodily-kinaesthetic intelligence physical education intervention on locomotor and object-control skills of early school children. The hypothesis was that the children who attended BKI-based programme would show more improvement in movement competency than those who were getting the typical physical education teaching intervention. In filling this gap, the study will help provide a body of evidence supporting the utilization of motor skills development using cognitively engaging, developmentally autonomous and inclusive methods in the physical education instruction in schools.

MATERIALS AND METHODS

Study design

The study was based on a randomized experimental design that utilized a pre-text post-test control-group design to investigate the influences of bodily-kinaesthetic intelligence (BKI) based bodily education intervention on children movement competency. It was carried out in a 12-week period between January and March 2025 in one of the primary schools that were privately owned in Chennai, India. An experimental group (which received the BKI-based programme) and a control group (which pursued a regular physical education program at school) were assigned to the participants randomly. The two groups were involved in three physical education sessions at 45 minutes per week with these sessions being conducted during school hours. The study design was chosen so as to reduce selection bias and make a causal inference about the effects of the intervention.

Participants

One hundred children between 6 and 8 years (Grades 1 to 3) were selected purposely in Seed Academy, Chennai, comprising of 50 boys and 50 girls. The eligibility criteria were: (a) medically qualified to engage in physical activity; (b) no known neurological, musculoskeletal or developmental disorder; and (c) must be able to attend at least 85 per cent of the intervention time. The children undergoing external sports training or having this process as a rehabilitation of injury were not eligible to participate. The participants were then selected through simple lottery to allocate participants to the experimental group ($n = 50$; 25 boys, 25 girls) and the testing condition, control group ($n = 50$, 25 boys, 25 girls). At the baseline, age, height, and body mass did not differ significantly between the groups ($p > .05$). Parents or guardians signed informed consent in writing and all children volunteering were required to give verbal consent before participation. The study

had an ethical approval of the Institutional Human Ethics Committee of Hindustan Institute of Technology and Science (Ref: HITS/PE-2025-03). A detailed description of all the procedures was done within the framework of the principles approved in the Declaration of Helsinki (2013). Figure 1 depicts the movement of the participants in the study, the allocation, and intervention stages, as well as the assessment of the outcome of the study.

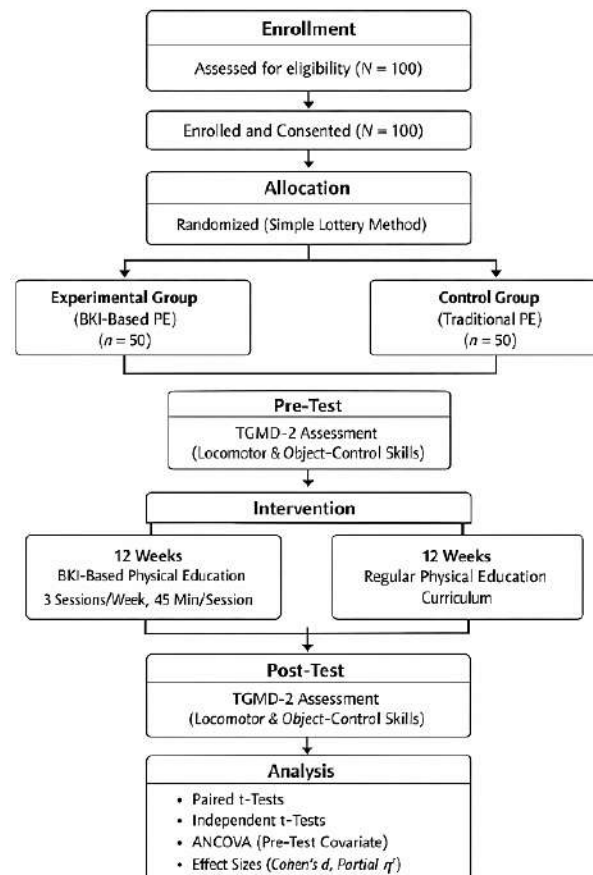


Figure 1. Flow diagram illustrating participant allocation, intervention phases, and outcome assessment.

Intervention protocol

The experimental group was engaged in a structured BKI-based physical education programme that was developed in line with the principles of psychomotor learning and the theory of multiple intelligences that conceptualises the bodily-kinaesthetic intelligences as the ability to make effective use of the body in learning and solving problems, and expressive movement (Gardner, 2011). The intervention was intended to improve movement competency with the use of activities that would focus on body awareness, spatial orientation, rhythm, and reflective movement execution. Every session (45 minutes) had a standardized format of Warm-up (5 minutes) Rhythmic mobility exercises and active stretching to stimulate joint mobility, neuromuscular preparation and coordination. Core activity (35 minutes): Developmentally ordered activities focused on locomotor skills, object-control skills, spatial awareness, and kinaesthetic memory using play-based and cognitively stimulating movement types of activities. Cool-down (5 minutes): Static stretching and guided breathing to help people recover physically and help ratify mind-body integration. The intervention went through the stages of progression in the simplest to more complex motor patterns throughout the 12 weeks of time in order to encourage the gradual development of skills and their retention. Education was conducted

by qualified physical education teachers who were followed using the BKI framework and the activities were modified to be safe, inclusive, and age appropriate. The control group adhered to the usual curriculum in the school physical education program that involved free play, calisthenics, and simple games (e.g., running, jumping, and balls playing) without systematic development of skills, reflective ones, and specific cognitive activity.

Outcome measures

The Test of Gross Motor Development-Second Edition (TGMD-2) has been extensively evaluated and is a reliable measure of gross motor development in children aged 3 to 10 years, which is why fundamentals of movement abilities have been tested using this tool (Ulrich, 2000; Field et al., 2020). The TGMD-2 has two subscales: locomotor skills (i.e. running and hopping and galloping), and object-control skills (i.e. throwing, catching, kicking, etc.). Evaluations were carried out an entire week prior to and a week following the period of intervention in a controlled setting by trained assessment blinded to the group assignment. The scores of performances have been rated based on the TGMD-2 protocol where the higher the score the higher is the movement competency.

Statistical analysis

The SPSS Statistics (Version 26.0) was used in data analysis. All the demographic and performance variables were analysed using descriptive statistics (mean $\pm$ standard deviation). To analyse within-group changes between pre- and post-tests, paired-sample t-tests were tested, whereas between-group changes between controls and experimental groups at baseline were tested in independent-sample t-tests. Analysis of covariance (ANCOVA) was performed to evaluate the pre-test scores as covariates so as to establish the impact of the intervention by abiding by the knowledge of baseline performance. The degree of effect was computed with the help of Cohen d of t-tests as well as the partial eta squared (η^2) of ANCOVA in accordance with traditional interpretive limits (Cohen, 1988). The statistical significance was predetermined as $p < .05$. The Shapiro-Wilk test of assumptions of a normal distribution and Levene test of tests of homogeneity variance of variance, respectively, were used to test the assumptions.

Quality control and reliability

The same group of trained evaluators carried out all tests in the same testing environment. Safety checks and equipment calibration were done every time there was a testing session. Fidelity to intervention was observed by the weekly supervision meeting to be compliant with the programme structure proposed. Assessors were blinded on group allocation during the data collection process to minimize the bias of measurement.

RESULTS

Before the inferential analysis, the assumptions that must be taken in parametric statistical test were checked. The Shapiro-Wilk test was used to verify that the locomotor and object-control skill scores were normally distributed between the two in the pre-test and post-test ($p > .05$). The homogeneity of variances was checked by the Levene test and no significant violations have been detected ($p > .05$). These findings justified the use of paired sample t-tests and analysis of covariance (ANCOVA).

To ensure that there was a similarity between the experimental and control group before the intervention, baseline comparisons were done. Analysis using the independent-sample t-tests showed no statistically significant differences among the groups in terms of locomotor or object-control skills at baseline ($p > .05$) which showed that there were no differences between the groups at the time they joined the study (Table 1).

Table 1. Baseline characteristics of participants.

Variable	Group	N	Mean	SD	p-value
Locomotor skills (Pre-test)	Experimental	50	19.76	3.46	>.05
	Control	50	18.16	3.87	
Object-control skills (Pre-test)	Experimental	50	24.52	3.07	>.05
	Control	50	21.04	4.48	

Note. No statistically significant baseline differences were observed between groups.

Table 2. Pre-post comparison of locomotor and object-control skills within groups.

Skill domain	Group	Test	N	Mean	SD	t	df	p-value
Locomotor	Experimental	Pre-test	50	19.76	3.46	-22.21	49	<.001
		Post-test	50	28.92	3.76			
	Control	Pre-test	50	18.16	3.87	0.65	49	.518
		Post-test	50	17.74	4.13			
Object-control	Experimental	Pre-test	50	24.52	3.07	-1.05	49	.300
		Post-test	50	35.14	3.43			
	Control	Pre-test	50	21.04	4.48	1.05	49	.300
		Post-test	50	20.36	4.43			

Note. Statistical significance was set at $p < .05$; $**p < .001$.

Paired-sample t -tests were analyzed to compare the pre and post -intervention locomotor and object-control skills between the groups. Experimental section showed statistically significant locomotor skill improvement whereby the mean scores of locomotor skills at pre-test stage became 19.76 ± 3.46 and at the post-test 28.92 ± 3.76 ($T = -22.21$, $p = .001$). Conversely, the change in locomotor skills was not statistically significant in the control group ($t(49) = 0.65$, $p = .518$), as the scores did not change significantly throughout the intervention. In case of object-control skills, the experimental group ($t(49) = -1.05$, $p = .300$) and the control group ($t(49) = 1.05$, $p = .300$) did not indicate statistically significant changes of the test scores in the pre- and post-test. These findings suggest that locomotor skills rather than object-control skills improved when related to the BKI-based intervention to a greater extent (Table 2).

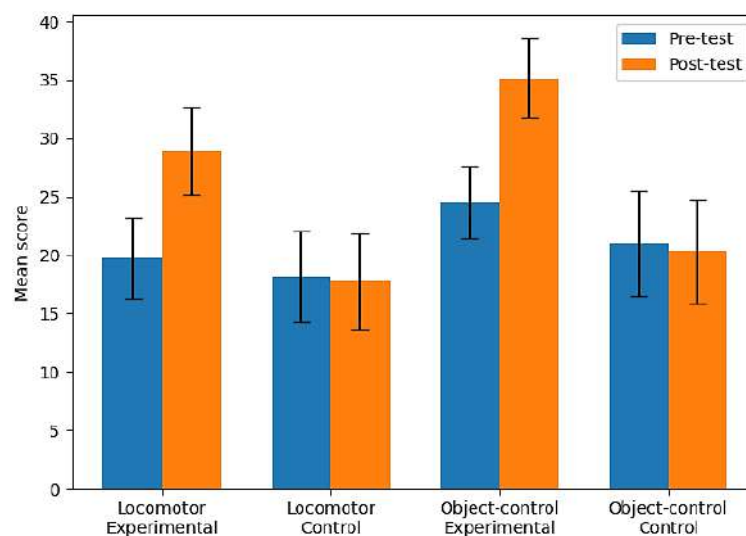


Figure 2. Pre- and post-test comparison of locomotor and object-control skill scores within experimental and control groups.

Figure 2 depicts changes in locomotor and object-control skills before and after the interventions in the experimental and a control group.

Table 3. ANCOVA for post-test locomotor skills controlling for pre-test scores.

Source	Sum of Squares	df	Mean Square	F	p-value	η^2
Group	414.40	1	414.40	37.10	<.001	.101
Error	1084.00	97	11.18			

Note. Statistical significance was set at $p < .05$.

ANOVA of pre-test scores as a covariate on post-test locomotor scores was conducted to identify the intervention effect controlling it by the baseline difference. The comparison indicated a large primary effect of group ($F(1, 97) = 37.10$, p less than .001). The eta squared value ($\eta^2 = .101$) was a partial one, which meant that only about 10.1% of the variance in post-test locomotor performance could be linked to the involvement in the BKI-based programme and this represents a significant educational effect (Table 3).

Table 4. ANCOVA for post-test object-control skills controlling for pre-test scores.

Source	Sum of Squares	df	Mean Square	F	p-value	η^2
Group	623.22	1	623.22	64.70	<.001	.127
Error	934.00	97	9.63			

Note. Statistical significance was set at $p < .05$.

An ANCOVA on post-test object-control scores in which pre-test scores were used as a covariate showed that the group effect was statistically significant ($F(1, 97) = 64.70$, $p < .001$). The effect size ($\eta^2 = .127$) showed that 12.7% of the variance in the post-test object-control performance was dependent on the group membership (Table 4). Although statistically significant, the change was small as compared to the locomotor skill results. The findings show that the 12-week physical education programme based on bodily-kinaesthetic intelligence brought about significant improvement in locomotor skills to early school-aged children and the improvement was statistically significant compared to physical education as usual. The results regarding the object-control skills showed less consistency with no significant within-group change, but statistically significant between-group changes after controlling the baseline performance. In general, the intervention had a greater and more significant impact on locomotor movement competency compared to tutoring object-control abilities.

DISCUSSION

The present research was aimed at studying the body-kinaesthetic intelligence (BKI)-based bodily-kinaesthetic programme of bodily-kinaesthetic intelligence physical education as an effective way to teach fundamental movement skills in early school-aged kids (Bailey, 2020; Bremer and Cairney, 2018; Newell, 2020). The main results reveal that the intervention resulted in statistically significant and significant change in the locomotor performance, but no systematic within-group change was observed in the object-control performance, although the difference between groups after accounting performance at the baseline was statistically significant (Hands, 2008; Wick et al., 2017). These results partly substantiate the hypothesis of the study and emphasize the effects specific to the field BKI-based instruction has with regard to movement competency (Brian, 2021).

The most prominent result of this analysis was the significant locomotor skill improvement in children that underwent BKI-based programme. The experimental group recorded high pre-post locomotor performance

when compared to the control group which recorded no significant change during the same period. Moreover, the outputs of ANCOVA confirmed that group membership explained about 10% of the post-test locomotor score, which proved that there was a significant educational effect due to other factors, rather than the developmental processes per se (Cohen, 1988; Praxades et al., 2024). The findings are part of the tools of the literature stressing the efficiency of the structured, developmentally sequenced motor interventions in the process of improving locomotor competence in early childhood (Jahagirdar et al., 2017; Kouli et al., 2024; Martínez-Bello and Estevan, 2021). The locomotor skills of running, hopping, and galloping are very sensitive to the teaching strategies based on the repetition, progression, and qualitative movement feedback (Newell, 2020; Williams et al., 2021). It could be expected that the BKI framework employed in the current article led to improve such processes by promoting body awareness, spatial orientation, and rhythm coordination, thus allowing to experience more efficient acquisition of motor patterns (Gardner, 2011; Macedonia, 2019).

Pedagogically, the findings have upheld the assumption that when cognitive involvement is combined with physical performance in motor learning, improvement in motor learning is achieved. The BKI-based activities might have been able to facilitate better muscle coordination and consistency of movement through the focus on the conscious exploration of movement instead of motor performance evaluating (Light and Clarke, 2021; Moreau, 2015). This result is aligned with the models founded on physical literacy screening locomotor competence as one of the core elements of lifelong engagement in physical activities (Bailey, 2020; Bremer and Cairney, 2018). Unlike in the locomotor outcome, object-control skills failed to exhibit statistically significant pre- to post- differences in both groups. Despite the fact that the experimental group showed increases in data descriptively, the variability of each individual performance inhibited the ability to consistently monitor the changes. Such a trend indicates that object-control skills might need the addition of a more extended intervention period, increased specificity of tasks, or an increased intensity of practices to provoke strong outcomes (Coker, 2018; Neville et al., 2019).

The ANCOVA findings indicated that there is a statistically significant between group effect of the object-control skills following a baseline performance factor. The size of this effect was, however, small compared to the locomotor outcomes meaning that statistical significance did not automatically mean that there is a large practical benefit. This difference supports the significance of the interpretation of statistical results, as well as the effect size and within-group trends, especially when research methods regarded are school-based interventions (Cohen, 1988; Field et al., 2020). The ability to control objects, e.g. throwing and catching, is more complicated by nature and requires greater perceptual-motor integration, timing, and interaction with the environment (Hands, 2008; Palmer et al., 2021). Although the BKI system has a cognitive and kinaesthetic component, the structure of the programme used in the study might have contributed to the preference of overall body movement patterns, rather than focusing on the precision of manipulative skills. Therefore, the positive results of object-control were perhaps limited due to rather scanty exposure to the task-specific manipulative exercises (Brian, 2021; Neville et al., 2019).

The locomotor and object-control skills differentiability detected in this research is in line with the previous studies showing that there is no even development of fundamental domains of movement skills (Wick et al., 2017; Praxades et al., 2024). Locomotor skills are usually acquired earlier and react to systematic training simpler and faster, whereas object-control skills may take a long time to develop under specific training and require guidance (Brian, 2021; Kouli et al., 2024). The current results support the originality of domain-specific programming creation in case of pursuing a balanced development of movement competency. Significantly, the findings indicate that the BKI-based interventions could be especially effective in terms of improving the quality of the locomotor movement in young children during the early school-aged. This has significant implications on curriculum design, since locomotor competence is a bridge to the involvement to many

physical activities and sporting activities (Hands, 2008). The further enhancement of this area in early childhood can thus result in some large-scale physical literacy outcomes (Bailey, 2020).

In educational terms, the results suggest that a BKI-based physical education programme can be effectively introduced into the normal school routine and yield significant changes in movement competency without the use of special gear (Nista-Piccolo, 2020; Matarma et al., 2020). The focus on body awareness, rhythm, and spatial control is also compatible with such inclusive pedagogical practices that should accommodate different levels of abilities and the learning styles (Li and Siriphan, 2023). Its lack of object-control gains could help demonstrate the significance of the individual approach to complementary instruction in the focus of manipulative skills. Teachers that attempt to fully develop movement can look at using BKI principles as supplements to more object-movement instruction, more task repetition, and more time of intervention. An integrated approach can be a way of improving the efficiency of school-based physical education programmes (Kouli et al., 2024).

The positive aspects of the current research are that it is a randomized controlled study, made use of a validated evaluation measure (TGMD-2), and is conducted in a natural school environment, which adds to the ecological validity (Ulrich, 2000; Field et al., 2020). ANCOVA has also enhanced the analysis since it has considered the baseline performance differences (Cohen, 1988). However, there are some drawbacks that must be taken into consideration. The research was carried out in one school which can be a limitation to the fact that the results can be applied to other educational settings. Also, the 12 weeks of intervention time, although adequate to induce locomotor improvements, might have been inadequate to increase the similar results of gains in object-control skills. Future studies need to investigate more time-span of intervention, a larger extent of task specificity and combining complementary instructional models to enhance the overall development of skills (Kouli et al., 2024; Williams et al., 2021). The longitudinal sustainability of BKI-based gains and the connection of bodily-kinaesthetic intelligence to other educational areas, i.e. spatial or interpersonal intelligence can also be researched in future studies. The use of qualitative indicators, including teacher observations or student-participation measures, could be a way to have a closer look at the cognitive and affective mechanisms that underlie motor learning (Moreau, 2015; Light and Clarke, 2021).

In short, the above research results reveal that a 12-week bodily-kinaesthetic intelligence-based physical education programme can be useful in improving locomotor movement competency among early school-aged children. Though the change in object-control abilities was not so significant, the overall outcomes reveal the usefulness of developmentally appropriate and cognitively challenging instructional methods in the field of school-based physical education. The results can be added to the body of knowledge on the optimization of physical education programs to prevent the development of underdeveloped movement skills and development of poor movement literacy (Bailey, 2020; Bremer and Cairney, 2018).

CONCLUSIONS

The current research paper discussed the impact of a 12-week bodily-kinaesthetic intelligence (BKI)-based physical education programme about basic movement skills among early school-aged children. The results show that the intervention had statistically significant and educationally significant positive changes over locomotor skills relative to conventional physical education. Conversely, object-control skills failed to exhibit within-group improvement although small between-group differences were noted when baseline performances are factored in. This evidence shows that BKI-based teaching is especially useful to improve the locomotor movement competency of the early childhood period in human development when the initial motor patterns are in a high degree of responsiveness to organized and mentally-involving practice. The

observed differences between the domains of skills emphasize the necessity of the domain-based teaching focus in drawing up school-based programmes of physical education. Practically speaking, the programme based on the BKI may be introduced into the usual schedule of schools without the additional equipment and can be a useful pedagogical strategy to enhancing locomotor competence in mixed educational establishments. The longest intervention length, higher specificity of object-control skills, and the sustainability of any improvements in the body movements in the long run should be examined in future to contribute to the development of the whole physical literacy.

AUTHOR CONTRIBUTIONS

Both authors have contributed equally to the following sections: study design, data collection, statistical analysis, manuscript preparation, funds collection.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL APPROVAL

The research received the approval of the Institutional Human Ethics Committee, Hindustan Institute of Technology and Science, Chennai (Ref: HITS/PE-2025-03). The procedures were compliant with the 2013 Declaration of Helsinki. The informed consent of the parents was taken.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AI USAGE DECLARATION

AI tools were used solely for language editing and formatting. All research design, data analysis, interpretation, and conclusions were performed by the authors.

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From volume to pattern: Sustained moderate-to-vigorous physical activity and its sociodemographic distribution in children and adolescents

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ABSTRACT

Most research on children's and adolescents' physical activity focuses on total daily moderate-to-vigorous physical activity (MVPA), with limited attention to its temporal structure. This cross-sectional study characterised MVPA accumulation patterns in 513 participants (256 boys, 257 girls; mean age 11.7 ± 3.2 years) from the Basque Country (Spain) using wrist-worn accelerometry (100 Hz; ENMO ≥ 100 mg; 5-s epochs; GGIR) over seven consecutive days. MVPA bouts were defined using a strict consecutive criterion at thresholds of ≥ 1 , ≥ 5 , and ≥ 10 minutes. On average, 66.2% of daily MVPA was accumulated in bouts ≥ 1 minute, 44.7% in bouts ≥ 5 minutes, and 34.8% in bouts ≥ 10 minutes. Boys accumulated more total MVPA and a greater proportion in sustained bouts than girls (40.9% vs. 28.8%). Both total and sustained MVPA declined progressively with age. In multivariable models, age ($\beta = -1.93$; 95% CI: -2.57 to -1.28) and female sex ($\beta = -14.00$; 95% CI: -18.50 to -9.50) were independently associated with lower sustained MVPA (model $R^2 = .126$). Sustained MVPA was inversely associated with body mass index after adjustment for age, sex, socioeconomic status, and residential setting ($\beta = -9.05 \times 10^{-6}$; $p = .028$; model $R^2 = .359$). These findings indicate that MVPA in youth is predominantly fragmented and that sustained accumulation varies systematically by demographic characteristics.

Keywords: Physical education, Accelerometry, Raw acceleration, ENMO, Bout duration, Adiposity.

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INTRODUCTION

Physical inactivity during childhood and adolescence remains one of the most pressing challenges facing public health systems worldwide. The World Health Organization recommends that children and adolescents accumulate at least 60 minutes of moderate-to-vigorous physical activity (MVPA) per day (WHO, 2020), yet global surveillance data consistently show that a substantial proportion of young people fail to meet this threshold (Guthold et al., 2020). The Global Matrix 4.0 corroborated these trends across the majority of evaluated countries, reinforcing the structural nature of the problem rather than attributing it to isolated contexts (Aubert et al., 2022). These patterns are consistent with broader global stagnation in physical activity promotion efforts observed over recent decades (Sallis et al., 2016). Insufficient physical activity during childhood and adolescence has been associated with adverse physical, metabolic, and psychosocial outcomes, underscoring the relevance of early-life behavioural patterns for long-term health trajectories.

Epidemiological research and health promotion policies have traditionally framed physical activity almost exclusively in terms of total daily volume, affording comparatively little attention to how that activity is distributed across the day (Verswijveren et al., 2018). This framing, however, overlooks a fundamental property of movement behaviour: MVPA is not a homogeneous construct. It can accumulate through brief, repeated bouts or through sustained, continuous efforts, and these structural differences may produce distinct physiological stimuli. Aadland et al. (2018) identified multivariate activity profiles associated with better metabolic indicators in young populations, while Tarp et al. (2018) showed that MVPA bout duration was differentially related to cardiometabolic risk. Compositional analyses have further demonstrated that the relative distribution of time across intensity levels provides information beyond what total volume alone can capture (Carson et al., 2019). Together, these findings challenge the assumption that volume is the sole determinant of health benefit.

Methodological advances in accelerometry have been central to this conceptual shift. Earlier work had already highlighted limitations of cut-point approaches in paediatric populations (Rowlands, 2007), paving the way for the adoption of raw-signal methodologies. The use of raw acceleration data, operationalised through metrics such as Euclidean Norm Minus One (ENMO), allows for more precise estimation of movement intensity (van Hees et al., 2015). Building on this, Rowlands et al. (2016, 2018) argued for moving beyond traditional intensity thresholds towards metrics capable of describing the full intensity profile across the day. Recent studies have applied raw-signal metrics to examine longitudinal trajectories of volume and intensity in paediatric samples, showing that temporal variation affects not only the quantity but also the distribution of effort (Fairclough et al., 2025). Open-source tools such as GGIR have enabled a more standardised approach to these questions, facilitating analysis of both total MVPA time and the continuity or fragmentation of activity bouts. The GRANADA consensus further underlines that the examination of temporal patterns is an essential component of any comprehensive interpretation of motor behaviour in young people (Migueles et al., 2021).

The available evidence suggests that children's physical activity is inherently intermittent in nature. Longitudinal studies have identified adolescence as a critical period of progressive decline in activity levels (Dumith et al., 2011; Farooq et al., 2018), and activity patterns established during childhood tend to track into adulthood, underscoring the preventive relevance of early intervention (Telama, 2009). Research has also documented meaningful differences in MVPA accumulation between school days and weekends, pointing to the role of contextual factors in shaping how effort is distributed over time (Brazendale et al., 2021). Understanding the temporal organisation of physical activity is therefore not a methodological refinement, but a substantive question for interpreting its health relevance.

Sex-related inequalities constitute another central axis of this research field. Objective measurement consistently shows that girls accumulate less MVPA and spend more time sedentary than boys (Cooper et al., 2015), with this gap widening through adolescence (Sherar et al., 2007). More recent evidence indicates that these differences extend beyond total volume: girls tend to exhibit less intense and more homogeneous activity profiles compared to boys (Kretschmer et al., 2023), suggesting that sex inequalities may manifest in the temporal structure of activity just as much as in the amounts accumulated.

Socioeconomic position and residential environment also shape how physical activity is organised. The Health Behaviour in School-aged Children study has documented systematic differences in the likelihood of meeting MVPA recommendations according to socioeconomic status (Inchley et al., 2020), and reviews of the built environment have shown that access to sports facilities and availability of recreational spaces are meaningful predictors of participation in physical activity (Ding et al., 2011). In addition, whole-school approaches have been identified as effective frameworks for embedding physical activity within daily routines (Langford et al., 2015), underscoring the role of institutional contexts in shaping behavioural patterns. Despite this body of evidence, the extent to which socioeconomic and environmental inequalities also affect the temporal structure of activity — rather than simply its total volume — remains insufficiently characterised.

Taken together, the literature reveals a number of persistent gaps. Population-level data on the proportion of MVPA accumulated in sustained versus fragmented bouts are scarce in large paediatric samples. Evidence on whether sociodemographic inequalities extend to the temporal structure of activity remains limited. And studies examining the independent association between sustained MVPA and body mass index (BMI) — after accounting for total volume — are few and present heterogeneous findings.

Against this background, the present study pursued two primary objectives: (1) to characterise MVPA accumulation patterns in a population-based sample of children and adolescents using wrist-worn accelerometry and raw-signal analysis; and (2) to examine differences in sustained MVPA according to sex, age, socioeconomic status, and residential setting. As a secondary aim, the study explored the association between sustained MVPA accumulation and BMI, premised on the notion that not all MVPA generates equivalent physiological stimuli and that continuous bouts may be linked to lower adiposity independently of total volume and sociodemographic characteristics.

MATERIAL AND METHODS

Participants

This study presents a secondary analysis of data collected as part of the Mugikertu study, a population-based cross-sectional investigation whose protocol has been previously published (Larrinaga-Undabarrena et al., 2022). For the present analysis, only participants from the historical territories of Álava and Gipuzkoa (Basque Country, Spain) were included. Recruitment followed a stratified, multi-stage cluster sampling design that ensured representativeness across territory, school type (state-funded or semi-private), and educational stage (Primary, Secondary, and Baccalaureate). Schools were randomly selected within each stratum, and all students from the selected classes were invited to participate.

The final analytical sample comprised 513 participants (256 boys, 257 girls) aged 6–17 years, all of whom provided valid accelerometry records according to pre-established criteria. Participation was voluntary. Written informed consent was obtained from parents or legal guardians prior to data collection, and assent was obtained from the students themselves. Ethical approval was granted by the Euskadi Research Ethics Committee for Medicinal Products (reference PI2020011).

Measures

Wrist-worn accelerometry. Physical activity was assessed using a triaxial accelerometer worn on the non-dominant wrist for seven consecutive days under free-living conditions. Participants were instructed to remove the device only during water-based activities or situations involving risk of damage. Raw acceleration data were recorded at 100 Hz.

Data processing was performed using the GGIR package (version 4.5.2) in R, which applies automatic calibration against local gravity, identifies non-wear time through a low-signal-variability algorithm, and derives intensity metrics directly from raw acceleration (van Hees et al., 2013; Migueles et al., 2017). Data processing and wear-time criteria were aligned with established methodological recommendations for accelerometer-based research in paediatric populations (Migueles et al., 2017). Movement intensity was quantified using the Euclidean Norm Minus One (ENMO) metric, calculated as the Euclidean norm of the three acceleration axes minus 1g, with negative values truncated to zero and no additional smoothing applied. ENMO values were summarised in non-overlapping 5-second epochs.

MVPA was defined as $ENMO \geq 100$ mg, a threshold widely adopted in wrist-accelerometry studies with paediatric populations (Rowlands et al., 2016; Migueles et al., 2017). Daily MVPA was expressed as the accumulated ENMO (mg) across all 5-second epochs classified as MVPA and averaged per valid day. To characterise the temporal structure of motor behaviour, daily MVPA was disaggregated by bout duration, identifying sustained blocks of ≥ 1 , ≥ 5 , and ≥ 10 consecutive minutes above the threshold. Bout identification followed a strict consecutive criterion: all 5-second epochs within the specified duration were required to remain above the cut-off, with no interruptions permitted.

Anthropometric and contextual variables. Body mass and height were measured directly at each school using standardised protocols. Body mass index (BMI) was calculated as body mass in kilograms divided by height in metres squared (kg/m^2) and used as a continuous indicator of adiposity. Socioeconomic status was estimated using an area-level deprivation index assigned according to census tract of residence, integrating indicators of income, employment, and educational attainment. Residential setting was classified as urban or rural according to official administrative criteria.

Procedures

Data collection took place during the academic year in coordination with participating schools. Trained research personnel provided standardised instructions on device fitting and use at each school visit. All measurements, including anthropometric assessments, were conducted by the same team under uniform conditions to minimise inter-observer variability.

Analysis

Analyses were conducted at the individual level using mean daily values as the unit of analysis. Descriptive statistics are reported as means and standard deviations. To identify independent predictors of sustained MVPA (≥ 10 minutes), multivariable linear regression models were fitted including age (continuous), sex, socioeconomic status, and residential setting as independent variables. A second model was estimated with BMI as the dependent variable, incorporating sustained MVPA alongside the same sociodemographic covariates as predictors. The significance threshold was set at $p < .05$. All analyses were conducted in R (version 4.5.2).

RESULTS

Overall MVPA accumulation pattern

Across the full sample, MVPA was predominantly accumulated in shorter and intermittent bouts. Mean daily total MVPA was $108,529 \pm 49,120$ ENMO units, of which $35,508 \pm 27,729$ were accumulated in sustained bouts ≥ 10 minutes, representing 34.8% of total MVPA. The proportion of MVPA declined progressively as bout duration increased (Table 1). Boys accumulated higher total MVPA than girls ($111,336 \pm 52,943$ vs. $105,744 \pm 44,939$ ENMO units). They also accumulated greater absolute amounts of MVPA in sustained bouts. In bouts ≥ 10 minutes, boys accumulated $42,467 \pm 31,333$ compared with $28,603 \pm 21,555$ in girls. In proportional terms, 40.9% of total MVPA in boys was accumulated in bouts ≥ 10 minutes, compared with 28.8% in girls. The difference in sustained MVPA (≥ 10 min) between boys and girls corresponded to a moderate effect size (Cohen's $d = 0.51$), indicating a meaningful sex-related disparity in the temporal accumulation of MVPA.

Table 1. MVPA accumulation patterns by sex.

Group	N	MVPA total (mean $\pm$ SD)	MVPA ≥ 1 min (mean $\pm$ SD)	MVPA ≥ 5 min (mean $\pm$ SD)	MVPA ≥ 10 min (mean $\pm$ SD)	% ≥ 1 min	% ≥ 5 min	% ≥ 10 min
Total	513	$108,529 \pm 49,120$	$65,442 \pm 33,525$	$44,941 \pm 29,230$	$35,508 \pm 27,729$	66.2%	44.7%	34.8%
Boys	256	$111,336 \pm 52,943$	$68,298 \pm 36,045$	$51,347 \pm 32,682$	$42,467 \pm 31,333$	68.4%	50.6%	40.9%
Girls	257	$105,744 \pm 44,939$	$62,610 \pm 30,629$	$38,584 \pm 23,753$	$28,603 \pm 21,555$	64.1%	38.9%	28.8%

Note. MVPA values are expressed as mean daily ENMO units $\pm$ standard deviation. Percentages refer to the proportion of total daily MVPA accumulated within each bout-duration category.

Age-related differences

MVPA volume and sustained accumulation declined markedly across age groups (Table 2). The youngest participants (6–9 years) exhibited the highest total MVPA and the greatest absolute accumulation in sustained bouts, whereas adolescents aged 16–17 years showed the lowest values. Between these age groups, mean daily MVPA decreased by approximately 44%, and MVPA accumulated in ≥ 10 -minute bouts declined by around 38%. The contrast in sustained MVPA between the youngest and oldest age groups represented a moderate-to-large effect size (Cohen's $d = 0.63$), reflecting a substantial age-related reduction in sustained physical effort. Although absolute values decreased with age, the relative proportions of MVPA accumulated within each bout-duration category remained broadly similar across age groups.

Table 2. MVPA accumulation patterns by age group.

Age group	N	MVPA total (mean $\pm$ SD)	MVPA ≥ 1 min (mean $\pm$ SD)	MVPA ≥ 5 min (mean $\pm$ SD)	MVPA ≥ 10 min (mean $\pm$ SD)	% ≥ 1 min	% ≥ 5 min	% ≥ 10 min
6–9	128	$132,818 \pm 45,849$	$79,059 \pm 33,474$	$51,649 \pm 29,809$	$39,246 \pm 29,706$	65.3%	41.0%	30.7%
10–12	138	$124,004 \pm 45,202$	$76,433 \pm 33,457$	$54,738 \pm 32,245$	$44,028 \pm 31,256$	66.4%	46.1%	36.0%
13–15	119	$101,232 \pm 49,584$	$61,823 \pm 30,882$	$41,095 \pm 28,327$	$30,593 \pm 21,908$	61.1%	40.6%	30.2%
16–17	108	$74,950 \pm 32,543$	$44,513 \pm 22,774$	$32,377 \pm 18,328$	$24,406 \pm 16,996$	59.4%	43.2%	32.6%

Note. MVPA values are expressed as mean daily ENMO units $\pm$ standard deviation. Percentages refer to the proportion of total daily MVPA accumulated within each bout-duration category.

Socioeconomic status

Total MVPA differed across socioeconomic categories (Table 3). Children from lower-SES backgrounds accumulated higher overall MVPA compared with those from very high SES groups. For example, mean total MVPA increased from $93,805 \pm 40,478$ ENMO units in the very high SES group to $119,602 \pm 38,834$ in the very low SES group. However, this higher overall volume was not consistently reflected in the proportional distribution of sustained MVPA. The difference in sustained MVPA (≥ 10 min) between the highest and lowest

socioeconomic categories was small-to-moderate in magnitude (Cohen's $d = 0.35$), suggesting that socioeconomic disparities were more evident in total volume than in sustained accumulation patterns.

Table 3. MVPA accumulation patterns by socioeconomic status.

SES	N	MVPA total (mean $\pm$ SD)	MVPA ≥ 1 min (mean $\pm$ SD)	MVPA ≥ 5 min (mean $\pm$ SD)	MVPA ≥ 10 min (mean $\pm$ SD)	% ≥ 1 min	% ≥ 5 min	% ≥ 10 min
Very high	93	93,805 $\pm$ 40,478	58,091 $\pm$ 33,163	39,122 $\pm$ 29,135	28,933 $\pm$ 25,966	61.9%	42.2%	32.0%
High	137	100,760 $\pm$ 52,504	63,476 $\pm$ 33,168	40,413 $\pm$ 29,259	37,174 $\pm$ 29,878	63.0%	41.1%	34.1%
Medium	122	104,627 $\pm$ 49,860	77,498 $\pm$ 35,442	53,421 $\pm$ 32,661	37,349 $\pm$ 22,091	73.1%	49.6%	35.7%
Low	111	114,998 $\pm$ 53,983	71,199 $\pm$ 37,388	50,387 $\pm$ 33,785	40,039 $\pm$ 29,912	68.2%	46.7%	38.4%
Very low	50	119,602 $\pm$ 38,834	70,379 $\pm$ 28,693	49,003 $\pm$ 24,024	37,350 $\pm$ 22,091	62.1%	43.0%	32.2%

Note. SES categories derived from an area-level deprivation index. MVPA values are expressed as mean daily ENMO units $\pm$ standard deviation.

Residential setting differences

Children living in rural areas accumulated greater total MVPA than their urban counterparts (115,577 $\pm$ 53,169 vs. 106,689 $\pm$ 47,906 ENMO units; Table 4). However, the proportional distribution of MVPA across bout durations differed slightly between settings. Urban participants accumulated a higher proportion of their MVPA in sustained bouts ≥ 10 minutes (35.7%) compared with rural participants (31.6%), despite similar absolute values of sustained MVPA.

Table 4. MVPA accumulation patterns by residential setting.

Setting	N	MVPA total (mean $\pm$ SD)	MVPA ≥ 1 min (mean $\pm$ SD)	MVPA ≥ 5 min (mean $\pm$ SD)	MVPA ≥ 10 min (mean $\pm$ SD)	% ≥ 1 min	% ≥ 5 min	% ≥ 10 min
Rural	106	115,577 $\pm$ 53,169	72,045 $\pm$ 37,522	48,565 $\pm$ 32,065	35,775 $\pm$ 28,766	68.9%	43.9%	31.6%
Urban	407	106,689 $\pm$ 47,906	63,719 $\pm$ 32,228	43,995 $\pm$ 28,409	35,438 $\pm$ 27,488	65.5%	44.9%	35.7%

Note. MVPA values are expressed as mean daily ENMO units $\pm$ standard deviation.

Multivariable regression models

The multivariable linear regression model examining predictors of sustained MVPA (accumulated in ≥ 10 -minute bouts) was statistically significant ($F(4, 507) = 19.42$; $p < .001$) and explained 12.6% of the variance ($R^2 = .126$), corresponding to an approximately medium overall effect size (Cohen's $f^2 = 0.14$). Older age was independently associated with lower sustained MVPA ($\beta = -1.927$; 95% CI: -2.570 to -1.283 ; $p < .001$), and female sex was likewise associated with lower sustained MVPA ($\beta = -14.001$; 95% CI: -18.504 to -9.498 ; $p < .001$). Socioeconomic status showed a small positive association, whereas residential setting was not statistically significant in the adjusted model (Figure 1).

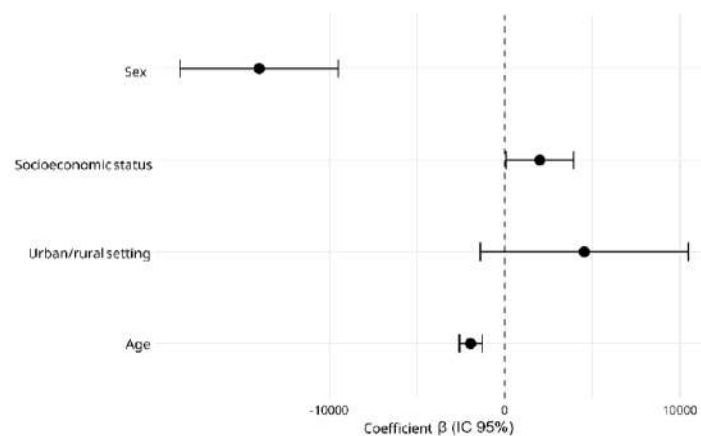


Figure 1. Sociodemographic predictors of sustained moderate-to-vigorous physical activity (≥ 10 min).

The regression model including BMI as the dependent variable was also statistically significant ($F(5, 506) = 58.19$; $p < .001$) and explained 35.9% of the variance ($R^2 = .359$), representing a large overall effect size (Cohen's $f^2 = 0.56$). Sustained MVPA (accumulated ENMO in ≥ 10 -minute bouts) was inversely associated with BMI ($\beta = -9.05 \times 10^{-6}$; 95% CI: -1.71×10^{-5} to -1.00×10^{-6} $p = .028$) after adjustment for age, sex, socioeconomic status, and residential setting. Although the regression coefficient is numerically small due to the scale of the ENMO metric, the association indicates that greater accumulation of sustained MVPA is independently related to lower BMI. Age was positively associated with BMI, whereas sex, socioeconomic status, and residential setting were not statistically significant predictors in the adjusted model (Figure 2).

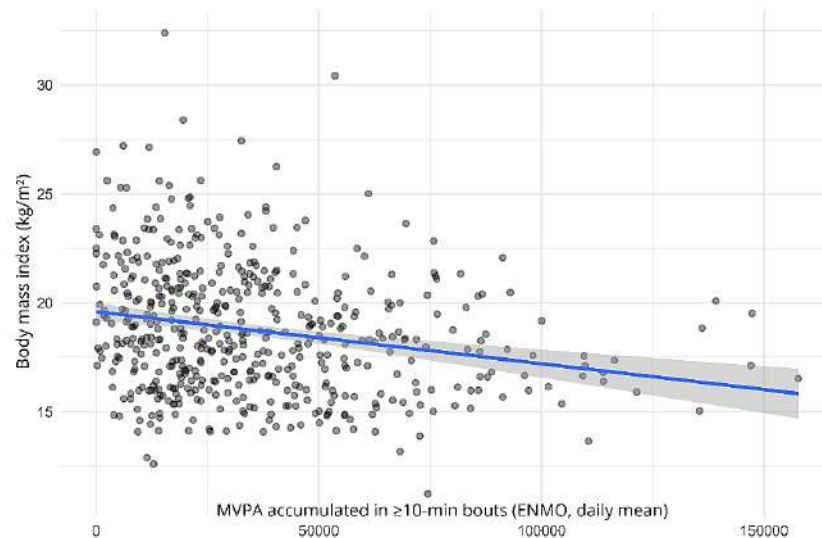


Figure 2. Association between sustained moderate-to-vigorous physical activity (≥ 10 -min bouts) and body mass index in Basque schoolchildren.

DISCUSSION

The present study provides population-based evidence that moderate-to-vigorous physical activity (MVPA) in children and adolescents is predominantly accumulated in fragmented bouts, with only approximately one third of daily MVPA occurring in sustained episodes of ≥ 10 minutes. While total volume remains a central indicator in surveillance systems (Tremblay et al., 2016; Physical Activity Guidelines Advisory Committee, 2018; WHO, 2020), the present findings demonstrate that the temporal structure of accumulation varies meaningfully across demographic groups and may represent an additional dimension of behavioural inequality. Emerging accelerometry frameworks have increasingly emphasised distribution- and profile-based metrics beyond simple threshold-derived minutes (Rowlands et al., 2018; Aadland et al., 2018), supporting the relevance of examining how activity is organised, not only how much is accumulated.

Sex differences were not only statistically significant but also of moderate magnitude ($d = 0.51$), indicating that boys accumulated a substantially greater proportion of their MVPA in sustained bouts compared with girls. Previous accelerometry-based research has consistently documented lower total MVPA in girls (Cooper et al., 2015; Sherar et al., 2007; Kretschmer et al., 2023), yet fewer studies have examined how this activity is temporally organised. The present results suggest that sex-related disparities extend beyond volume to include the continuity of effort. Evidence indicates that both intensity and bout duration may be relevant for

cardiometabolic health in youth (Tarp et al., 2018; Verswijveren et al., 2018). If sustained activity provides a distinct physiological stimulus—through prolonged cardiovascular loading or metabolic demand—such differences may have implications for long-term health trajectories that are not captured by volume alone.

Age-related differences were even more pronounced. The contrast between the youngest and oldest age groups yielded a moderate-to-large effect ($d = 0.63$), reflecting a substantial decline in sustained MVPA across adolescence. This finding is consistent with longitudinal evidence showing progressive reductions in overall activity during adolescence (Dumith et al., 2011; Farooq et al., 2018) but extends it by indicating that the decline affects not only quantity but also the structure of effort. International accelerometry data have shown marked age-related reductions in MVPA and shifts in intensity distribution (Cooper et al., 2015). School-based structures represent one of the most consistent settings for promoting sustained physical activity in youth (Dobbins et al., 2013), yet engagement tends to decline with increasing age.

Socioeconomic differences were smaller in magnitude ($d = 0.35$) and did not follow a clear linear gradient. Although lower socioeconomic groups accumulated higher total MVPA, this did not consistently translate into a higher proportion of sustained bouts. One possible interpretation is that activity in more deprived contexts may be more utilitarian or informal in nature—characterised by frequent, shorter episodes—rather than structured or sport-based participation that encourages sustained effort. This interpretation aligns with broader literature on contextual and environmental influences on youth physical activity opportunities (Ding et al., 2011; Giles-Corti et al., 2016; Inchley et al., 2020). Together, these findings highlight that volume-based inequalities may not fully reflect structural differences in activity patterns.

The multivariable analyses further clarified these associations. Age and sex independently predicted sustained MVPA, and the model explained a moderate proportion of variance ($R^2 = .126$; $f^2 = 0.14$), consistent with the multifactorial determinants of youth physical activity behaviour. In contrast, the BMI model demonstrated a large overall effect size ($R^2 = .359$; $f^2 = 0.56$), indicating that the included predictors collectively accounted for a substantial proportion of BMI variability. Sustained MVPA was inversely associated with BMI after adjustment for sociodemographic factors. Although the regression coefficient appears numerically small due to the scaling of ENMO-derived units, the direction and independence of the association indicate that greater accumulation of sustained effort is related to lower BMI. While BMI is not a direct measure of body composition, it remains a widely used anthropometric proxy in paediatric epidemiology and public health surveillance (Ekelund et al., 2012; Poitras et al., 2016; WHO, 2020). The present findings therefore suggest that temporal accumulation patterns may be relevant to weight-related health indicators beyond demographic influences.

From a conceptual perspective, these findings align with the growing shift in accelerometry research from threshold-based minutes toward intensity distribution and pattern metrics (Rowlands et al., 2018; Aadland et al., 2018; Carson et al., 2019). Traditional cut-point approaches quantify time spent above predefined thresholds but do not capture how activity is structured across the intensity continuum. Analytical approaches incorporating bout duration and intensity gradients have demonstrated that cardiometabolic risk markers may relate not only to total MVPA but also to its accumulation pattern (Tarp et al., 2018; Verswijveren et al., 2018). While current guidelines emphasise total accumulated MVPA regardless of bout duration (Physical Activity Guidelines Advisory Committee, 2018; WHO, 2020), the present data suggest that examining how activity is structured may provide complementary insight. This does not imply that short bouts are ineffective; rather, it indicates that behavioural patterning may reflect underlying physiological exposure in ways not captured by volume alone.

Several limitations should be considered. The cross-sectional design precludes causal inference, and reverse causality between BMI and sustained MVPA cannot be excluded. The strict definition of consecutive bouts without interruption tolerance may underestimate physiologically meaningful activity accumulated with brief pauses. In addition, MVPA was expressed in accumulated ENMO units rather than minutes per day, prioritising intensity-based profiling over guideline-aligned metrics; while this approach is consistent with current raw-accelerometry recommendations (van Hees et al., 2013; Rowlands et al., 2016; Migueles et al., 2017), it may limit direct comparison with time-based studies.

Nevertheless, the study has notable strengths. It employed wrist-worn raw accelerometry processed using open-source GGIR methodology, applied a strict and transparent bout-definition criterion, and examined multiple sociodemographic dimensions within a population-based sample. By integrating total volume and temporal accumulation within a single analytical framework, the present study contributes to a more refined characterisation of youth physical activity behaviour.

CONCLUSIONS

The findings of this study indicate that moderate-to-vigorous physical activity in children and adolescents is predominantly accumulated in fragmented bouts, with sustained episodes representing a limited proportion of total daily MVPA. The temporal organisation of activity varied meaningfully by sex and age, with boys and younger participants accumulating a greater proportion of sustained MVPA. Moreover, sustained MVPA was independently and inversely associated with BMI after adjustment for sociodemographic factors.

These results suggest that the structure of MVPA accumulation may represent an additional behavioural dimension beyond total volume, potentially contributing to weight-related health indicators in paediatric populations. While current public health guidelines appropriately emphasise total MVPA, the present findings indicate that considering how activity is accumulated may provide complementary insight for research and surveillance.

Future longitudinal studies are warranted to determine whether sustained activity patterns confer distinct health advantages over more fragmented accumulation and to clarify the directionality of the association between sustained MVPA and BMI across developmental stages.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Material preparation and data collection were performed by N. A., A. L-U., and X. R. Statistical analyses were performed by N. A. The first draft of the manuscript was written by N. A., and X. R. and A. L-U. contributed to subsequent revisions and refinement of the manuscript. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

INFORMED CONSENT

All participants and their families or legal guardians were informed in advance about the aims and procedures of the study. Participation was voluntary. Written informed consent was obtained from parents or legal guardians, as well as assent from participating students, prior to data collection.

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.

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Key performance indicators discriminating winners and losers in Men's Volleyball Nations League

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ABSTRACT

The study identified performance indicators that differentiate winning from losing teams in the Men's Volleyball Nations League. Total of 208 matches from two consecutive Volleyball Nations League seasons (2023 and 2024) were analysed. Matches were categorized with the final set difference (3-0, 3-1, and 3-2). We analysed four performance indicators: attack points, block points, serve points, and opponent error points. The normality of data was verified using Kolmogorov-Smirnov test and an independent t-test was employed to compare the differences between winners and losers for all indicators. Variables that showed significant differences between two groups were selected for discriminant analysis. Discriminant analysis revealed all match types, block and serve points were the most important predictor. In 5-set type matches attack, block and serve were found the significant predictor of match outcome. In 3-set type matches, all performance indicators significantly influenced the match outcome. These results demonstrate that serve and block points are consistently critical in all match types. These findings offer insights for coaches on how performance indicators impact match outcomes in high level volleyball matches. Future researches should investigate different scoring phases and other indicators to enhance the application of volleyball performance analysis.

Keywords: Performance analysis, Volleyball National League, Discriminant analysis, Performance indicators, Match analysis.

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INTRODUCTION

In modern volleyball, the integration of match statistical analysis has fundamentally transformed coaching methodologies and performance evaluation across all competitive levels. Coaches and performance analysts increasingly rely on comprehensive statistical data to identify key performance indicators (KPIs) and uncover the underlying dynamics of game success. This data-driven approach replaces traditional observational methods with objective and quantifiable measures that support evidence-based decision-making (Palao & Hernández-Hernández, 2014). Advances in analytical tools and video analysis technologies have further enhanced coaches' ability to track, predict, and recall critical match situations with higher precision (Anderson, 2021; Wright et al., 2012). Researchers have emphasized that the objective assessment of game-related statistics enables coaches to shift from subjective evaluation toward data-informed strategies, thereby improving tactical planning and player development (Dunarea de Jos University, Romania & Harabagiu, 2021; Prakoso & Lumintuarso, 2021). Such analytical frameworks offer deeper insight into the technical and tactical elements that differentiate winning from losing performances, ultimately contributing to a more systematic and effective model for competitive success (Drikos et al., 2009).

A volleyball match report is a comprehensive document that includes team and player statistics, used to analyse frequencies and provide easily understood information for players and coaches to apply in training and match situations. A study by (Giatsis, 2023) on women's Olympics (2016-2021) and world championships (2014-2018) serves, block, and attack, and opponent error, which showed a dominant predictor in 3-0 and 3-1 set matches. In 3-2 set matches, block points are the primary predictor of match success. Similarly, (Giatsis et al., 2023) study on the men's Olympics (2016-2021) and world championships of 2014-2018 revealed that attack, block, and serve came to be the predictors for team success in 3-0 and 3-1 set matches. On the other hand, 3-2 set matches serve and block points become the key factors determining the team's success. In addition, Drikos et al. (2024) compared men's and women's Asian competition (AVC Challenge Cup 2023) and found that for men's team's attack win percentage and serve win percentage were the predictors, and for women's teams, attack win percentage after reception was the discriminating factor. In their study, (Stankovic et al., 2019) point-scoring plays during the U23 Men's Volleyball World Championship under new regulations, to examine which aspects of these plays affected the match outcome of sets and each player's role in the game. The author's findings suggested that if those tested experimental rules are implemented in future competitions, the development of blocking, serving, and attacking skills may have a greater influence on set outcomes.

Notational analysis is essential for coaches and sports scientists seeking objective, quantifiable data of athletes' performance across tactical, technical, and physical dimensions (Hughes & Franks, 2007). Technical elements were the most critical predictors of winning and losing in international competitions. Technical elements refer to executing skills such as attack, block, and serve. High-level men's volleyball results were primarily determined by these performance indicators: attack, block, serve, and opponent error (Drikos & Vagenas, 2011; Mocanu et al., 2024; Rodriguez-Ruiz et al., 2011). As a result, these four performance indicators were selected for this study because they are the only scoring elements that consistently discriminate performance in high-level volleyball competitions. The Volleyball Nations League, with its highly competitive, unique tournament format and participation of the world's top-ranked 16 teams of comparable skill levels, creates an exceptional opportunity to identify the most significant performance discriminators determining winning at the high-level men's international volleyball competition.

To our knowledge, there are limited recent studies in the literature on the Men's Volleyball Nations League, and most studies have examined the performance indicators for the Olympics and the World Championship.

Further results should be of considerable value to coaches and researchers concerning improving team performance in different contexts, determining the trends, and making effective practice plans and match strategies. The present study examines the impact of performance indicators between winning and losing teams in the Volleyball Nations League (2023-2024), depending on the final score difference of matches.

METHODOLOGY

Study participants

This study includes 208 matches from two consecutive Volleyball Nations League 2023 and 2024 seasons. It includes 104 matches from each league season. The data were collected from the official website of FIVB (volleyball world). All the matches are played per the Federation of International de Volleyball rules.

Research procedures

The performance indicators selected for the study were adopted from the previous literature. The performance indicators examined in this research included Attack Points, Block Points, Serve Points, and Opponent Error Points. The matches were analysed from two different editions, and the combined year-wise data were also analysed. Matches were systematically categorized according to their final set score.

Statistical analysis

Descriptive statistics (mean and standard deviation) were calculated for each performance indicator of winners and losers of the Volleyball Nations League across different set types. The normality of data was verified using the Kolmogorov-Smirnov test, after which an independent sample t-test was employed to compare the difference between winners and losers for all indicators of 5-set, 4-set, and 3 set matches of Volleyball Nations League. For the variable that did not follow a normal distribution, the Mann–Whitney U test was used instead.

To understand the differences for the t-test, the standardized mean differences, i.e., Cohen's d effect size, was calculated and interpreted as d less than 0.2 trivial, d between 0.2 to 0.5 small, d between 0.5 to 0.8 medium, and greater than 0.8 large effect. Whereas the effect size for Mann–Mann-Whitney U test was calculated using the formula $r = z/\sqrt{n}$. The effect size was small if r is less than 0.3, r between 0.3 and 0.5 indicates medium effect, r greater than 0.5 means large effect Karadimitriou S. M., Marshall, E. & Knox, C., Mann-Whitney U Test (Sheffield Hallam University, 2018, Volker, 2006).

Variables that showed significant differences between two groups were selected for discriminant analysis. In a significant discriminant function, if the absolute value of the structural coefficient (SC) was greater than 0.30 (Sampaio et al., 2006), then a performance indicator was considered a meaningful contributor to differentiating winners from losers. The alpha level was set at $p < .01$ for all tests. All analyses were conducted using Statistical Package for the Social Sciences 24 (SPSS Inc., Chicago, IL, United States).

RESULTS

Tables 1 and 2 show the descriptive statistics and comparison of the performance indicators between winning and losing teams in different set-type matches of the Volleyball Nations League.

In 3-2 set matches, winners outperform losers in performance indicators, including attack ($p < .01$, Cohen's $d = 0.53$) and serve points ($p < .01$, $r = 0.286$). It was noted that the average winning team scored 62.95 points from direct attack, and the losing team scored 59.04.

Table 1. Descriptive statistics.

Performance Indicators	Set 5 (n = 53)		Set 4 (n = 73)		Set 3 (n = 82)	
	Winner	Loser	Winner	Loser	Winner	Loser
Attack	62.92 (7.6)	59.04 (6.92)	54.24 (5.01)	50.72 (5.52)	40.92 (4.7)	35.09 (4.26)
Block	10.11 (3.57)	10.4 (3.65)	9.24 (3.07)	6.66 (2.43)	7.86 (2.99)	4.95 (2.48)
Serve	6.58 (2.59)	5.21 (2.87)	6.15 (2.4)	4.2 (2.04)	5.23 (2.51)	2.89 (1.76)
Error	30.53 (5.25)	30.32 (6.16)	27.29 (4.94)	25.53 (4.46)	22 (4.15)	17.79 (4.1)

Table 2. Results of independent t-test and Mann-Whitney U test along with their effect size.

Performance indicators	Independent T-test			Mann-Whitney U Test			Effect Size ("Cohen's d" or "r")		
	Sig. value			Sig. value					
	Set 5	Set 4	Set 3	Set 5	Set 4	Set 3	Set 5	Set 4	Set 3
Attack	0.007	0	0	NA	NA	NA	0.53 ^M	0.671 ^M	1.3 ^L
Block	NA	NA	0	NA	0	NA	-0.08 ^T	0.423 ^M	1.05 ^L
Serve	NA	NA	NA	0.003	0	0	0.286 ^S	0.412 ^M	-0.486 ^M
Error	NA	NA	0	NA	0.015	NA	NA	0.202 ^S	1.02 ^L

Note. Effect Size "Cohen's d" – for independent t-test; Effect size "r" – for Mann-Whitney U Test; S – Small Effect Size; M – Medium Effect Size; L – Large Effect Size; NA – Not Applicable.

In contrast, in the case of 3-1 set matches univariate result showed that the most important indicator is attack, block and serve points. More specifically observed that in 3-1 set matches winners demonstrate a significant higher percentage of points from block (Mean = 9.24, $p < .01$, Cohen's $d = 0.423$), as compared to losing teams (Mean = 6.66, $p < .01$, $r = 0.423$).

In 3-0 set matches, the teams were successful (winners) had scored more points through direct attack (Mean = 40.92, $p < .001$, Cohen's $d = 1.3$) as compared to the unsuccessful teams (losers) (Mean = 35.09, $p < .001$, Cohen's $d = 1.05$). In addition, winning teams in the 3-0 set matches had an average of 7.86 points from the opponent error, but for losers it was an average of 4.95 points.

The discriminant functions (Table 3) proved to be effective in discriminating between the winners and losers because the reclassification accuracy rates were 0.156, 0.602, and 0.72 in 3-2 set matches, 3-1 set matches, and 3-0 set matches respectively.

Table 3. Discriminant function Structure Coefficients (SC) and tests of statistical significance.

Performance indicators	Set 5	Set 4	Set 3
Attack	0.628	0.273	0.399
Serve	0.591	0.358	0.33
Block	-0.399	0.381	0.325
Error	#	0.154	0.314
Eigenvalue	0.185	1.511	2.668
Wilks Lambda	0.844	0.398	0.273
Canonical correlation	0.395	0.776	0.853
Chi-Square	17.465	130.752	207.942
Significance	<.001	<.001	<.001
Reclassification	67.00%	91.80%	94.50%

Note. SC discriminant value $\geq .30$ | # means that the variable was not significant and was not used in discriminant analysis.

The performance indicators that significantly contributed to the discriminant function in 3–2 set matches were attack points, serve points, and block points, with structural coefficients (SC) for the winning group ranging from –0.39 to 0.62.

Conversely, in 3-1 set matches, performance indicators, contributed to the discriminant function were serve points and block points, with |SC| value ranging from- 0.35 to 0.38.

According to 3-0 set matches, performance indicators, contribute to the discriminant function were attack points, serve points, block points, and opponent error points, |SC| ranging from-0.31 to 0.39.

DISCUSSION

Scientific training in volleyball is rapidly growing due to technological advancements. Therefore, it is essential to constantly analyse variables that affect performance. The primary objective was to identify key performance indicators that distinguish winners from losers across various matches in the 2023- and 2024- Men's Volleyball Nations League tournaments, depending on the final score difference of matches. The results reveal critical performance differentials between winners and losers in these tournaments. Notably, the superior performance of winners across several key indicators highlights the complex nature of success in high-level matches.

Attack points

Studies consistently highlights the critical role attack points in determining match outcomes (Eom & Schutz, 1992; Rodriguez-Ruiz et al., 2011; Stankovic et al., 2019). Most studies identified attack points as the most frequent predictor in high-level volleyball tournaments both men and women's matches (Drikos et al., 2024; Silva et al., 2013). A previous study by (Drikos & Vagenas, 2011) demonstrated that attack points as an important predictor in 3-0 and 3-1 set types, and attack points' effectiveness was found to be considerably lower in 3-2 set type matches. The novel study reveals contradictory against (Castro et al., 2011; Drikos & Vagenas, 2011) in 3-1 set type matches our study reveals that the attack point is not a significant factor. The highest canonical coefficient (0.628) observed in 3-2 set type matches in our study reveals that attack effectiveness becomes increasingly critical in 3-2 set type matches. These findings challenge previous research suggesting lower attack effectiveness in 3-2 set type matches. The balanced nature of 3-2 set type matches creates scenarios where sustained attacking pressure and efficiency become the supreme element for victory, as teams must maintain high performance levels across five sets under increasing physical and psychological stress.

Serve points

Previous research highlights the critical role of serve points in determining competitive success in extending beyond three sets, previous studies corroborating the importance of serve performance (Giatsis et al., 2023; Rocha et al., 2020; Silva et al., 2014). Serve points contribute fewer total points compared to attack and opponent errors points, the differential between winners and losers (Valladares et al., 2016) teams remains stable and meaningful across with values of 2.34, 1.95, and 1.37 for sets 3, 4, and 5, respectively. The effect size of serve points demonstrates greater impact in three-set (0.486) and four-set (0.412) type matches compared to five-set type matches. This pattern aligns with findings indicating that higher-ranked men's volleyball teams exhibit superior serve point success rates (Drikos & Tsoukos, 2018; Marcelino et al., 2012; Peña et al., 2013), thereby supporting the results of the present study. Successful teams use serves tactically to disrupt opponent formations and weaken reception quality, not merely for direct scoring. This approach creates enhanced transition attack and block point opportunities for the serving team.

Block points

The ability to score by blocking becomes a decisive factor in high-level men's competitions (Giatsis et al., 2023; Mikolajec et al., 2025; Rodriguez-Ruiz et al., 2011), according to these studies, block points significant predictor of all set types of matches. Contrary to a previous study (Giatsis, 2023), this study revealed that losing teams had slightly higher block points than winners in 5-set matches (10.40 vs 10.11), with a minimal effect size (0.08). However, 3-set matches showed the largest block point effectiveness for winners, with a 2.91 point difference and substantial effect size (1.05). The present study suggests block point effectiveness varies significantly by match type.

Opponent error point

Opponent error points play a significant predictor of the match outcomes, and same time, winners have made fewer errors than the losing team (Peña et al., 2013; Rodriguez-Ruiz et al., 2011). According to (Giatsis, 2023), in 3-set and 4-set matches, the opponent's error point is statistically significant. But in the present study, the impact of opponent error was only significant in 3-set matches. The effective size of the 3-set matches was higher (1.02). These findings reveal a significant variation in the predictivity of the opponent error points between the types of matches. In 5-set matches, both teams are equally skilled, but in 3-set matches shows greater skill difference.

CONCLUSION

In conclusion, this study reaffirms the critical importance of attacking efficiency, serving effectiveness, and minimizing errors in determining match outcomes at the elite level of the Volleyball Nations League. By identifying the performance indicators that most clearly distinguish winners from losers, the research provides a deeper understanding of competitive dynamics and offers actionable insights for coaches and analysts to optimize tactical strategies. Future research could further examine these indicators across different volleyball leagues and competitive contexts, thereby strengthening the strategic framework for achieving success in professional volleyball.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Conceptualization K.V and T.P. K.V and Mattakottil methodology. K.V and T.P data collection. Formal analysis K.V and Mattakotttil. Investigation Sundar. Writing—review and editing K.V, T.P, Mattakottil and Sundar. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

DATA AVAILABILITY

The data used in the analysis are presented in the study as Table(s) and Figure(s). Any other data requirement should be directed to the corresponding author and will be provided upon reasonable request.

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Contribution of breaststroke start and turn parameters to competitive performance in elite male swimmers

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ABSTRACT

This study examined the relationship between selected temporal parameters of the breaststroke start and turn and overall race performance in elite male swimmers. The analysis included the 50 m, 100 m, and 200 m breaststroke events at the World Aquatics Championships. Race performance was defined as final race time (FT). Start-related variables included reaction time (RT) and time at 15 m after the start (T15S). Turn-related variables included time at 5 m before the wall (T5BT), turn duration (TT), and time at 15 m after the turn (T15T). Relationships were assessed using Pearson's correlation coefficient (r) with effect size interpretation. In the 50 m event, FT was significantly associated with T15S ($r = .534$, $p < .05$), whereas RT showed no significant relationship. In the 100 m event, start variables were not significantly related to FT; however, T15T demonstrated a significant correlation ($r = .511$, $p < .05$). In the 200 m event, start variables were not significant, while TT ($r = .824$, $p < .05$) and T15T ($r = .667$, $p < .05$) showed strong associations. The findings indicate distance-specific contributions of race segments, with increasing importance of turn efficiency as race distance increases.

Keywords: Performance analysis, Race analysis, Performance metrics, Swimming, Efficiency.

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INTRODUCTION

Swimming performance at the elite level is strongly determined by technical precision, where small temporal differences frequently decide final rankings. In modern competitive swimming, race analysis has increasingly adopted a segment-based framework that distinguishes between start, clean swimming, turn, and finish phases. Within this framework, non-cyclical race segments—particularly the start and the turn—represent critical opportunities to gain or lose time.

The start phase has been widely recognized as a decisive determinant of performance, especially in sprint events. Cossor and Mason (2001) demonstrated that the start up to 15 m may account for more than one quarter of total race time in 50 m events. Subsequent biomechanical analyses have shown that start performance is influenced not only by reaction time but also by take-off force production, flight trajectory, underwater path, and transition efficiency (Vantorre et al., 2014, Matúš et al., 2024). Although reaction time is commonly measured in competition, its relative contribution to overall performance appears limited among elite swimmers, where inter-individual variability is small (Silva et al., 2019, Tor et al., 2015). Therefore, performance analysis frequently emphasizes early split times (e.g., 15 m) as more comprehensive indicators of start effectiveness.

Breaststroke presents unique biomechanical characteristics compared with other competitive strokes. It is characterized by pronounced intracyclic velocity fluctuations and alternating propulsive and resistive phases, requiring precise coordination to minimize drag and maintain forward momentum (Maglischo, 2003, Barbosa et al., 2005). The underwater pull-out and glide phases following both the start and turns are especially important in breaststroke due to their potential to maximize propulsion while reducing resistance (Seifert et al., 2007). Recent performance-analysis research has highlighted that underwater actions can significantly influence outcomes in short-course 50 m and 100 m breaststroke events (Sánchez et al., 2021), reinforcing the performance value of optimizing transitional phases beyond surface stroking.

Turn performance becomes increasingly relevant in races longer than one pool length, as its cumulative effect grows with distance. The breaststroke turn requires a simultaneous two-hand touch followed by rapid body repositioning and a streamlined push-off, making it a technically demanding transition. Biomechanical investigations have demonstrated that post turn velocity and underwater efficiency significantly influence overall race outcomes (Veiga & Roig, 2017). Moreover, recent analyses have documented meaningful relationships between turn related kinematic variables and competitive performance in elite swimmers (Gonjo et al., 2020). Intra and inter-individual variability in underwater pull-out techniques during 200 m breaststroke turns further suggests that turn execution remains a performance differentiating factor even at high levels of competition (Gonjo et al., 2023). Additionally, evidence indicates that the contribution of turn and underwater phases to overall performance may increase with race distance (Morais et al., 2019).

Although previous studies have examined start and turn phases independently, fewer investigations have directly compared their relative contribution across multiple race distances within the same stroke and competition context. Given the increasing importance of marginal gains in elite swimming, understanding how the relevance of start- and turn-related parameters differs between 50 m, 100 m, and 200 m breaststroke events is of both theoretical and practical importance.

Therefore, the aim of this study was to examine the relationship between selected temporal indicators of the start and the breaststroke turn and overall race performance in elite male swimmers competing at the World Aquatics Championships.

MATERIALS AND METHODS

Participants

The research sample consisted of elite male swimmers competing at the highest international level. The analysis included performances achieved in the 50 m, 100 m, and 200 m breaststroke events during the World Aquatics Championships held in Fukuoka in 2023.

For each event, data from sixteen swimmers competing in the semifinal heats were analysed. The inclusion of semifinal performances ensured a high and relatively homogeneous performance level while providing a larger sample size compared to final-only analyses.

All races were conducted in a 50 m long-course swimming pool under standardized competition conditions and in accordance with World Aquatics regulations. The study focused exclusively on male swimmers to eliminate the potential influence of sex-related physiological and biomechanical differences on start and turn performance.

The final dataset consisted of officially recorded race times and phase-specific timing data obtained from electronic timing systems and official race analysis protocols provided by the event organizers.

Variables and measurements

This study employed a cross-sectional correlational design aimed at examining the relationships between selected temporal parameters of the start and the breaststroke turn and overall race performance in elite male swimmers.

Race performance was assessed using the final race time (FT, s) in each breaststroke event (50 m, 100 m, and 200 m). Selected temporal parameters related to the start and the breaststroke turn were obtained from official semifinal race analyses.

Start performance was evaluated using reaction time (RT, s), defined as the time interval between the starting signal and the initiation of the swimmer's movement, and the time at 15 m after the start (T15S, s), representing the time elapsed from the starting signal until the swimmer reached the 15 m mark.

Turn performance was assessed using the time at 5 m before the turn (T5BT, s), defined as the time recorded from the start of the race until the swimmer reached the 5 m mark before the wall. The duration of the turn (TT, s) was defined as the time interval between the swimmer reaching the 5 m mark before the wall and the 5 m mark after the wall. Additionally, the time at 15 m after the turn (T15T, s) was analysed as the time elapsed from the wall push-off until the swimmer reached the 15 m mark after the turn.

Video analysis

The analysed races were sourced from publicly available broadcast footage of the semifinal heats. Video analysis was conducted using iMovie and DaVinci Resolve software. All measurements were performed using frame-by-frame inspection of the video recordings. Temporal reference points used for the determination of RT, T15S, T5BT, TT, and T15T were identified visually, including the start signal, movement initiation, reaching the 15 m mark after the start, approach to the wall, wall contact, push-off, and reaching the 15 m mark after the turn.

Distance reference points corresponding to T5BT, T15S, and T15T were determined based on official pool markings visible in the broadcast footage. Corresponding timestamps were extracted directly from the video timeline. Given the frame rate of 30 frames·s⁻¹, the temporal resolution of the measurements was 0.033 s. The temporal resolution of the analysis was limited by the video frame rate.

All analysed variables (RT, T15S, T5BT, TT, and T15T) were derived consistently using the same methodological procedure across all performances.

Statistical analysis

Relationships between race performance (FT) and selected start- and turn-related variables (RT, T15S, T5BT, TT, and T15T) were examined using Pearson's correlation coefficient (*r*). Alongside statistical significance testing, the practical relevance of relationships was evaluated using effect size interpretation based on the magnitude of *r*. Correlation magnitudes were classified according to Hopkins (2002) as trivial (<.10), small (.10 – .29), moderate (.30 – .49), large (.50 – .69), and very large (.70 – .89). Statistical significance was set at *p* < .05.

All statistical analyses were conducted using standard statistical software.

RESULTS

The relationships between race performance (FT) and selected start- and turn-related variables are summarized in Table 1. The magnitude of correlations ranged from trivial to very large across the analysed events, indicating variability in the contribution of start and turn phases depending on race distance.

Table 1. Pearson's correlation coefficients (*r*) between final race time (FT) and start- and turn-related variables.

Distance	Variable	Abbreviation	<i>r</i>	Effect size	<i>p</i> -Value
50 m	Reaction time	RT	-.310	Moderate	>.05
	15 m time after start	T15S	.534	Large	<.05*
100 m	Reaction time	RT	.138	Small	>.05
	15 m time after start	T15S	.318	Moderate	>.05
	5 m time before turn	T5BT	-.089	Trivial	>.05
	Turn duration	TT	.066	Trivial	>.05
	15 m time after turn	T15T	.511	Large	<.05*
200 m	Reaction time	RT	.245	Small	>.05
	15 m time after start	T15S	.305	Moderate	>.05
	5 m time before turn	T5BT	.447	Moderate	>.05
	Turn duration	TT	.824	Very large	<.05*
	15 m time after turn	T15T	.667	Large	<.05*

Note. * indicates statistically significant correlations.

50 m Breaststroke

In the 50 m breaststroke event, start performance demonstrated a stronger association with overall race time compared to turn-related parameters, as only the start phase is present in this sprint event. A statistically significant positive correlation was observed between FT and T15S (*r* = .534, *p* < .05), classified as a large effect size. This indicates that swimmers who required more time to reach the 15 m mark after the start tended to achieve slower final race times.

In contrast, reaction time (RT) was not significantly associated with FT ($r = -.310, p > .05$), despite showing a moderate negative correlation. The absence of statistical significance suggests that variability in RT did not meaningfully influence overall sprint performance within this elite semifinal sample.

Overall, for the 50 m event, the underwater and transition phase represented by T15S appeared more closely related to race performance than the initial reaction phase.

100 m Breaststroke

In the 100 m breaststroke event, the relationships between start-related variables and overall performance were weaker compared to the 50 m distance. Neither RT ($r = .138, p > .05$) nor T15S ($r = .318, p > .05$) demonstrated statistically significant associations with FT. Although T15S reached a moderate effect size, the relationship did not achieve statistical significance.

Turn-related variables displayed differentiated patterns. The strongest association within this event was found between FT and T15T ($r = .511, p < .05$), representing a large effect size. This indicates that swimmers with longer post-turn 15 m times tended to record slower final race times.

In contrast, T5BT ($r = -.089, p > .05$) and TT ($r = .066, p > .05$) showed trivial correlations with FT and were not statistically significant. These findings suggest that, in the 100 m event, the phase following wall push-off may be more closely related to overall performance than the approach to the wall or the turn duration itself.

200 m Breaststroke

In the 200 m breaststroke event, start-related variables did not show statistically significant relationships with overall race performance. Reaction time (RT) demonstrated a small positive correlation with FT ($r = .245, p > .05$), while T15S showed a moderate positive correlation ($r = .305, p > .05$), neither reaching statistical significance.

In contrast, turn-related parameters demonstrated substantially stronger associations with FT compared to shorter race distances. A very large positive correlation was observed between FT and TT ($r = .824, p < .05$), indicating that longer turn durations were strongly associated with slower final race times. This was the strongest relationship identified across all analysed events.

Additionally, T15T showed a significant large positive correlation with FT ($r = .667, p < .05$), further emphasizing the importance of post-turn performance in the 200 m event. Although T5BT demonstrated a moderate positive correlation ($r = .447, p > .05$), it did not reach statistical significance.

Overall, the 200 m breaststroke event exhibited the most pronounced relationships between turn performance and final race outcome, whereas start-related variables appeared less influential within this distance.

A comparison across race distances revealed distinct patterns in the relationships between start- and turn-related variables and overall race performance.

In the 50 m event, the only significant association was observed for T15S, indicating that early-phase performance following the start was most closely related to final race time in this sprint distance. No turn-related variables were analysed for this event due to the absence of a turn phase.

In the 100 m event, start-related variables did not demonstrate significant associations with FT. However, among turn-related parameters, T15T showed a significant large correlation with race performance, whereas TT and T5BT did not. This suggests that, in the 100 m distance, the post-turn phase displayed a stronger statistical relationship with final performance compared to both the start phase and the turn duration itself.

In the 200 m event, turn-related variables demonstrated the strongest associations with FT. TT showed a very large correlation, and T15T exhibited a large correlation, both reaching statistical significance. In contrast, start-related variables remained non-significant. The progressive increase in correlation magnitude for TT from the 100 m to the 200 m event indicates a greater statistical association between turn performance and overall race outcome as race distance increased.

Across all distances, reaction time (RT) did not demonstrate a statistically significant relationship with final race time. Similarly, T5BT did not reach statistical significance in either the 100 m or 200 m events, despite showing a moderate correlation in the 200 m distance.

Overall, the results indicate that the statistical association between turn-related variables and race performance becomes more pronounced with increasing race distance, whereas the contribution of start-related parameters appears relatively stronger in the shortest event.

DISCUSSION

The present study examined the relationship between selected start- and turn-related temporal parameters and overall race performance in the 50 m, 100 m, and 200 m breaststroke events. The findings indicate that the relative contribution of start and turn phases varies as a function of race distance.

In the 50 m breaststroke, time at 15 m after the start (T15S) demonstrated a significant association with final race time (FT), whereas reaction time (RT) did not. These findings align with previous research emphasizing the performance relevance of the start in sprint events. Cossor and Mason (2001) reported that the start phase up to 15 m accounts for a substantial proportion of total race time in 50 m events. Similarly, Mason and Cossor (2000) highlighted the importance of optimizing the underwater phase and transition to surface swimming in short-distance races. The absence of a significant relationship between RT and FT suggests that, in elite swimmers, performance is more strongly influenced by the quality of the underwater and propulsion phases than by reaction time alone, which has also been observed in high-level sprint analyses (Morais et al., 2019, Matúš, et. al. 2024).

In the 100 m breaststroke, start-related variables were not significantly associated with performance, whereas time at 15 m after the turn (T15T) showed a significant correlation with FT. This supports the notion that middle-distance performance depends on the integration of race segments rather than dominance in a single phase. The turn has been described as a complex biomechanical sequence involving approach, wall contact, push-off, streamline, and underwater propulsion (Maglischo, 2003). Previous investigations have demonstrated that post-turn velocity and streamline efficiency significantly influence race outcomes (Veiga & Roig, 2017). The present results reinforce the importance of the post-turn phase over isolated turn duration in middle-distance breaststroke events.

In the 200 m breaststroke, turn-related variables demonstrated the strongest associations with performance, particularly turn time (TT) and T15T. The progressive increase in correlation magnitude with race distance is consistent with literature indicating that turns represent a critical determinant of performance in longer events

(Gonjo et al., 2020). Repeated push-offs and underwater phases may cumulatively influence overall race time, especially as fatigue develops. It has been suggested that technical consistency during turns becomes increasingly important as race distance increases (Morais et al., 2019). The strong association observed in the present study supports the hypothesis that small differences in turn efficiency may accumulate across multiple repetitions and substantially affect final performance.

Breaststroke technique is characterized by alternating propulsive and resistive phases, making velocity maintenance highly dependent on coordination efficiency (Maglischo, 2003). Given the technical demands of breaststroke, performance determinants may differ from other strokes, particularly in the underwater and transitional phases. The present findings suggest that sprint performance is more strongly associated with start efficiency, whereas longer events demonstrate greater sensitivity to turn execution.

Overall, the results confirm the distance-specific contribution of race segments in elite breaststroke swimming. From a practical perspective, sprint-focused training should emphasize start mechanics and underwater propulsion, whereas preparation for longer distances should prioritize turn efficiency, push-off force production, and streamline optimization.

CONCLUSION

The present study investigated the relationships between selected start and turn-related temporal parameters and overall race performance in elite male swimmers competing in the 50 m, 100 m, and 200 m breaststroke events. The findings demonstrate that the contribution of race segments to performance is distance specific.

In the 50 m breaststroke, performance was primarily associated with the time at 15 m after the start, highlighting the importance of start efficiency and underwater propulsion in sprint events. In contrast, start-related variables were not significantly related to performance in the 100 m and 200 m events. Instead, turn-related parameters—particularly turn duration and time at 15 m after the turn—showed stronger associations with race outcome, especially in the 200 m breaststroke.

These results suggest that while explosive start performance is critical in sprint events, turn execution and post-turn efficiency become increasingly influential as race distance increases. From a practical perspective, training programs should adopt a distance-specific approach, emphasizing start mechanics in sprint disciplines and optimizing turn technique and underwater phases in middle- and long-distance breaststroke events.

Future research should integrate biomechanical and physiological analyses to further clarify the determinants of performance in elite breaststroke swimming.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Grznár, Labudová and Hromník wrote the paper and collected the data. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Acute effects of inter-set static stretching on hamstring strength and range of motion (ROM)

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ABSTRACT

Purpose: Inter-set stretching has been proposed as a strategy to influence subsequent performance during resistance exercise, yet its acute effects remain controversial. While some studies suggest potential benefits for flexibility and range of motion (ROM), concerns persist regarding possible impairments in strength output and total training volume (TTV). **Methods:** Seventeen trained males were randomly assigned to one of two protocols: (a) inter-set static stretching (ISS); and (b) no stretching between sets (WSS). The ISS protocol involved passive hip flexion with the knee extended on the dominant lower limb, consisting of four 45-second sets at maximum perceived discomfort level, performed between exercise sets. In the WSS protocol, participants rested passively between sets without stretching. **Results:** A main effect for condition was found in the number of repetitions ($p = .006$), indicating that the ISS protocol led to fewer repetitions compared to the WSS protocol. A main effect for sets was also observed ($p \leq .0001$), showing a progressive decrease in repetitions across sets in both protocols. Regarding TTV, the WSS protocol resulted in higher values than the ISS protocol ($p = .01$), although the effect size was moderate and non-statistically significant ($d = .55$; $CI_{95\%} = -0.15$ to 1.22). Both protocols promoted a significant acute increase in ROM, with a greater improvement observed in the ISS protocol ($p < .05$). **Conclusion:** These results suggest that while ISS may slightly reduce performance measures such as volume and repetition count, it can be effective strategy for enhance range of motion in trained individuals.

Keywords: Performance analysis, Resistance training, Neuromuscular response, Flexibility, Training volume, Lower limb exercise.

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INTRODUCTION

In the scientific literature, the most commonly used stretching methods are the following: static stretching (SS), ballistic stretching, dynamic stretching, and proprioceptive neuromuscular facilitation (PNF), with SS being the most used when the objective is to increase flexibility. (Medeiros et al., 2016). However, when SS is performed before the start of a resistance training session, it can generate deleterious effects on muscle strength performance. (Behm et al., 2016; Simic et al., 2013; Thomas et al., 2023). Conversely, stretching exercises performed between sets may not interfere with muscle strength performance (Marin et al., 2019; Souza et al., 2020), although other investigations discuss possible negative effects in this condition (JBB et al., 2022; Padilha et al., 2019).

For example, Camargo et al. (JBB et al., 2022) observed that performing inter-set SS on the pectoral muscle, lasting 45 seconds, without any additional rest period after stretching, between sets (7 sets) of the cable fly exercise, provided a 29.9% decrease in the total training volume, when compared to the group without stretching. Nevertheless, Padilha et al. (Padilha et al., 2019) observed a 15.4% decrease in the total volume in the isokinetic knee extension exercise (7 sets), when an inter-set SS was implemented in the quadriceps muscles, lasting 25 seconds, preceded by 15 seconds of passive rest (transition between machines). Therefore, in addition to the duration of the stretching and the muscle group stretched, passive rest after inter-set SS may be a relevant factor in the possible decrease in muscle performance induced by the training method.

In contrast, the findings of Marin et al. (Marin et al., 2019) did not show significant differences in the total number of repetitions when applying an inter-set SS protocol lasting 1 minute, without any additional passive rest for the pectoral muscles, during six sets of the bench press exercise with a load of 80% of 8RM, when compared to the exercise with traditional passive rest. It is plausible that the exercise intensity (80% of 8RM) may have reduced the impact of stretching on strength performance (Ribeiro et al., 2014). Additionally, the authors do not describe the intensity at which the stretching was performed. Therefore, the overload imposed by stretching may not have been sufficient to generate deleterious effects on strength (Kataura et al., 2017; Nakamura et al., 2021), allowing performance in subsequent repetitions to remain unchanged.

Currently, inter-set SS has been widely used as a strategy to increase muscle hypertrophy through its potential effects on intracellular anabolic signalling pathways, stimulated by active and passive force sensors. (Schoenfeld et al., 2022; Van Every et al., 2022). However, none of the aforementioned studies investigated the acute effect of inter-set SS on the range of motion, especially of the hamstring muscles. For the hamstring muscles, improvements in flexibility and strength are considered key modifiable risk factors involved in the occurrence of injuries. (Wan et al., 2021). In contrast, prescribing stretching and strength exercises in the same training session may lead to adaptive mismatches in terms of flexibility and strength. (Behm & Chaouachi, 2011; Bryant et al., 2023; Chaabene et al., 2019; Kay & Blazevich, 2012). Therefore, it is essential to develop new training strategies that aim to improve both the flexibility and strength of the hamstring muscles (Cai et al., 2023).

Thus, the present study aimed to investigate the acute effects of inter-set static stretching of the agonist muscles on total training volume (TTV) during the unilateral leg curl exercise, as well as on the range of motion of the hamstring muscles in trained men. We hypothesized that the experimental protocol consisting of inter-set SS exercises of agonist muscles would increase the range of motion (Covert et al., 2010; Medeiros et al., 2016) and promote small deleterious effects on the total training volume, when compared to the traditional RT protocol.

MATERIALS AND METHODS

Study design

The study was conducted using a randomized crossover design, evaluating the effects of inter-set static stretching of the hamstring muscles during the execution of the unilateral leg curl exercise in strength-trained men. For this, 17 participants attended the laboratory for four sessions, with a 72-hour interval between visits. At the first visit, participants completed the Physical Activity Readiness Questionnaire (PAR-Q) (Adams, 1999), underwent an anthropometric assessment, performed the 10RM load test, and were familiarized with the experimental procedures. At the second visit, participants performed the 10RM retest. During the third and fourth visits, participants were randomly assigned (<https://www.randomizer.org>) to the conditions: (a) a protocol with inter-set static stretching (ISS); and (b) a protocol without static stretching between sets (WSS). Outcome assessors and data analysts were blinded to the intervention conditions. The ISS protocol was performed through passive hip flexion with the knee extended on the dominant lower limb, consisting of four 45-second sets at the maximum perceived discomfort intensity, performed between the exercise sets. This protocol was defined based on previous studies (Austin, 1999; Padilha et al., 2019), due to its positive effects on the range of motion and lower deleterious effects on strength performance. All sessions were performed in the morning (between 8 am and 12 pm), in a controlled environment with temperatures between 20° and 22°C.

Participants

The sample consisted of 17 male individuals aged between 24 and 40 years (age = 26.8 ± 5.6 years; body mass = 84.2 ± 10.0 kg; height = 1.76 ± 0.1 m; body fat = 15.5 ± 6.0 %) and selected by convenience. Given that the sample selection was based on convenience, the statistical power of the results [β] was assessed. The following inclusion criteria were adopted: a) having at least two years of experience in strength training; b) not having physical limitations, health problems that could interfere with strength exercise performance, or injuries during all procedures; c) not using medications, drugs, or supplements that could alter their physical performance during the research period. Participants were excluded if: a) They presented any type of disease; b) they had a history of musculoskeletal injuries at least 12 months prior to the study that compromised the performance of the experimental protocols; c) Resting blood pressure $\geq 140/90$ mmHg. In addition, individuals were instructed to: a) avoid consumption of alcoholic or caffeine-based beverages for at least 24 hours before the procedures; b) refrain from physical activities involving effort of the lower limbs up to 48 hours before data collection. Informed consent was obtained from all participants, and the study was approved by the local University Ethics Committee (protocol number 7.474.096), in accordance with the Declaration of Helsinki.

Furthermore, this research was conducted in full compliance with the ethical standards of the Journal of Sports Medicine and Physical Fitness, in accordance with the ethical policies of Committee on Publication Ethics (COPE) and International Committee of Medical Journal Editors (ICMJE).

Table 1. Characteristics of individuals.

Variables	Mean	SD
Age (years)	26.8	5.6
Height (cm)	176	0.05
Body mass (kg)	84.2	10.0
Body fat (%)	15.5	6.0
BMI	27.0	2.6

Note. BMC = body mass index; SD = standard deviation.

Anthropometric assessment

The participants' body mass and height were measured using a scale and a stadiometer (Filizola model 31, São Paulo, Brazil). Next, abdominal, pectoral, and medial thigh skinfolds were measured with a skinfold calliper (Sanny, São Bernardo do Campo, Brazil). Subsequently, body composition was estimated by calculating body density. (Jackson & Pollock, 1978) and fat percentage (Siri, 1993), respectively.

10RM test

Before the test, participants performed a specific warm-up consisting of a series of 15 repetitions with approximately 50% of the estimated load for the 10RM, followed by a brief 2-minute rest period. Then, each participant performed the first attempt with the estimated load for the 10RM. The maximum number of attempts was three to five, with rest intervals of 2 to 5 minutes between attempts. In each attempt, there was a progressive increase of between 2.5% and 10% of the load used. If the individual did not reach less than 10RM, the load was reduced by a similar proportion. After a 72-hour interval, a new 10RM test session was performed in order to ensure the reproducibility of the load (retest). To minimize the margin of error in the tests, the following strategies were used: a) all individuals received standardized instructions regarding the tests; b) an experienced evaluator was attentive to the execution technique of the proposed exercise; c) verbal stimuli were used to maintain a high motivational level. The reliability of the 1RM measurements across two trials was high for the single leg curl (ICC = 0.98; 95% CI = 0.96–0.99) exercise.

Resistance exercise protocol

The resistance exercise protocol consisted of the unilateral leg curl exercise, performed for four sets to concentric muscular failure, using a 10RM load and 90-second rest intervals between sets. The training protocol was designed to reflect the number of sets commonly recommended in the literature for muscle hypertrophy-oriented programs and routinely adopted in fitness settings (Santos et al., 2022).

Experimental conditions

Two conditions were used in the study: (a) a protocol with inter-set static stretching (ISS); and (b) a protocol without static stretching between sets (WSS). The ISS protocol consisted of four sets of 45 seconds at maximum perceived discomfort intensity. This protocol was applied at the beginning of the interval between sets, targeting the hamstring muscles of the dominant limb. To do this, the subject was positioned as follows: in a supine position (*“lying on their back on the floor”*), with their knees fully extended and ankles in dorsiflexion. Then, the limb being evaluated was flexed to approximately 90 degrees. Subsequently, the evaluator passively flexed the hip, raising the participants dominant foot to the threshold of discomfort associated with the hamstring muscles, remaining in this position for 45 seconds. (Fakhro et al., 2020). According to Fakhro et al. (Fakhro et al., 2020), this stretching protocol provides stretching of the hamstring muscles to their maximum length. In addition, the stretching time was selected to generate acute increases in the range of motion of the hamstring muscles and avoid a possible decline in strength performance. (Bandy et al., 1997; Palmer et al., 2019). On the other hand, the WSS protocol involved only passive rest between sets.

Range of motion assessment

To measure range of motion (ROM), the protocol adapted from Schuback et al. (Schuback et al., 2004) was used, where the flexibility of the hamstring muscles is measured through the maximum amplitude achieved in knee extension. The range of motion was measured with the aid of a digital goniometer (Shahe Factory Direct, China), which was positioned as follows: fixed arm following the alignment of the greater trochanter of the femur to the lateral epicondyle of the femur and mobile arm following the line of the lateral malleolus to the lateral epicondyle of the femur (Chagas et al., 2008); the evaluated limb was stabilized at approximately

90 degrees with the aid of a box, measuring: 40 cm high by 35 cm wide; the range of motion was measured at the moments: before and immediately after the end of the resistance exercise protocol. This assessment was always performed by the same evaluator.

Assessment of total training volume

The total training volume was expressed by the product of the number of sets, total number of repetitions achieved, and high load, to obtain a measure that represents the total work performed during a session (Tran & Docherty, 2006; Tran et al., 2006).

Statistical analysis

Initially, the normality was assessed using the Shapiro–Wilk test. A two-way repeated-measures ANOVA was conducted for range of motion (ROM), with condition (ISS and WSS) as the first factor and time point (PRE and POST) as the second factor. All participants were included in the statistical analysis.

Regarding the number of repetitions, the data were analysed using a repeated-measures analysis of variance (ANOVA), with condition (ISS and WSS) as the first factor and set (1st, 2nd, 3rd, and 4th set) as the second factor. In the case of a significant F-value, post hoc analyses were performed using the Bonferroni correction for multiple comparisons. Moreover, when the assumption of sphericity was violated in analyses related to the number of repetitions, the Greenhouse–Geisser correction was applied. Additionally, the paired t-test was used to compare the total training volume (TTV) between conditions. Statistical significance was set at $\alpha = .05$ ($p \leq .05$). All statistical analyses were performed using a specialized software program (IBM SPSS, version 25.0, Chicago, IL, USA). Partial eta squared (η^2) was used as a measure of effect size for the repeated-measures ANOVA and interpreted as follows: small ($\eta^2 \geq 0.01$), medium ($\eta^2 \geq 0.06$), and large ($\eta^2 \geq 0.14$) (Cohen, 2013). Additionally, to evaluate the magnitude of differences in pairwise comparisons, Cohen's d effect sizes (d) with 95% confidence limits [90% CI] were calculated. Effect sizes values were interpreted as follows: trivial ($<.19$), small ($.20 - .49$), moderate ($.50 - .79$), and large ($>.80$) (Cohen, 2013).

RESULTS

Regarding the number of repetitions, a main effect for condition was found ($F_{(1, 16)} = 10.149$; $p = .006$; $\beta = 1.00$; $\eta^2 = 0.388$; large), indicating that the ISS protocol resulted in a lower number of repetitions compared to the WSS protocol (mean difference = 1.2 ± 0.4 reps). Additionally, a main effect for sets was observed ($F_{(2.241, 35.854)} = 88.126$; $p \leq .0001$; $\beta = 1.00$; $\eta^2 = 0.846$; large), revealing a progressive reduction in repetitions across sets (see Figure 1a). On the other hand, no significant interaction was found between condition and set ($F_{(3, 48)} = 2.160$; $p = .11$; $\beta = 0.46$; $\eta^2 = 0.119$; large).

With respect to total training volume, the WSS protocol showed higher values compared to the ISS protocol (WSS = $1,099.8 \pm 333.7$ kg vs. ISS = 923.8 ± 310.5 kg; Figure 1b), but with a moderate and non-significant effect size ($d = .55$; CI95% = -0.15 to 1.22 ; moderate).

Regarding ROM, a main effect for condition was observed ($F_{(1, 16)} = 7.815$; $p = .01$; $\beta = 1.00$; $\eta^2 = 0.328$; large), indicating that the ISS protocol resulted in higher ROM values compared to the WSS protocol (mean difference = 1.8 ± 0.6 degrees). A main effect for time point was also found ($F_{(1, 16)} = 49.378$; $p \leq .0001$; $\beta = 1.00$; $\eta^2 = 0.755$; large), showing that ROM increased in the post-set measurement compared to the pre-set (mean difference = 4.3 ± 0.6 degrees). In turn, a significant interaction between condition and time point

was detected ($F_{(1, 16)} = 25.743$; $p \leq .0001$; $\beta = 0.89$; $\eta p^2 = 0.617$; large), indicating specific differences (see Figure 2).

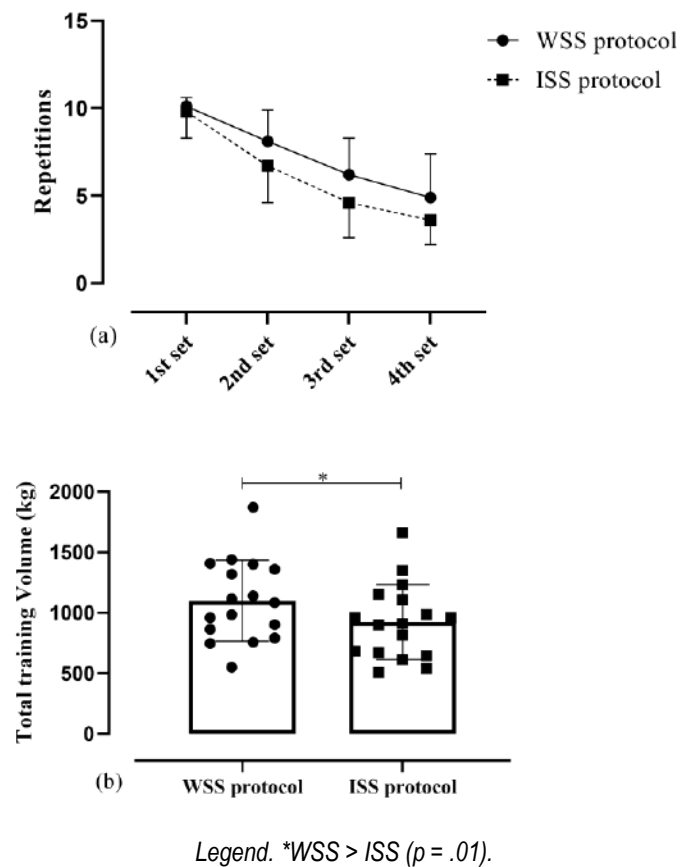
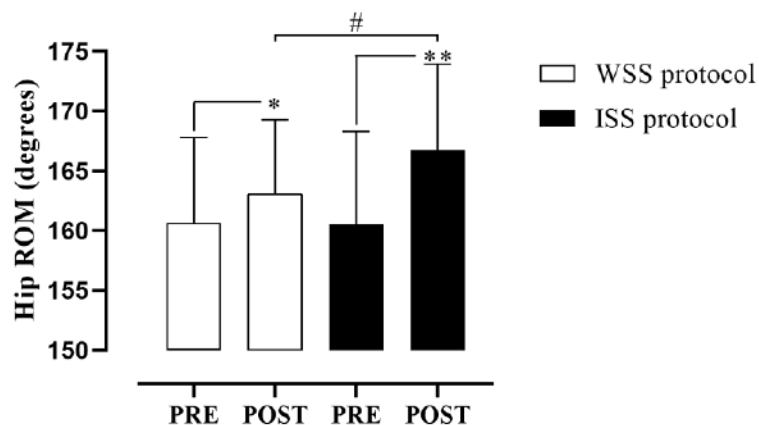


Figure 1. Number of Repetitions per Set (a) and Total Training Volume (b) in WSS and ISS Protocols.



Legend. *Post > Pre in the WSS protocol ($p = .001$); *Post > Pre in the ISS protocol ($p \leq .0001$); # ISS > WSS at post-set ($p = .001$).

Figure 2. Changes in Range of Motion (ROM) Pre- and Post-Set in WSS and ISS Protocols.

Figure 2 shows that there was no difference between conditions at the pre-set time point ($p = .84$). On the other hand, both conditions exhibited an increase in ROM after the sets, with greater increases observed in the ISS protocol ($p \leq .0001$; mean difference = 6.2 ± 0.8 degrees; $d = .84$; CI95% = 0.12 to 1.52; large) compared to the WSS protocol ($p = .001$; mean difference = 2.4 ± 0.6 degrees; $d = .38$; CI95% = - 0.31 to 1.04; small). Finally, post-set ROM values were significantly higher in the ISS protocol compared to the WSS protocol ($p = .001$; mean difference = 3.7 ± 0.8 degrees; $d = .55$; CI95% = - 0.15 to 1.22; moderate).

DISCUSSION

The aim of this study was to evaluate the acute effects of an inter-set static stretching (ISS) protocol on muscle performance in the unilateral leg curl exercise and on the range of motion (ROM) of the hamstring muscles. Our main findings were: (a) total training volume was higher in the WSS protocol compared to the ISS protocol, but with a non-significant effect size; (b) both protocols promoted a significant acute increase in ROM, with a greater increase observed in the ISS protocol; and (c) both protocols showed a similar progressive decrease in the number of repetitions across sets; however, the ISS protocol resulted in a lower mean total number of repetitions. Therefore, our initial hypotheses were confirmed, indicating a potentially favourable cost-benefit ratio of the inter-set static stretching technique, as it significantly increased ROM at the expense of only a minor performance decrement.

In this context, although the literature shows deleterious effects on muscle strength when static stretching is performed concomitantly with resistance training (Behm et al., 2016; Chaabene et al., 2019; Gomes et al., 2011; Simic et al., 2013; Thomas et al., 2023), the ISS technique has gained prominence as a strategy to increase ROM (Junior et al., 2017; Nakamura et al., 2021) and favour long-term muscular adaptations (Nakamura et al., 2021; Schoenfeld et al., 2022; Van Every et al., 2022). However, one of the main factors that may limit its practical application is the possible drop in performance during the performance of the target exercise of the session (JBB et al., 2022; Padilha et al., 2019). However, based on our findings, it should be considered that inserting a 45-second passive rest period between the execution of the ISS and the subsequent exercise may contribute to reducing the deleterious effects of the technique on strength performance.

In this regard, some evidence suggests that introducing an additional passive rest time can reduce the acute negative effects of stretching in a similar way to that observed in our study. In this sense, according to Souza et al. (Souza et al., 2020), performing an ISS protocol in the anterior chain of the trunk (i.e. pectoralis and anterior deltoid) lasting 30 seconds and 90 seconds of additional passive rest before performing the Bench Press exercise resulted in a decrease of only 8.2% in the total number of repetitions (mean = -1.5 reps) compared to the traditional passive rest protocol. Furthermore, Ribeiro et al. (Ribeiro et al., 2014) had already observed that performing a static stretching protocol of the muscles involved in the execution of the Bench Press exercise (i.e. pectoral, and triceps), lasting 30 seconds and with an additional passive rest of 2 minutes, before performing 4 sets of the target exercise, did not result in negative effects on strength performance.

In contrast, the findings of Camargo et al. (JBB et al., 2022) point to a greater negative effect on total training volume (29.9%), observed through the reduction in the total number of repetitions (mean = 10.9 reps) of the seated cable fly exercise, when this is performed immediately after the execution of the ISS of the anterior chain of the trunk. Corroborating this, Padilha et al. (Padilha et al., 2019) demonstrated that a quadriceps ISS protocol, lasting 25 seconds preceded by a passive rest of 15 seconds (movement to the apparatus) promoted a 23.77% decrease in the total work (joules) of the isokinetic leg extension exercise, associated with a significant reduction in muscle activation seen by EMG.

Therefore, when comparing the results of previous literature with the results obtained in our study, it is observed that the proportion between the stretching time and the rest period before performing the target exercise constitutes a relevant factor to enhance the effectiveness of the ISS method, favouring gains in range of motion and attenuating its negative effects on muscle performance. Regarding the factors responsible for the reduction in neuromuscular capacity associated with the ISS method, the literature mainly highlights mechanisms of a mechanical and neural nature, such as decreased transfer of muscle elastic energy, through decreased stiffness of the muscle-tendon unit, reduced muscle activation, loss of strength due to central neuromuscular inhibition, and decreased local blood flow due to compression of blood vessels (Otsuki et al., 2011; Schoenfeld et al., 2016; Trajano et al., 2013; Wilson et al., 1994). Therefore, adjusting the stretching time so that it is possible to perform an additional period of passive rest between sets of the target exercise appears to be an efficient strategy to dissipate, at least partially, these physiological effects that induce neuromuscular fatigue, without increasing the total session time.

Furthermore, regarding the ROM variable, our results demonstrate that resistance training itself is capable of promoting acute increases in hamstring muscle flexibility, as previously seen (Alizadeh et al., 2023; Favro et al., 2025). However, the ISS regimen promoted significant additional increases (mean difference = $3.7 \pm 0.8^\circ$), through the performance of only 4 stretching series lasting 45 seconds. In addition to duration, stretching intensity plays a crucial role in ROM. In this sense, evidence shows that greater stretching intensities, especially those approaching pain thresholds, tend to promote greater improvements in flexibility. (Bryant et al., 2023; Kataura et al., 2017; Muanjai, Jones, Mickevicius, Satkunskiene, Snieckus, Rutkauskaite, et al., 2017; Muanjai, Jones, Mickevicius, Satkunskiene, Snieckus, Skurvydas, et al., 2017). Although some evidence suggests that higher stretching intensities impair strength development (Kataura et al., 2017), our findings did not observe major negative effects when stretching the hamstring muscles to the maximum point of pain tolerance.

Regarding the clinical relevance of increasing the ROM of knee extension, previous studies indicate that shortening of the hamstring muscles and greater passive stiffness of the biceps femoris muscle are associated with a higher incidence of injuries and are correlated with compensatory movements and pain in the lumbar spine (Danielsson et al., 2020; Kato et al., 2022; Rudisill et al., 2023; Sadler et al., 2017; Timmins et al., 2016; Yagiz et al., 2024). Thus, the ISS technique performed in this study represents a highly efficient alternative for increasing ROM, preventing the aforementioned factors, without major negative effects on strength development.

However, it is important to consider some methodological limitations of the present study, including: (a) the analysis of a resistance training session consisting of only one exercise; (b) the absence of comparisons between different durations of additional passive rest; (c) inclusion of only male participants; (d) the limited sample size; and (e) the absence of analysis of physiological markers of fatigue. Therefore, future studies are strongly encouraged to more comprehensively investigate the effects of the ISS method on neuromuscular performance.

CONCLUSION

The findings of this study indicate that inter-set static stretching leads to a reduction in the number of repetitions and total training volume compared to a traditional protocol without stretching. However, inter-set static stretching proved to be more effective in acutely increasing hamstring flexibility. Based on our results, we recommend the use of the ISS method in individuals who wish to improve the range of motion of their hamstring muscles and who do not have time available to perform stretching separately from resistance

training. However, it is essential to include an additional period of passive rest between stretching and subsequent exercise. This strategy can reduce the deleterious effects of static stretching on neuromuscular performance, especially in exercises performed to concentric muscular failure. By preserving, even partially, the force production capacity, this strategy can make ISS more feasible in practical contexts, balancing the benefits of increasing range of motion with maintaining performance during resistance training.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. I. M. and M. F. conceived and designed the study, coordinated data collection, and wrote the main manuscript text. D. V. G., W. M., F. H. F., and H. M. contributed to data interpretation, manuscript revision, and methodological validation, and assisted with formatting. E. L. and B. R. R. O. supervised the study design, analysed the results, provided critical feedback, and revised the final version of the manuscript. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

DATA AVAILABILITY STATEMENTS

The data supporting the findings of this study, including the datasets used for statistical analyses, have been made available as supplementary material and were uploaded during the manuscript submission process. These datasets contain anonymized information derived from the experimental sessions and are accessible to reviewers through the supplementary files accompanying this article. No additional restrictions apply to data sharing, as all participants provided informed consent for the use of their anonymized data for research purposes.

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Correlation between kinematic features and grade of execution in pair skating throw jumps: A case study at the World Figure Skating Championships

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ABSTRACT

Throw jumps represent a distinctive technical element in pair figure skating; however, the kinematic determinants underlying the grade of execution (GOE) remain unclear. Previous studies in ladies' single skating have demonstrated that greater horizontal distance and higher post-landing skating speed are associated with higher GOE scores. However, throw jumps involve a partner-assisted take-off, suggesting that the factors influencing execution quality may differ from those observed in single skating. This study examined the relationships between GOE and kinematic variables in triple throw jumps performed at the 2023 World Figure Skating Championships. Twenty-three jumps that received non-negative GOE scores from all nine judges were analysed. Vertical height, horizontal distance, take-off speed, and skating speed after landing were quantified using a broadcast-based tracking system, and GOE values were calculated as a trimmed mean. Across all jumps, GOE demonstrated significant positive correlations with vertical height and skating speed after landing. In edge-type jumps, vertical height showed a strong association with GOE, whereas no significant relationships were observed for toe-type jumps. These findings provide quantitative evidence that judges' GOE scores in competition reflect specific kinematic indicators, advancing the objective understanding of subjective evaluation in pair skating.

Keywords: Performance analysis, Sports performance, Artistic sports, Judged sports, Performance evaluation, Tracking system, Sports analytics.

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INTRODUCTION

Figure skating comprises three disciplines: singles, pairs, and ice dance. Among these, jumps represent a fundamental technical element in singles and pairs, whereas they are prohibited in ice dance (Vescovi & VanHeest, 2018). In pair skating, skaters perform side-by-side jumps where partners execute the same jump simultaneously, and throw jumps, in which the male skater launches the female partner into the air (Madsen et al., 2024). Throw jumps are a distinctive and essential element unique to pair skating and play a critical role in competitive performance.

The scoring system for figure skating was revised following a judging scandal at the 2002 Salt Lake City Olympics, leading to the introduction of the International Skating Union (ISU) Judging System (IJS) in 2004. In the previous 6.0 system, technical performance was evaluated relatively based on the overall impression, and skaters were scored on a scale ranging from 0.0 to 6.0 in 0.1-point increments. In contrast, under the IJS, each element is assigned a predefined base value according to its difficulty, and execution quality is quantified through the Grade of Execution (GOE) (Zitzewitz, 2006, 2014). In the current system, GOE is evaluated using an 11-point scale ranging from -5 to +5. The final GOE is calculated using a trimmed mean by excluding the highest and lowest scores awarded by nine judges.

Similar to single skating, the criteria for a positive GOE in throw jumps emphasise kinematic features such as height and distance, as well as creativity and musicality (Table 1). Even in the criteria related to the kinematic aspect, subjective terms such as “good” are used, allowing for individual judge interpretation. Therefore, clarifying the kinematic characteristics that contribute to higher GOE scores would provide valuable insights for skaters and coaches.

Rauer et al., (2022) reported a significant upward trend in the average total scores of the top five pair teams at the Olympics, World Championships, and European Championships since 2005. While the number of triple side-by-side jumps performed at the World Championships has increased over time, the number of rotations in throw jumps has remained relatively unchanged. This indicates that executing higher-quality throw jumps at the elite level, reflected in higher GOE, even when the difficulty level remains constant, has become an increasingly important factor for distinguishing performance among top pairs.

Previous studies on pair skating have primarily focused on injury incidence and characteristics (Dubravcic-Simunjak et al., 2003; Kowalczyk et al., 2021; Madsen et al., 2024; Smith & Ludington, 1989) as well as off-ice physical capacities such as power (Sands et al., 2012) and balance ability (Colby et al. 2023). In contrast, studies focusing on technical performance unique to pair skating remain limited. For example, research on twist lifts has shown that rotational speed is a more critical factor than jump height in increasing the number of revolutions. (D. L. King et al., 2008).

Most technical performance studies in figure skating have focused on jumps performed by single skaters. D. L. King et al. (1994) stated that theoretically, jumping as high as possible while rotating as quickly as possible is the best technique to maximise the number of revolutions completed in the air. However, in practice, several studies have reported that skaters achieve difficult jumps primarily by increasing rotational speed rather than jump height (Arnold et al., 1994; D. L. King et al., 1994; Albert & Miller, 1996; D. King et al., 2004; Mazurkiewicz et al., 2018). Based on these findings, Ridge et al., (2022) examined the effectiveness of weighted gloves in enhancing rotational speed. However, studies focusing on skaters attempting high-difficulty jumps with few successful examples suggest that greater jump height may be essential for skill acquisition (Aleshinsky et al., 1988; Hirosawa, 2025; D. King et al., 2004) indicating that the required

kinematic characteristics may vary depending on the level of jump proficiency. Research comparing jump types has shown that top-level female skaters achieved greater jump height during toe jumps (Lutz, Flip, and Toe loop) than during edge jumps (Salchow and Loop), likely because toe-tapping at take-off allows the kinetic energy of preparatory skating to be utilised more effectively. (Sakurai et al., 1999). Furthermore, a recent review suggested sex-related differences in jump characteristics, with male skaters more commonly performing higher-rotation jumps and female skaters tending to show greater angular velocity and flexibility (Sperlich et al., 2026).

Regarding GOE, previous studies focusing on single skating have shown that, in women's double Axel jumps, greater horizontal distance and skating speed after landing are associated with higher GOE (Hirosawa, 2025; Hirosawa et al., 2022). These findings suggest that, in single skating, judges may place greater emphasis on post-take-off displacement and post-landing flow than on vertical height alone when evaluating execution quality. Furthermore, it has been reported that models predicting GOE based on kinematic characteristics (Hirosawa, 2025) achieve higher accuracy than GOE assessments made by novice-level judges (Hirosawa et al., 2025, 2023). This finding highlights the potential utility of kinematic data as an objective framework to complement the inherently subjective nature of execution evaluation in judged sports. Recent scoping reviews have also highlighted the growing use of wearable sensors, marker less computer vision, and pose-based deep learning in figure skating performance analysis. (Drazdova, 2026) However, competition-based kinematic evidence on pair-specific elements such as throw jumps remains scarce.

Given the partner-assisted nature of the take-off in throw jumps, these relationships may differ from those reported in single skating. According to the ISU criteria for positive GOE (Table 1), throw jumps are evaluated based on elements such as “*very good height and distance*” and “*good speed, flow, and control on release and landing.*” In line with these evaluation criteria, the present study hypothesized that multiple kinematic variables, including vertical height, horizontal distance, take-off speed, and landing speed, would each show positive associations with GOE in pair throw jumps.

Therefore, the purpose of this study was to examine the relationships between kinematic characteristics and GOE in triple throw jumps performed in the pair skating discipline at the 2023 World Figure Skating Championships, treating GOE as a case study and treating GOE as a competition-relevant performance indicator.

Table 1. Criteria for the positive aspects of grade of execution (GOE) (International Skating Union, 2022).

Pair skating (throw jumps)	Single skating (jump elements)
Very good height and very good distance	Very good height and very good length
Good speed, flow, and control on release and landing	Good take-off and landing
Effortless throughout	Effortless throughout
Difficult, unexpected, or creative entry	Steps before the jump; unexpected or creative entry
Very good air position	Very good body position from take-off to landing
Element matches the music	Element matches the music

Note. FOR + 1: one bullet, FOR + 2: two bullets, FOR + 3: three bullets, FOR + 4: four bullets, FOR + 5: five or more bullets. FOR + 4 and +5, the first three bullets must be present.

MATERIALS AND METHOD

Data sample

This study focused on triple throw jumps performed during the short program and free skating segments of the pair event at the 2023 World Figure Skating Championships in Saitama, Japan. We included only jumps

that received non-negative GOE scores from all nine judges and excluded any jump with a negative score from at least one judge. As part of this case study, the data sample comprised 23 valid triple throw jumps performed by 16 pair teams (male: mean age = 26.44 ± 3.78 years; female: mean age = 22.81 ± 5.71 years): 16 edge jumps (Salchow: 5, Loop: 11) and seven toe jumps (Flip: 2, Lutz: 5). The GOE scores were obtained from the official ISU competition results (International Skating Union, 2023). We calculated the GOE as a trimmed mean by removing the highest and lowest scores from the nine judges' evaluations, which were based on an 11-point scale ranging from -5 to +5. Consequently, the theoretical range of the GOE variable in this analysis is 0 to 5.

The explanatory variables comprised four kinematic features extracted from the broadcast-oriented tracking system Ice Scope: vertical height (m), horizontal distance (m), take-off speed (m/s), and landing speed (m/s). This system was introduced by the Fuji Television Network, which holds broadcasting rights for certain competitions, to help viewers better understand skaters' technical performance. The data obtained from this system are not used for official judging purposes. The system employs two 4K cameras (3840×2160 pixels) recording at 30 frames per second (fps), and the cameras are positioned to capture the entire 60×30 m skating rink. Using the rink layout, it estimates real-world coordinates for each pixel based on the two-dimensional direct linear transformation method.

- Vertical height (m): The maximum vertical value measured from the frame where the toe-pick leaves the ice at take-off to the frame where it contacts the ice upon landing.
- Horizontal distance (m): The horizontal displacement measured between the frame of toe-pick take-off and the frame of landing contact.
- Take-off speed (m/s): This is calculated from the skating distance covered during the five frames preceding the frame in which the toe-pick fully leaves the ice. Given that the system records at 30 fps, each frame corresponds to approximately 0.033 s. Take-off speed is obtained by dividing the total distance by the elapsed time. This value is not publicly disclosed through media broadcasts and was provided directly to the researchers by the company.
- Landing speed (m/s): This is calculated from the skating distance covered during the five frames following the frame in which the heel edge fully contacts the ice upon landing. As with take-off speed, each frame represents approximately 0.033 s. Landing speed is derived by dividing the measured distance by the elapsed time.

This system is intended for real-time use in broadcast footage and is not a high-precision motion capture system designed for controlled experimental environments. Despite its limitations in measurement accuracy, data obtained from this system have been reported in several peer-reviewed publications (Hirosawa, 2025; Hirosawa et al., 2023, 2022).

Statistical analysis

The normality of each variable was assessed using the Shapiro–Wilk test. For normally distributed variables, Pearson's product-moment correlation coefficients were calculated to examine the relationships between GOE and the kinematic variables. Statistical significance was set at 5%. Given the small sample size, nonparametric bootstrapping was employed to assess the robustness of the correlation estimates. Specifically, for each variable, 1,000 bootstrap samples were generated with replacement, and Pearson's correlation coefficient was computed for each iteration. The 2.5th and 97.5th percentiles of the resulting distribution were used to derive the 95% confidence intervals (CIs). In addition, simple linear regression analyses (ordinary least squares) were performed to quantify the associations between GOE and each kinematic variable. Unstandardized regression coefficients and their 95% confidence intervals were estimated, and the regression lines were visualized with 95% confidence intervals of the mean response.

Analyses were conducted on all jumps combined and separately for edge-type and toe-type jumps. All statistical procedures were performed using Python (version 3.11.13; Python Software Foundation, Wilmington, DE, USA) with the Statsmodels package (version 0.14.4).

RESULTS

Table 2 presents the means, standard deviations, and ranges for throw jumps and result of Shapiro-wilk test. Theoretically, the GOE scores range from 0.000 to 5.000. However, the observed values in this sample ranged from 1.000 to 4.000. None of the variables showed significant deviations from normality at the 5% significance level, indicating that all variables were normally distributed.

Table 2. Summary of descriptive statistics for throw jumps and result of Shapiro-Wilk test.

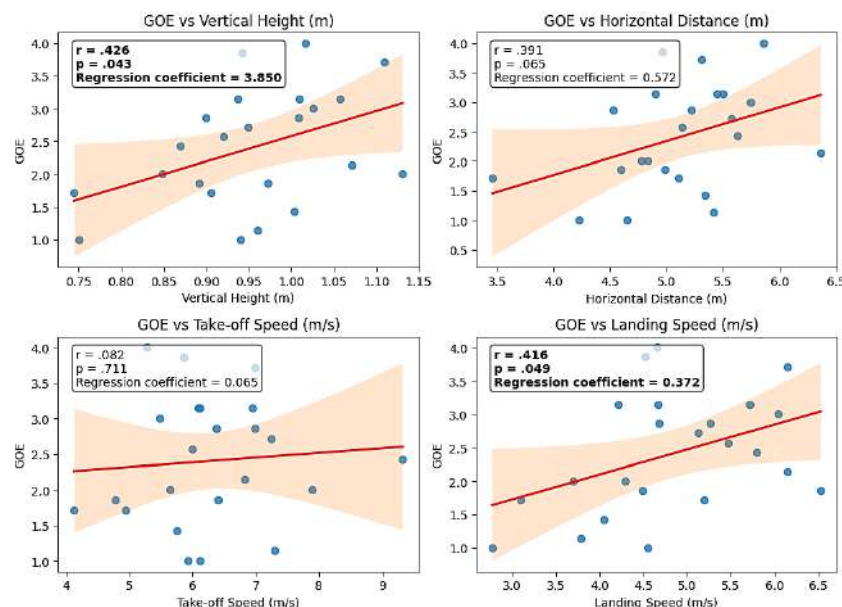
Variables	Mean $\pm$ SD	Range	Shapiro–Wilk test <i>p</i> -value	
Vertical height [m]	0.955 $\pm$ 0.098	0.745–1.131	.684	
Horizontal distance [m]	5.111 $\pm$ 0.607	3.457–6.364	.711	
Take-off speed [m/s]	6.278 $\pm$ 1.108	4.132–9.323	.567	
Landing speed [m/s]	4.820 $\pm$ 0.991	2.771–6.527	.821	
GOE	2.404 $\pm$ 0.888	1.000–4.000	.493	
Edge-type jumps (N = 16)			Toe-type jumps (N = 7)	
Variables	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range
Vertical height [m]	0.938 $\pm$ 0.100	0.745–1.071	0.993 $\pm$ 0.088	0.920–1.131
Horizontal distance [m]	5.177 $\pm$ 0.711	3.457–6.364	4.960 $\pm$ 0.218	4.653–5.310
Take-off speed [m/s]	6.332 $\pm$ 1.311	4.132–9.323	6.157 $\pm$ 0.432	5.643–6.981
Landing speed [m/s]	4.780 $\pm$ 0.890	3.094–6.144	4.912 $\pm$ 1.267	2.771–6.527
GOE	2.321 $\pm$ 0.832	1.000–4.000	2.592 $\pm$ 1.048	1.000–3.857

Table 3. Pearson's correlation coefficients between GOE and kinematic variable for throw jumps.

All throw jumps (N = 23)			
Variables	Corr.	<i>p</i> -value	Bootstrap 95% CI
Vertical height [m]	.426	.043	0.088 to 0.707
Horizontal distance [m]	.391	.065	0.084 to 0.684
Take-off speed [m/s]	.082	.711	–0.260 to 0.409
Landing speed [m/s]	.416	.049	0.025 to 0.703
Edge-type jumps (N = 16)			
Variables	Corr.	<i>p</i> -value	Bootstrap 95% CI
Vertical height [m]	.551	.027	0.184 to 0.834
Horizontal distance [m]	.448	.082	0.074 to 0.745
Take-off speed [m/s]	.079	.772	–0.368 to 0.468
Landing speed [m/s]	.408	.117	0.027 to 0.725
Toe-type jumps (N = 7)			
Variables	Corr.	<i>p</i> -value	Bootstrap 95% CI
Vertical height [m]	.098	.834	–0.705 to 0.760
Horizontal distance [m]	.684	.090	–0.089 to 0.998
Take-off speed [m/s]	.262	.571	–0.842 to 0.832
Landing speed [m/s]	.419	.349	–0.748 to 0.968

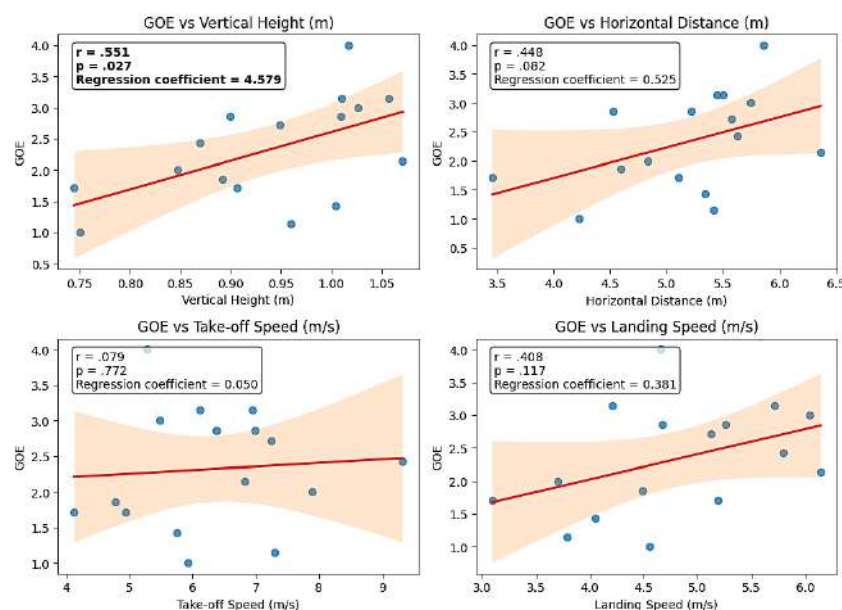
Table 3 summarises the Pearson correlation coefficients, *p*-values, and 95% CIs obtained from bootstrapping for the relationships between each kinematic variable and GOE. The corresponding scatterplots with

regression lines and 95% confidence intervals of the mean response are shown in Figure 1,2,3. In terms of all throw jumps, moderate and statistically significant positive correlations were observed for vertical height and landing speed. In addition, horizontal distance showed a moderate positive correlation with GOE, but this correlation was not statistically significant in the current sample. Nonetheless, the 95% CI from the bootstrap analysis did not include zero, indicating a potentially meaningful association. No significant correlation was observed between take-off speed and GOE.



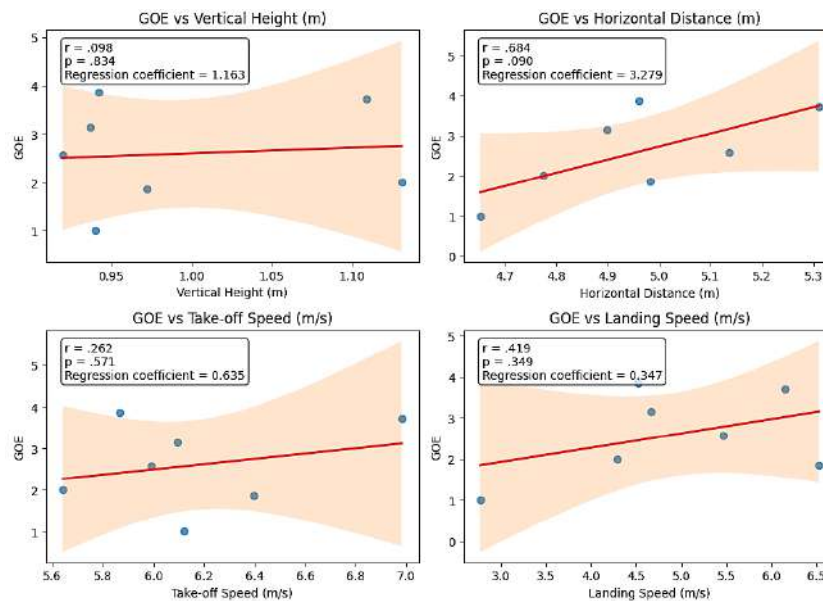
Note. Scatterplots showing the relationships between GOE and each kinematic variable. Solid lines indicate ordinary least squares regression lines, and shaded areas represent the 95% confidence intervals of the mean response.

Figure 1 Relationship between GOE and kinematic variables in clean triple throw jumps.



Note. Scatterplots showing the relationships between GOE and each kinematic variable. Solid lines indicate ordinary least squares regression lines, and shaded areas represent the 95% confidence intervals of the mean response.

Figure 2 Relationship between GOE and kinematic variables in edge-type triple throw jumps.



Note. Scatterplots showing the relationships between GOE and each kinematic variable. Solid lines indicate ordinary least squares regression lines, and shaded areas represent the 95% confidence intervals of the mean response.

Figure 3. Relationship between GOE and kinematic variables in toe-type triple throw jumps.

In edge jumps, a statistically significant positive correlation with a large effect size was observed for only vertical height. Horizontal distance and landing speed showed moderate positive correlations with GOE; however, these were not statistically significant in the current sample. However, their 95% CIs based on bootstrapping did not include zero, indicating potentially meaningful associations. No correlation was observed between take-off speed and GOE. In toe jumps, none of the kinematic variables were significantly correlated with GOE. Notably, the correlation pattern differed from that of edge jumps: vertical height showed virtually no correlation with GOE, whereas horizontal distance exhibited a relatively stronger association.

DISCUSSION

In this study, we investigated the relationship between kinematic variables obtained from a broadcast-based tracking system and the GOE for throw jumps in pair figure skating. Given the limited sample size, Pearson's correlation analysis and nonparametric bootstrapping were employed to enhance the reliability of our findings.

Across all jumps, vertical height and landing speed exhibited moderate, statistically significant positive correlations with GOE. Horizontal distance showed a moderate correlation with GOE, but this distance was not statistically significant; however, its bootstrap-based CI excluded zero, suggesting a potential association. Take-off speed showed no meaningful correlation with GOE.

The ISU criteria for positive GOE include elements such as “*very good height and very good distance*” and “*good speed, flow, and control on release and landing*”; however, our findings suggest that judges prioritise vertical height over distance and place greater emphasis on the flow after landing than on the speed before release. Compared to previous findings in women's single skating, where greater horizontal displacement was associated with higher GOE (Hirosawa et al., 2022), throw jumps appear to be more influenced by vertical height. The male partner's assistive throwing action may increase the relevance of jump height when

evaluating quality. Horizontal distance was not statistically significant; however, the bootstrap results suggest a possible contribution to GOE, warranting further investigation with a larger sample.

When stratified by jump type, edge jumps showed a significantly strong positive correlation between vertical height and GOE. Horizontal distance and landing speed exhibited moderate correlations, which were not significant, but showed consistent patterns with bootstrap estimates. No significant correlation was observed between take-off speed and GOE, reinforcing the idea that judges emphasise post-landing flow over pre-release velocity. Previous studies in women's singles reported lower jump heights in edge jumps compared to toe jumps, due to inefficiencies in converting horizontal to vertical force (Sakurai et al., 1999). In edge-type throw jumps, the male partner's ability to efficiently convert the female partner's horizontal momentum into vertical lift through the throw becomes a key technical factor. This may explain why vertical height strongly influences GOE, which is subjectively assigned by judges. For horizontal distance and landing speed, the 95% CI based on the bootstrap method did not include zero, suggesting a potential association. Further investigation with a larger sample size is warranted to confirm these trends. In contrast, no clear association was observed for take-off speed, indicating that, at least for edge jumps, judges may place greater emphasis on landing speed than on speed before the release.

For toe jumps, none of the kinematic variables correlated significantly with GOE. Notably, vertical height demonstrated almost no association with GOE, while horizontal distance exhibited a stronger correlation compared to edge jumps, indicating a potentially different pattern between the two jump types. As suggested by (Sakurai et al., 1999), toe jumps, where the skater uses the toe pick at take-off, allow for more efficient conversion of horizontal momentum into vertical force, resulting in greater jump heights. The Lutz is considered the most technically demanding toe jump, as it involves rotation in the direction opposite to the take-off edge, thereby requiring greater vertical elevation.

In the present sample, five out of seven toe jumps were Lutz jumps, which are typically associated with higher vertical height. Consequently, the results suggest that in toe-type throw jumps, horizontal distance, rather than vertical height, may play a greater role in determining GOE. Landing speed also exhibited a stronger positive correlation with GOE than in edge jumps, implying that the kinematic features associated with better execution scores in toe jumps may reflect greater horizontal rather than vertical performance characteristics. However, due to the limited sample size, further investigation with a larger dataset is necessary to validate these trends.

In summary, the results indicate that in triple throw jumps performed in pair skating, vertical height and landing speed showed moderate, statistically significant positive correlations with GOE. This suggests that judges place particular emphasis on jump height and landing flow when evaluating execution. The influence of vertical height was especially pronounced in edge jumps, where a significant positive correlation with GOE was observed. The limited sample size prevents definitive conclusions; however, our findings suggest that the kinematic features associated with higher GOE may differ between edge and toe jumps. Previous studies have noted that pair and ice dance skaters, who perform lifting manoeuvres regularly, tend to possess greater upper-body strength, and strength training programs should specifically target upper-body development (Slater et al., 2016). This may be particularly relevant for enhancing vertical lift in throw jumps, ultimately contributing to improved execution scores.

This study has some limitations. One concerns the accuracy of data acquisition. The tracking system used in this research was designed for media purposes and operates at 30 fps, which is relatively low compared to motion capture systems or high-speed cameras typically used for analysing fast movements in sports.

Collecting data during competitions poses practical challenges, and it would be desirable to use higher-precision equipment with higher sampling frequencies when possible. Another limitation is the sample size. Only 23 jumps were included in the analysis out of a total of 44. Trials were excluded if they received any GOE deductions or were downgraded to double rotations. Even at the level of World Championship competitors, executing triple throw jumps without GOE deductions is not easy. Ongoing data collection from other competitions is necessary to build a more robust dataset.

Despite these limitations, this is the first case study to examine the relationship between kinematic features and the GOE awarded by judges for triple throw jumps performed by world-class pair skaters in actual competitions. The findings suggest that throw jumps in pair skating may have different determinants of GOE compared to double Axel jumps in singles, as reported in previous studies. This research contributes to a more objective understanding of the inherently subjective evaluation in judged sports and may offer valuable insights for coaching and judging guidelines.

CONCLUSION

We examined the relationship between kinematic features derived from tracking data and the GOE awarded by judges for triple throw jumps in pair figure skating. Our findings revealed significant positive correlations between vertical height and GOE as well as between landing speed and GOE, with vertical height playing a particularly important role in edge jumps. In contrast, although not statistically significant, toe jumps tended to show higher correlations between GOE and horizontal distance, suggesting that the kinematic characteristics associated with higher GOE may differ between toe and edge jumps. Future research should aim to improve the generalisability of findings and deepen our understanding by employing higher precision tracking equipment and expanding the sample size.

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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. English editing support was obtained using ChatGPT (OpenAI; San Francisco, CA, USA), which was employed to refine the grammar and readability of the manuscript.

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Applying Artificial Intelligence to predict Olympic triathlon performance at Paris 2024 Olympic Games

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ABSTRACT

The aim of the present study was to predict triathlon performance at Paris 2024 Olympic Games using conventional statistics and a machine learning-based approach. It was hypothesized that both predictive models would grant sufficiently accurate results. Data were extracted from the API service on the World Triathlon website. A custom Python code was written for the analyses during data collection. Conventional statistics and machine learning analyses were performed by creating a Jupyter Notebook via Google Colab. Data for machine learning were divided into training (80%), and testing (20%). Run time was the best-predicted discipline for males (average difference: $-0.21\% \pm 5.45\%$), and total time was the best-predicted variable for females (average difference: $-5.43\% \pm 3.81\%$). For males, the linear regression based on Olympic Games races data was the most accurate technique overall (average relative difference: $-3.03\% \pm 10.79\%$). For females, TensorFlow achieved the best precision (average relative difference: $-1.95\% \pm 10.43\%$). Both techniques are reliable approaches for predicting performance in Olympic triathlon. Based on our findings, statistical methods can be effectively employed by coaches to predict individual discipline performance and overall race times. When comparing statistical techniques that considered all data, machine-learning techniques showed better predictions than conventional statistics.

Keywords: Performance analysis, Aerobic endurance, Quantitative data, Multi-sports, Machine learning.

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INTRODUCTION

Triathlon is a sport composed of three disciplines performed non-stop on different distances (short: from supersprint to Olympic distance; long: from middle-distance or Ironman 70.3 to full Ironman or superior). The Olympic distance triathlon involves 1.5 kilometres swim, 40 kilometres bike and 10 kilometres run. Since the invention of triathlon, several researchers have studied the physiological and psycho-social determining factors in Olympic triathlon (O'Toole & Douglas, 1995; Ruiz-Tendero & Salinero Martín, 2012), highlighting the importance of maximal capacity (VO_{2max}), economy of motion (submaximal VO_2), and fractional utilization of maximal capacity ($\%VO_{2max}$) of the triathlete.

Several papers aimed to analyse or predict triathlon performance, either using race data or considering athlete characteristics (García-González & González-Jurado, 2024a, 2024b, 2025b, 2025a; Sousa et al., 2021; Van Schuylenbergh et al., 2004). The most traditional approaches have used anthropometric and physiological variables to model overall and split performance with good accuracy (Van Schuylenbergh et al., 2004). Other authors aimed to predict race outcomes from shorter-distance tests in each discipline, talent-identification batteries, or longitudinal performance trajectories (Cuba-Dorado et al., 2021; Malcata et al., 2014), linking these measures to later competition results and career progression. Recently, performance prediction moved to integrate statistical and machine-learning approaches that give importance to the interaction between disciplines, transitions, and contextual factors such as athlete's pacing strategies and environmental conditions (Olaya-Cuartero et al., 2022; Sousa et al., 2021). This theoretical background shows how triathlon performance prediction can inform individualized training, talent development, and race strategy.

Machine learning (ML) is revolutionizing various sectors, including sports. Artificial Intelligence (AI) is a powerful tool that is reshaping citizen's lives, interactions and environments, transforming profoundly the current habitat (Cath et al., 2018). Several researchers have attempted to apply artificial intelligence to predict certain situations such as musculoskeletal injuries (Bullock et al., 2022). In the context of sport, the impact of AI has been investigated widely (Dindorf et al., 2023; Reis et al., 2024; Sperlich et al., 2023). Several authors have focused on injury prediction in team sports (Claudino et al., 2019; Rossi et al., 2021). Moreover, several mathematical models have also been applied to predict performance in different type of sports (Lim & Song, 2024; Nagovitsyn et al., 2023; Tam & Yao, 2024). In endurance sports, several models have been applied to predict marathon performance, with an accuracy of over 94% (Lerebourg et al., 2022) and to predict daily recovery prediction (Rothschild et al., 2024).

Machine Learning has also been applied to triathlon including different topics: to determine the fastest race course for professional athletes competing in Ironman (Thuany et al., 2024) and Ironman 70.3 (Thuany et al., 2023), to predict running-related injuries in young triathletes (Martínez-Gramage et al., 2020) or to solve the classic problem regarding the most influential discipline in triathlon (García-González et al., 2026; Martínez-Sobrino et al., 2023; Ofoghi et al., 2016; Weiss et al., 2024). In long-distance events, several researchers used tree-based and gradient-boosting regressors trained on large historical datasets of professional Ironman and Ironman 70.3 to rank course locations and environmental conditions by their expected impact on finish times (Knechtle et al., 2025), highlighting the importance of race venue, air and water temperature, and athletes' country of origin when selecting "fast" courses. Collectively, these studies show that supervised learning methods are increasingly used to (i) model complex, non-linear relationships between split performances and overall results, (ii) characterize optimal pacing and course selection strategies, and (iii) identify modifiable biomechanical and training-load risk factors, thereby positioning ML/AI as a central

methodological tool for both performance prediction and injury prevention in triathlon (Knechtle et al., 2025; Ofoghi et al., 2016; Thuany et al., 2023; Weiss et al., 2024).

Following an extensive literature review, no prior studies were identified that employed Machine Learning to predict Olympic distance triathlon performance at one specific event.

The aim of the present study is to predict triathlon performance at the Paris 2024 Olympics using conventional statistics and a Machine Learning-based approach. It is hypothesized that both predictive models would grant sufficiently accurate results.

The secondary aim of this study is to compare machine learning methods and conventional statistical technique analyses to evaluate precision and accuracy in predicting triathlon performance outcomes. It is hypothesized that machine learning methods could be more accurate than conventional statistical techniques.

MATERIAL AND METHODS

Participants

Data were extracted from the API service (Application Programming Interface) on the World Triathlon website (<https://triathlon.org/>) by signing up for the free service. Since the data were in the public domain and available on the Internet, no formal request was made to the Ethics Committee. To perform data collection, custom Python code (Python Software Foundation, Wilmington, DE, USA; ver. 3.12) was written for different operations. The Python codes used are available on the GitHub repository (https://github.com/AEONPHYTON/triathlon_analysis). Once the data were extracted, cleanup operations were performed using Python as the programming language and Jupyter Notebook (Project Jupyter, San Francisco, CA, USA; ver. 7.2) as the working tool (Rule et al., 2019). Two databases were created including Olympic distance races (one for males and one for females) of the elite category. Previous editions of the Olympics were also included.

Files identifying the races by the race number (prog_id and event_id) were downloaded and used to obtain the corresponding results data. The dataset was restricted to Elite and U23 athletes, with U23 retained due to their participation alongside Elite competitors. Standard-distance events were considered, separated by sex. Different variables were generated to track record of each athlete's discipline positions. Athletes lacking data for any discipline or transition, as well as athletes who were disqualified, did not start (DNS), or did not finish (DNF), were removed. Races without complete podium results or with implausible overall times (lower than 1 hour, 28 minutes and 20 seconds and higher than 2 hours and 30 minutes) were also excluded. These procedures granted a heterogeneous but valid dataset including more than 30 years of races, from 6 November 1989 to 24 May 2024.

Procedures

Once the cleaning was completed, two databases (males and females) were obtained for conventional statistical and machine learning analyses. The selected competitions were: Continental Championships, World Championships, World Cup, Continental Cup, Recognised Event, Regional Championships, Recognised Games, Major Games (editions of the Olympics from 2000 to 2021), World Championship Series. The reason behind including different types of competitions was to obtain a large amount of data for analysis. Regarding classical statistical techniques, a linear regression was performed using only the dataset from previous Olympic Games editions. Similarly, another linear regression was conducted using the entire

dataset. Finally, a third-degree polynomial regression was applied to the complete dataset. All the aforementioned analyses were used to estimate performance in the three triathlon disciplines, as well as the overall finish time. Scatter plots representing the distribution of data points were also generated.

To determine the average swimming, cycling, running, and overall times of the podium finishers, a sub-database was created in which only the top 3 finishers were considered for each event and averaged to obtain a unique time for each race; the data were filtered according to the final position of each race. Two databases were created: one with only the Olympic races and the other containing all races (always divided by males and females).

Statistical analyses

Statistical analyses and analyses using machine learning were performed by creating a Jupyter Notebook file (Project Jupyter, San Francisco, CA, USA; ver. 7.2) through the Google Colab service (Google Corp, Mountain View, CA, USA; ver. 2.14). Google Colab provides a faster computation service than regular computers in use to speed up processing. TensorFlow (Google Corp, Mountain View, CA, USA; ver. 2.14) and PyTorch (Meta AI, Menlo Park, CA, USA; ver. 2.3.1) libraries were used for machine learning analyses. For the projection of times to the date of the Paris 2024 Olympics, the last date on which a standard-distance event was held was taken into account, generating an interval of 67 days between that event and the Paris competition.

Data for evaluation through machine learning models was divided into training and testing data with the former used to fit the model and the latter used to assess its predictive performance. The data were split chronologically into 80% training and 20% testing, filtered to fall within the mean $\pm$ two standard deviations to reduce the influence of outliers. Machine learning techniques implemented with PyTorch and TensorFlow were employed to analyse data trends with scatter plots generated to visualize data distributions.

RESULTS

In total, the database contained a total of 45,884 and 37,106 male and female triathletes, respectively. The number of races included in the analysis is 1,384 for males and 1,387 for females. For the creation of the Olympics-only database, only competitions with Major Game indication were considered. The total number of events per year is shown in Figure 1.

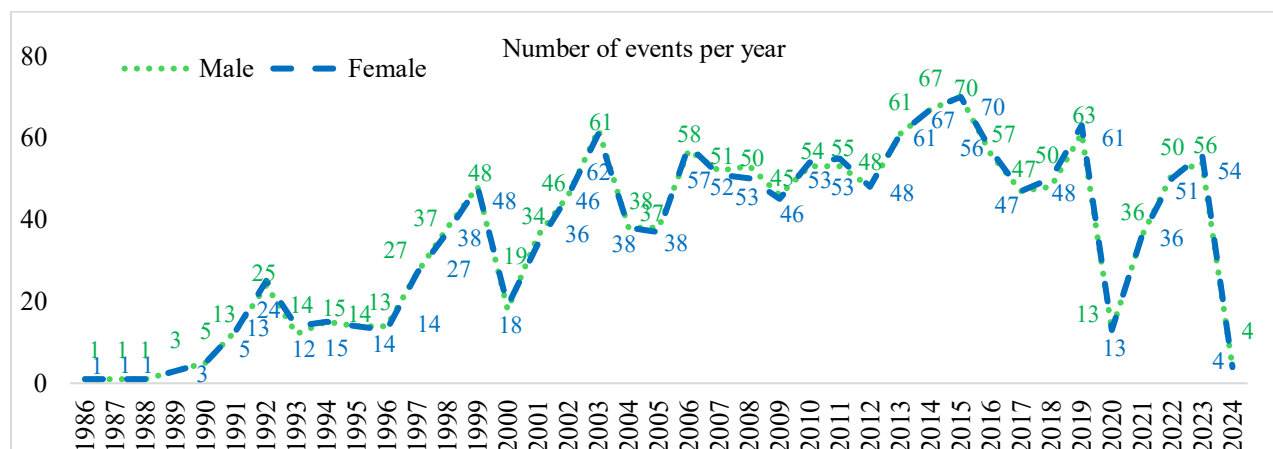


Figure 1. Number of events per year for male (A) and female (B) category.

Linear regression – Olympic Games

The average times of the top 3 finishers in each event at the Olympic Games are described in Table 1. The proportion of time for each discipline in the final result is illustrated in Figure 2. The prediction of the average of the top 3 times for Paris 2024, based on the data in Table 1 (excluding Paris 2024), is presented in Table 2.

Table 1. Average podium finishers time (s) at the Olympic Games.

		Swim	Bike	Run	Total
Sydney 2000	Male	1078	3527	1867	6515
	Female	1157	3915	2128	7249
Athens 2004	Male	1096	3628	1935	6677
	Female	1166	4122	2145	7494
Beijing 2008	Male	1098	3536	1850	6538
	Female	1192	3857	2048	7158
London 2012	Male	1022	3552	1760	6399
	Female	1161	3933	2022	7189
Rio de Janeiro 2016	Male	1044	3323	1885	6317
	Female	1151	3681	2078	7004
Tokyo 2020	Male	1090	3374	1783	6314
	Female	1110	3777	2026	6990
Paris 2024	Male	1249	3104	1790	6218
	Female	1356	3495	1971	6902
Mean $\pm$ SD	Male	1096.71 $\pm$ 72.97	3434.86 $\pm$ 180.48	1838.57 $\pm$ 63.26	6425.43 $\pm$ 159.10
	Female	1184.71 $\pm$ 79.36	3825.71 $\pm$ 200.39	2059.71 $\pm$ 61.69	7140.86 $\pm$ 198.98

Note. Mean $\pm$ SD = average time (s) and standard deviation of the discipline across all Olympic Games events.

Table 2. Podium finishers time estimation for Paris 2024. Linear Regression considering Olympic Games data.

		Swim	Bike	Run	Total
Slope	Male	-4.91	-47.54	-18.86	-63.54
	Female	-8.89	-55.34	-21.06	-78.11
Intercept	Male	1088.53	3656.40	1912.67	6682.40
	Female	1187.27	4074.53	2148.20	7454.07
R ²	Male	.22	.72	.37	.79
	Female	.19	.67	.72	.72
p-value	Male	<.001	<.001	<.001	<.001
	Female	<.001	<.001	<.001	<.001
Real Paris 2024 time (s)	Male	1249	3104	1790	6218
	Female	1356	3495	1971	6902
Estimated Paris 2024 time (s)	Male	1054	3324	1781	6237
	Female	1125	3687	2001	6907
Absolute difference (s)	Male	195	-220	9	-19
	Female	231	-192	-30	-5
Relative difference (%)	Male	18.49	-6.61	0.52	-0.30
	Female	20.53	-5.21	-1.49	-0.07

Note. Intercept = Point where the regression line crosses the Y-axis when all predictor variables are zero; X = Model coefficient reflecting the impact of predictor variables on the estimated time; R² = Coefficient of determination; p-value = p-value (polynomial regression); Significance level = .05; Absolute difference (s) = Real time - Estimated time; Relative difference (%) = $\{[(\text{Real time} - \text{Estimated time}) / \text{Estimated time}] * 100\}$. Positive values indicate the predicted time is less than the real time, while negative values indicate the predicted time exceeds the real time.

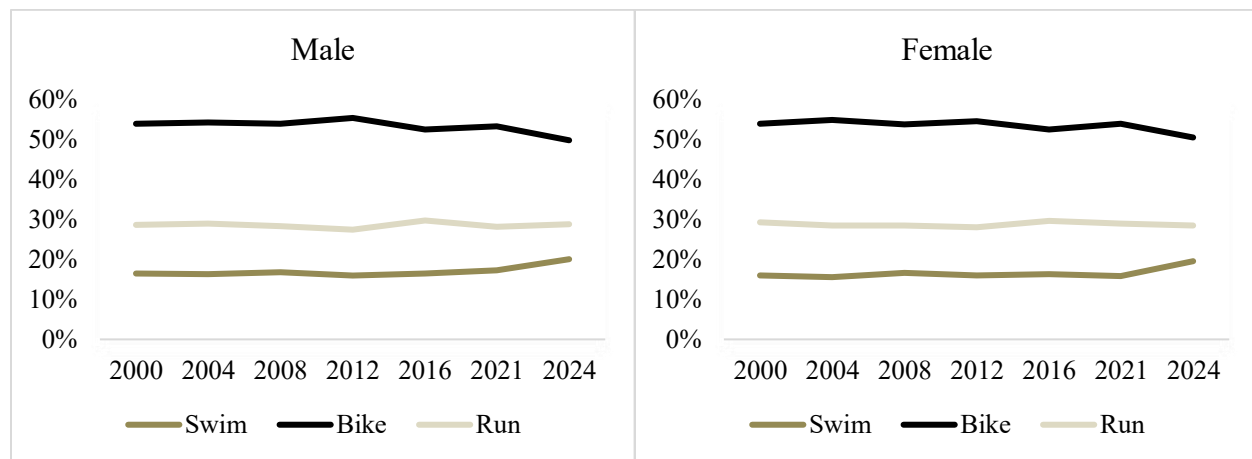


Figure 2. Discipline proportion (%) evolution for podium finishers at the Olympic Games.

When analysing previous Olympic editions, a trend of decreasing race times across the years can be identified (Table 2). For the predicted times, only the individual discipline times excluding transitions were considered, whereas the total time includes transitions (Table 2). Linear regression analysis indicates substantial differences in swim times (differences: 18.49% for males; 20.53% for females), moderate increased estimations in bike times (differences: -6.61% for males; -5.21% for females), and minimal differences in run times (differences: 0.52% for males; -1.49% for females). The prediction for total race time showed remarkable accuracy, with a difference of -0.30% for males and -0.07% for females (Table 2).

Linear regression – All data

Table 3. Podium finishers time estimation for Paris 2024. Linear Regression considering all data.

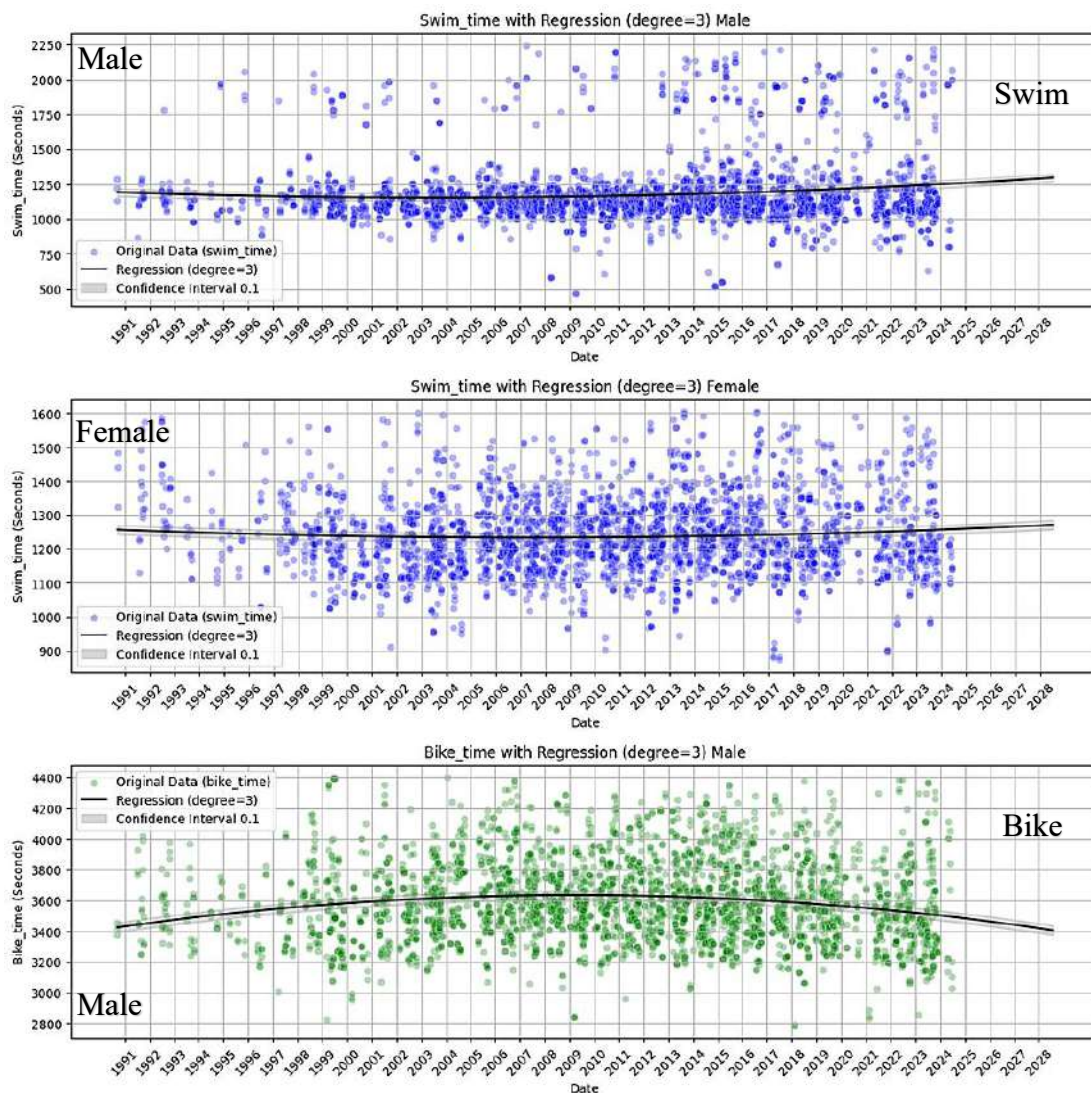
		Swim	Bike	Run	Total
Slope	Male	0.008	-0.003	-0.006	0.007
	Female	0.001	-0.004	0.001	0.006
Intercept	Male	-4745.554	5802.640	5989.906	1492.228
	Female	404.609	6773.265	1545.449	2998.050
R ²	Male	.009	.001	.003	.003
	Female	.001	.001	.0002	.001
p-value	Male	<.001	.074	.002	.003
	Female	.141	.079	.427	.052
Real Paris 2024 time (s)	Male	1249	3104	1790	6218
	Female	1356	3495	1971	6902
Estimated Paris 2024 time (s)	Male	1221	3582	1891	6791
	Female	1244	4001	2275	7627
Absolute difference (s)	Male	28	-478	-101	-573
	Female	112	-506	-304	-725
Relative difference (%)	Male	2.29	-13.34	-5.34	-8.44
	Female	9.00	-12.65	-13.36	-9.51

Note. Slope = Change in the dependent variable (time) for each one-unit change in the independent variable (year); Intercept = Point where the regression line crosses the Y-axis when all predictor variables are zero; R² = Coefficient of determination; p-value = p-value (polynomial regression); Significance level = .05; Absolute difference (s) = Real time - Estimated time; Relative difference (%) = $\{[(\text{Real time} - \text{Estimated time}) / \text{Estimated time}] * 100\}$. Positive values indicate the predicted time is less than the real time, while negative values indicate the predicted time exceeds the real time.

In the analysis of the time projections leading up to the Paris 2024 Olympic distance race, a total of 67 days passed between the most recent Olympic distance event and the Olympic Games race. Linear regression analysis indicates significant minimal decreased estimations in swim times for males (2.29%; p -value < .001), substantial increased estimations in run times for males (-5.34%; p -value < .001) and moderate increased estimations in total times for males (-8.44%; p -value < .001) in comparison with the real time (Table 3).

Third-degree polynomial regression

A third-degree polynomial regression was conducted to analyse the data trends. Figure 3 presents a scatter plot showing all considered data points alongside the resulting polynomial relationship. The graphs extend up to the year 2028, allowing for a clear visualization of the regression trend and its implications for future performance predictions. Once again, when analysing all the data, the same trend is confirmed as observed with the Olympic data alone: the times are projected to decrease in the future, particularly in the male category. The illustration shows a consistent pattern of performance improvement over time across various competitive events (Figure 3).



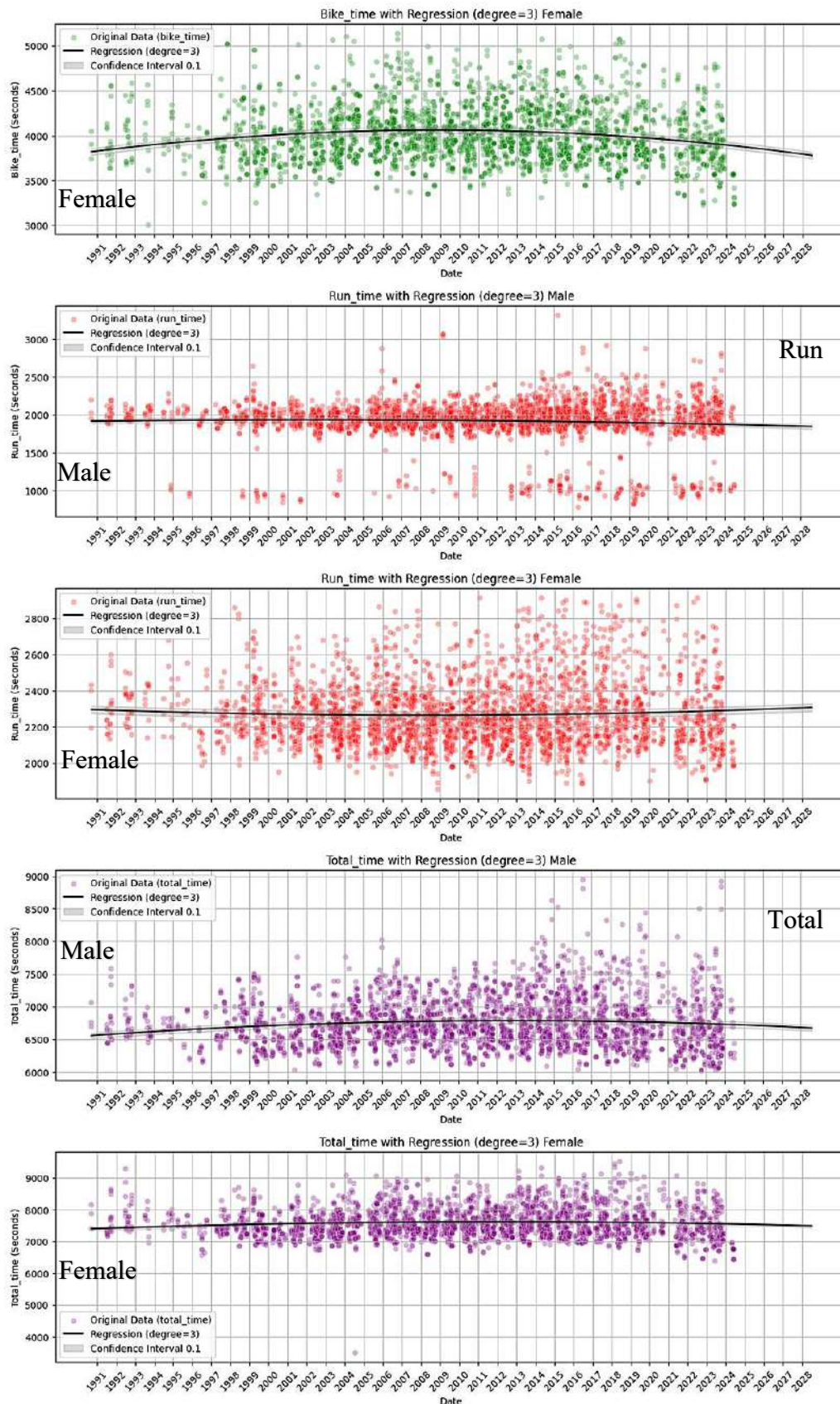


Figure 3. Podium finishers third-degree Polynomial Regression considering all data.

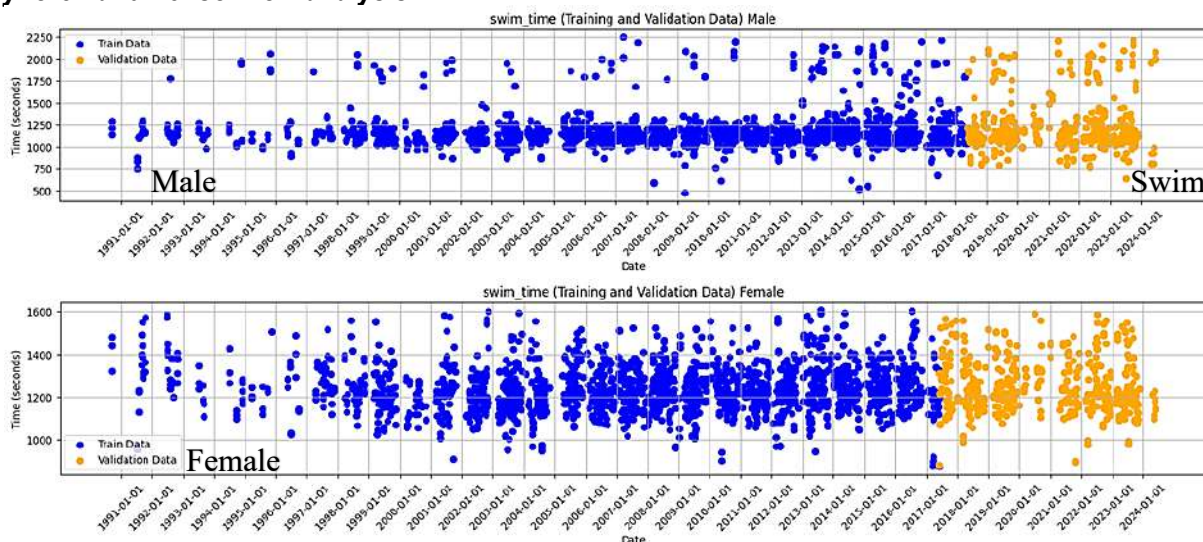
Table 4. Podium finishers time estimation for Paris 2024. Third-degree polynomial regression.

		Swim	Bike	Run	Total
Coefficients	Male	$0, -2.27 \times 10^{-12},$	$0, 6.21 \times 10^{-12},$	$0, 1.33 \times 10^{-12},$	$0, 4.70 \times 10^{-12},$
		$-1.66 \times 10^{-6},$	$4.55 \times 10^{-6},$	$9.79 \times 10^{-7},$	$3.45 \times 10^{-6},$
		1.52×10^{-12}	-4.14×10^{-12}	-8.93×10^{-13}	-3.13×10^{-12}
	Female	$0, -8.46 \times 10^{-13},$	$0, 7.53 \times 10^{-12},$	$0, -1.06 \times 10^{-12},$	$0, 4.98 \times 10^{-12},$
Intercept	Female	$-6.20 \times 10^{-7},$	$5.52 \times 10^{-6},$	$-7.75 \times 10^{-7},$	$3.65 \times 10^{-6},$
		5.64×10^{-13}	-5.02×10^{-12}	7.52×10^{-13}	-3.31×10^{-12}
R ²	Male	297805.64	-812835.31	-172398.29	-614134.78
	Female	112194.93	-985682.36	141185.98	64869.81
p-value	Male	.013	.024	.004	.009
	Female	.003	.025	.002	.006
Real Paris 2024 time (s)	Male	.017	<.001	<.001	<.001
	Female	.001	<.001	<.001	<.001
Estimated Paris 2024 time (s)	Male	1249	3104	1790	6218
	Female	1356	3495	1971	6902
Absolute difference (s)	Male	1253	3494	1872	6724
	Female	1257	3885	2291	7550
Relative difference (%)	Male	-4	-390	-82	-506
	Female	99	-390	-320	-648
Relative difference (%)	Male	-0.32	-11.16	-4.38	-7.53
	Female	7.88	-10.04	-13.97	-8.58

Note. Coefficients: Values associated with each term of the polynomial fitted to the data; Intercept = Point where the regression line crosses the Y-axis when all predictor variables are zero; R² = Coefficient of determination; p-value = p-value (polynomial regression); Significance level = .05; Absolute difference (s) = Real time - Estimated time; Relative difference (%) = $\{[(\text{Real time} - \text{Estimated time}) / \text{Estimated time}] \times 100\}$. Positive values indicate the predicted time is less than the real time, while negative values indicate the predicted time exceeds the real time.

Third-degree polynomial regression reveals that the estimated Olympic race times demonstrate slightly lower percentage differences when compared with the results from Table 3. Third-degree polynomial regression analysis indicates significant substantial and moderate decreased estimations in swim times (differences: 14.28% for males; 8.22% for females), moderate increased estimations in bike times (differences: -7.48% for males; -9.97% for females), moderate and substantial increased estimations in run times (differences: -6.12% for males; -13.63% for females) and minimal and moderate increased estimations in total times (differences: -3.53% for males; -8.34% for females) (Table 3).

PyTorch and TensorFlow analysis



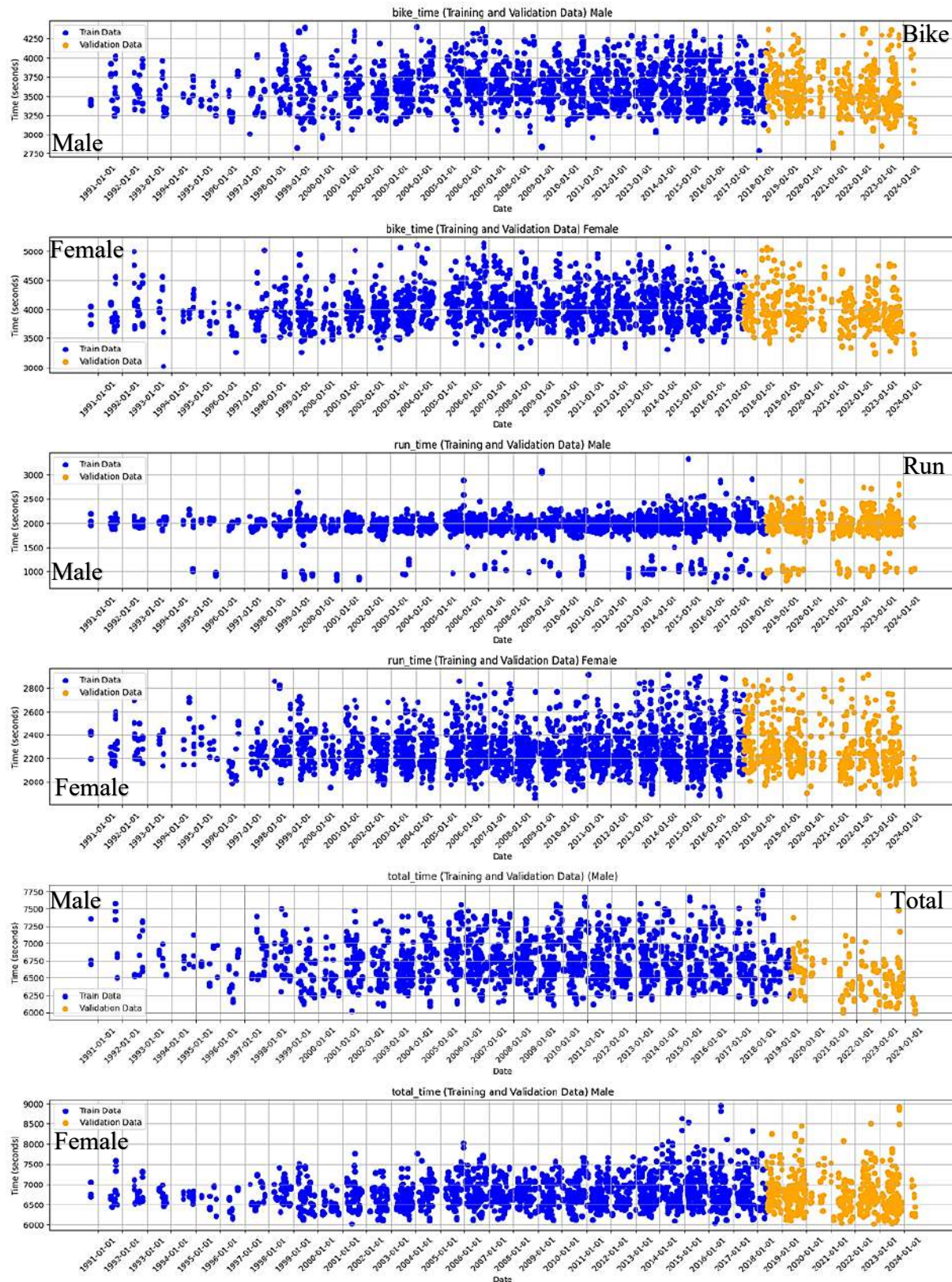


Figure 4. Podium finishers estimation. Training and validation data. Machine learning.

Table 4. Podium finishers time estimation for Paris 2024. Machine learning.

	Real Paris 2024 time (s)	Estimated Paris 2024 time (s)	Absolute difference (s)	Relative difference (%)
Males				
PyTorch				
Swim	1249	1204	45	3.74
Bike	3014	3409	-395	-11.59
Run	1790	1795	-5	-0.28
Total	6218	6499	-281	-4.32
TensorFlow				
Swim	1249	1333	-84	-6.30
Bike	3014	3457	-443	-12.81
Run	1790	1651	-139	-8.42
Total	6218	6442	-224	-3.48
Females				
PyTorch				
Swim	1356	1206	150	12.44
Bike	3495	3829	-334	-8.72
Run	1971	2195	-224	-10.21
Total	6902	7283	-381	-5.23
TensorFlow				
Swim	1356	1197	159	13.28
Bike	3495	3799	-304	-8.00
Run	1971	2174	-203	-9.34
Total	6902	7171	-269	-3.75

Note. Absolute difference (s) = Real time - Estimated time; Relative difference (%) = $\{[(\text{Real time} - \text{Estimated time}) / \text{Estimated time}] * 100\}$. Positive values indicate the predicted time is less than the real time, while negative values indicate the predicted time exceeds the real time.

Machine learning techniques were employed to analyse data trends. Figure 4 presents a scatter plot illustrating data points, with training data depicted in blue and predicted times represented in yellow. Both techniques (PyTorch and TensorFlow) showed comparable results in the male category, with bike times of -11.59% for PyTorch and -12.81% for TensorFlow, and total times of -4.32% for PyTorch and -3.48% for TensorFlow (Table 4). The average relative difference in the male category is -3.11% for PyTorch and -3.54% for TensorFlow, indicating a difference between them of 0.43% (Table 5). In the female category, all disciplines showed similar relative differences values, as well as the average relative difference (Table 4).

Overall summary

Run time was the best-predicted discipline for males (average difference: $-0.21\% \pm 5.45\%$), and total time was the best-predicted variable for females (average differences: $-5.43\% \pm 3.81\%$) (Table 5). Bike time exhibited the worst predictions for males (average difference: $-11.10\% \pm 2.66\%$) whereas swim time produced the worst predictions for females (average difference: $-12.63\% \pm 4.97\%$) (Table 5).

In the male category, the third-degree polynomial regression, linear regression considering Olympic Games races data, PyTorch and linear regression considering Olympic Games races data again were the most accurate predictions for swim (-0.32%), bike (-6.61%), run (-0.28%), and total times (-0.30%), respectively. Notably, TensorFlow was never the best technique for predicting any specific discipline.

In the female category, the third-degree polynomial regression was the best technique to predict the swim times (7.88%) whereas linear regression considering Olympic Games races data, was the most accurate for

bike (-5.21%), run (-1.49%), and total times (-0.07%). As in the male category, TensorFlow never emerged as the best technique for predicting any particular discipline (Table 5).

Table 5. Summary of relative differences (%) among the different prediction models.

	Conventional			Machine Learning		*Mean (%) ± SD
	LR-OG (%)	LR-AD (%)	PR-3D (%)	PyTorch (%)	TensorFlow (%)	
Male						
Swim	18.49	2.29	-0.32	3.74	-6.30	3.58 ± 9.18
Bike	-6.61	-13.34	-11.16	-11.59	-12.81	-11.10 ± 2.66
Run	0.52	-5.34	-4.38	-0.28	8.42	-0.21 ± 5.45
Total	-0.30	-8.44	-7.53	-4.32	-3.48	-4.81 ± 3.27
°Mean ± SD	3.03 ± 10.79	-6.21 ± 6.56	-5.85 ± 4.61	-3.11 ± 6.54	-3.54 ± 8.88	
Female						
Swim	20.53	9.00	7.88	12.44	13.28	12.63 ± 4.97
Bike	-5.21	-12.65	-10.04	-8.72	-8.00	-8.92 ± 2.73
Run	-1.49	-13.36	-13.97	-10.21	-9.34	-9.67 ± 4.99
Total	-0.07	-9.51	-8.58	-5.23	-3.75	-5.43 ± 3.81
°Mean ± SD	3.44 ± 11.60	-6.63 ± 10.55	-6.18 ± 9.64	-2.93 ± 10.46	-1.95 ± 10.43	

Note. LR-OG = Linear Regression using only Olympic Games data; LR-AD = Linear Regression using all available data; PR-3D = Third-degree polynomial Regression using all data; PyTorch = Machine Learning Neural Network implemented with PyTorch; TensorFlow = Machine Learning Neural Network implemented with TensorFlow; Mean (SD) = Average relative change (%) of the model (row) or discipline (column), with standard deviation. Relative change was calculated as $\{[(\text{real time} - \text{predicted time}) / \text{predicted time}] * 100\}$. Positive values indicate the predicted time is less than the real time, while negative values indicate the predicted time exceeds the real time.

*: Mean average and standard deviation of the different disciplines.

°: Mean average and standard deviation of the different estimations of the different statistical techniques.

For males, the linear regression based on Olympic Games races data was the most accurate technique overall, as it showed the lowest average relative difference (-3.03% $\pm$ 10.79%), and providing the most precise predictions in two disciplines (bike and total times), although all methods showed acceptable average accuracy. In the female category the linear regression using Olympic Games race data exhibited the most accurate prediction across most disciplines (bike, run and total times), but TensorFlow achieved the best precision (average relative difference: -1.95% $\pm$ 10.43%). All variables were better predicted by the same statistical techniques in both sexes except for run time, that was better predicted by PyTorch for males (-0.28%) and by linear regression based on Olympic Games races data for females (-1.49%).

DISCUSSION

The aim of the present study was to predict triathlon performance at the Paris 2024 Olympics using conventional statistics and a Machine Learning-based approach. The secondary aim of this study was to compare machine learning methods and conventional statistical techniques to evaluate their precision and accuracy in predicting triathlon performance outcomes. It was hypothesized that both predictive models would grant sufficiently accurate results and that machine learning methods could be more accurate than conventional statistical techniques. General statistical methods and machine learning techniques have proven to be reliable approaches for predicting performance in Olympic triathlon, especially when estimating the running performance for males and the total time for women. For males, the linear regression based on Olympic Games races data was the best predictable technique (average difference: -3.03% $\pm$ 10.79%), followed closely by machine learning-based technique (average differences: -3.11% $\pm$ 6.54%; 3.54% $\pm$ 8.88% for PyTorch and TensorFlow respectively). For females, the TensorFlow machine learning-based

technique was the most accurate on average (average difference: $-1.95\% \pm 10.43\%$), although the linear regression based on Olympic Games races data was the technique that predicted best most variables.

Linear regression analysis considering data from previous Olympic Games events indicates substantial differences between predicted and actual performance times in the swimming segment. Indeed, in swimming, the differences were 18.49% for males and 20.53% for females, indicating an overestimation of the time to complete the section. Conversely, the cycling section shows a moderate prediction with differences of -6.61% for males and -5.21% in females. Similarly, the running prediction shows a good agreement between the prediction and the actual performance times (differences: 0.52% for males; -1.49% for females). The prediction for total race time showed remarkable accuracy, with a difference of -0.30% for males and -0.07% for females (Table 2). Considering the accuracy results reported by other authors (Lerebourg et al., 2022; Lim & Song, 2024), this technique demonstrates comparable accuracy levels for cycling and running times, higher accuracy for total race time, and lower accuracy for swimming time predictions.

The considerable difference observed in the swimming leg can likely be attributed to the unique conditions experienced in Paris, particularly the swimming course in the river, which differed from those of previous editions. These conditions may have influenced the athletes' performance, either through environmental factors or psychological effects. Notably, in the cycling segment, a small difference occurred despite the fact that the circuit featured negligible elevation gain, unlike previous editions. In the running leg, the reduced difference may be attributed to the assumption that the running course was the most consistent across Olympic editions, typically being flat, and this database only considered data from previous Olympic Games. Finally, the minimal difference in total race time highlights the potential of this predictive approach to reliably forecast outcomes in future editions.

The results are different when extending the analysis to include all data in the database (i.e., ETU, WC, WTS). Linear regression analysis indicates minimal and moderate overestimation of swim times (differences: 2.29% for males; 9.00% for females), substantial underestimations in bike times (differences: -13.34% for males; -12.65% for females), moderate and substantial underestimations in run times (differences: -8.44% for males; -13.36% for females) and moderate underestimations in total times (differences: -8.44% for males; -9.51% for females) (Table 3). The discrepancies between predictions may be attributed to 1) differences in the database of each sex, as historically there have been fewer female participants in Olympic triathlon events compared to male participants, and 2) performance differences between sexes, a factor that has been extensively explored in the literature. (García-González & González-Jurado, 2025b; Lepers et al., 2014; Lepers & Stapley, 2010; Piacentini et al., 2019).

Third-degree polynomial regression analysis indicates an accurate prediction in men's swim times and a moderate overestimation in the female category (differences: -0.32% for males; 7.88% for females), substantial underestimations in cycling times (differences: -11.16% for males; -10.04 % for females), minimal and substantial underestimations in run times (differences: -4.38% for males; -13.97% for females) and moderate underestimations in total times (differences: -5.85% for males; -6.18% for females) (Table 4).

Liew et al. (2022) advocated for caution in the optimism of applying machine learning in prognostic modelling, and its benefit is likely dependent on factors like sample size, variable type, disease investigated, to name a few. This statement aligns with our findings. While TensorFlow may be observed as the best overall predictor of performance in the female category, it should not be applied indiscriminately. Specifically, for the male category, the linear regression analysis considering data from previous Olympic Games demonstrated the highest accuracy among all techniques, despite all methods showing acceptable performance (Table 5).

Likewise, in the female category, the linear regression based on Olympic Games races data was the technique that predicted best most variables. These findings suggest that no single technique can be considered clearly superior. Instead, the optimal predictive model depends on the sex category, the structure and availability of the data, and the specific outcome being predicted. Consequently, model selection should be driven by empirical performance under clearly defined conditions, instead of by a general preference for more complex machine learning approaches.

Run was the best-predicted discipline with all methods used for the male category ($-0.21\% \pm 5.45\%$) whereas total time was the best-predicted discipline for the female category ($-5.43\% \pm 3.81\%$). Bike time exhibited the worst predictions for males ($-11.10\% \pm 2.66\%$) and swim time was the worst predicted variable for females ($12.63\% \pm 4.97\%$). The estimated swim times were lower than the actual event times, likely due to the unique environmental features. TensorFlow was never the best technique for predicting any specific discipline in any sexes, although it showed the best average difference in the female category. Although the linear regression analysis using data from previous Olympic Games was the most accurate statistical technique, it should be noted that the sample size used for this method was considerably smaller than that of the other techniques. Therefore, when comparing statistical methods based on the same dataset, a slight improvement in prediction accuracy can be observed with artificial intelligence-based techniques.

Both techniques utilized (PyTorch and TensorFlow) showed nearly identical average results for both sexes (Table 5). The total times presented a difference of -4.32% for males and -5.23% for females in PyTorch, and -3.48% for males and -3.75% for females in TensorFlow (Table 5). To contextualize these results and compare them with other studies utilizing Machine Learning for event prediction, Nagovitsyn et al. (2023) reported an 11% error probability in predicting a wrestler's competitive performance. Moreover, Lim & Song (2024) presented a model that explained approximately 93% of the variability in clean & jerk performance. Additionally, Lerebourg et al. (2022) achieved a prediction accuracy above 94% for marathon performance, with the KNN model performing better than ANN, reaching an accuracy above 98%. Lastly and focusing on triathlon, other authors reported a model accuracy of 81.25% in predicting triathlon mixed relay successful race positions from their validation sample (Martínez-Sobrinó et al., 2023). The largest total time difference between the estimated time predicted by our models and the real time achieved is -8.58% , which demonstrates similar accuracy compared to the aforementioned studies.

The present study has some limitations. This study adopts a quantitative approach, which implies a lack of consideration for physical or other nature-related variables, such as training, previous experience, circuit layout or climatic conditions. Finally, analysing together competitions over a long period, including a small number of competitions where drafting was allowed and competitions where drafting was forbidden may have a small influence on the results, although preliminary analysis show that the results would be similar to those exposed in this study.

This study has practical implications for training in Olympic distance triathlon. This insight provides an indication of where the sport of triathlon is heading and may help refine future race strategies. Furthermore, these findings can be applied when setting performance targets for major events, allowing for more precise goal-setting and preparation. The model's results showed a considerable degree of reliability. For context, predictive accuracy in meteorology for a 7-day forecast ranges between 76% and 87%, while predictions extending beyond this period decrease to an accuracy range of 31 to 40% (Chen et al., 2023). Several other factors, including genetic predisposition, environmental conditions, access to technological advancements, and evolving training techniques, play pivotal roles in influencing an athlete's performance.

CONCLUSION

In conclusion, general statistical methods and machine learning techniques have proven to be reliable approaches for predicting performance in Olympic triathlon. PyTorch and TensorFlow showed better predictions than conventional statistics. For men, the linear regression based on Olympic Games races data was the most accurate technique overall. For women, TensorFlow achieved the best precision but the linear regression using Olympic Games race data exhibited the most accurate prediction across most disciplines. The estimated times were almost always higher than the actual times in Paris 2024, except in the swimming discipline, probably due to specific conditions.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Luca A. Bianchini was responsible for data handling and analyses, and contributed to investigation, writing, and editing. Pablo García González focused on conceptualization, investigation, drafting, and visualization. Andrea Fuk and Simone Villanova contributed to review and editing. José Antonio González Jurado contributed to validation, resources, supervision, and editing. Maria Francesca Piacentini contributed to validation, editing, supervision, and project administration. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Effects of combined square stepping and BOSU training on balance, postural control, and vertical jump in badminton players: Protocol for a randomized controlled trial

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ABSTRACT

Square stepping exercise (SE) and BOSU ball exercise (BE) have independently shown beneficial effects on balance, strength, and coordination; however, their combined effects in badminton players remain unclear. This study aims to present the protocol of a randomized controlled trial designed to investigate the effectiveness of combined SE and BE on postural sway, dynamic balance, and vertical jump performance. Fifty-one badminton players will be randomly allocated into three groups: combined SE and BOSU group (SBG, $n = 17$), BOSU group (BG, $n = 17$), and control group (CG, $n = 17$). The intervention will last 8 weeks. The SBG will perform SE (three sessions per week) and BE (two sessions per week), the BG will receive BE with conventional training, and the CG will follow conventional training only. Outcomes will be assessed at baseline, week 4, and week 8, and post-intervention using the Y-Balance Test for dynamic balance, Wii Balance Board measures for postural sway, and the Sargent jump test for vertical jump performance. Data will be analysed using repeated-measures analysis of variance to determine within- and between-group differences over time. The findings of this study are expected to provide evidence on the effectiveness of combined neuromuscular and balance training strategies for improving lower limb performance and postural control in badminton players and reduce health risks in these athletes.

Keywords: Performance analysis, Dynamic balance, Postural stability, Vertical jump, Square stepping exercise, BOSU training, Health risks, Human well-being.

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INTRODUCTION

Badminton is a common sport that calls for rapid powerful shots and quick footwork. One of the world's fastest racquet sports (Malwanage et al., 2022a). In addition, badminton players must conduct extremely quick and asymmetrical movements of their upper limbs while keeping their centre of gravity within the base of support (Teu et al., 2005). Therefore, improved body balance is essential for developing badminton skills, improving sports performance, and preventing injuries (Refahi et al., 2022). Competent badminton players must maintain exceptional postural control, dynamic balance, accuracy in their shots, and strength in their lower extremities to perform at their best. Balance is the ability to support the body while standing or moving with little to no movement (static balance), whereas dynamic balance involves some level of anticipated movement around the centre of gravity projection (Rizzato et al., 2023). Postural sway, dynamic balance, and lower limb strength are vital components of athletic performance, influencing the execution of fundamental movements such as lunging, pivoting, and sudden shifts in weight distribution (KAVIYARASAN et al., 2025). To achieve optimal performance and prevent injuries during rapid movements in the court, the players need a high level of dynamic balance (Han et al., 2022; Hassan, 2017). Multiple evidence suggested a correlation between dynamic balance and the incidence of lower extremity injuries in different populations (Farhadi, 2013; Kurihara et al., 2024; Sarto et al., 2019). Furthermore, rapid nature of the sport demands elements like maximum strength, rapid strength, explosive power, agility, and balance when performing dynamic movement patterns such as change of direction and jumping actions (Manjrekar et al., 2023). In badminton, lower body strength is crucial because it promotes quicker and more accurate footwork. The powerful lower body enhances speed when moving around the badminton court by enabling quick stops and direction changes. Additionally, by transmitting energy from the legs to the upper body, stronger lower limb muscles enable the production of stronger smashes (Hassan, 2017). Therefore, Vertical jump performance was used as paradigm for explosive strength and lower limb abilities (Nishiumi et al., 2023; Praveenkumar et al., 2025).

BOSU ball is a tool specifically designed for balance training in athletes. It has a flat, stable surface that produces an unstable surface on a flat, stable surface. Additionally, it is employed to enhance stability in both upright and horizontal position (Yaggie & Campbell, 2006). The BOSU ball can be used as an additional tool for balance training since it improves static and dynamic balance, agility and functional performance (Cigrovski et al., 2017; Loh & Chong, 2018). In this context, BOSU ball training significantly improved single-leg hop and jump height in football athletes.

The square-stepping exercise (SE) was developed by Shigematsu and Okura to augment the lower limb functional fitness in elderly population and to reduce their fall risk. The SE pattern consists in stepping on the floor alternately forward, backward, to the side and diagonal. The task is performed on a thin mat (250 cm x 100 cm) with the surface divided into 40 equated squares. SE is a form of motor task that challenges motor and cognitive capabilities (Shigematsu & Okura, 2006). The precise footwork and spatial orientation utilized in the SE pattern may facilitate enhanced movement patterns and body control in older adults (Y.-H. Wang et al., 2021). Evidence suggested that SE may accelerate the executive function in individuals with Parkinson (Liu et al., 2022) and enhances balance in individuals with stroke (Yumlembam et al., 2025). However, there is no evidence that SE can effectively help badminton players. In addition, Bosu ball exercises performed on a semi-stable surface challenge proprioception, muscle activation and balance control and could conceivably improve an individual's capacity to negotiate different terrains and court conditions. Whereas the effectiveness of individual exercises—square stepping exercises and Bosu ball exercise has been investigated, there is paucity of literature whether combining them will have effect on postural sway and balance in badminton players well-being. Therefore, the objective of this study is to investigate the synergistic effect of square stepping and Bosu ball exercises on enhancing postural sway, dynamic balance and jump

height in badminton players. First phase of the study will be running a randomized pilot study to determine the effect of SE on balance and agility in badminton players. Second phase of the study will be implementing the combination of both SE and BE to examine its synergistic effect on balance and jump height in badminton athletes. The proposed hypothesis for this study is that there will be a significant improvement in postural stability, balance and jump height following 8 weeks of structured intervention.

MATERIAL AND METHODS

Study design and participants

The study employed a assessor-blinded randomized controlled trial that adhered to the CONSORT guidelines for randomized trials. A priori sample size calculation was conducted using G*Power version 3.1.9.4. Given an effect size of 0.23 obtained from dynamic balance ability from a previous study (Z. Lu et al., 2022) with an alpha level of .05 and a desired statistical power of 80%. The estimated sample size was 42. Considering a 20% attrition rate, the final sample size was computed as 51 participants. After screening, the eligible participants will be allocated to SBG (n = 17), BG (n = 17) and CG (n = 17) based on the generated random number at the time of group allocation as shown in Figure 1. Participants' inclusion criteria were: Both genders, aged between 18 and 30, having a minimum of 1 year of experience in badminton, and having competed in a minimum of 2 club-level badminton tournaments in the past 6 months. The exclusion criteria were any lower limb surgery, ACL injury, or any other injury in the lower extremity in the past 1 year, involved any other form of physical training other than badminton-specific training, or neurological disorders that may affect the balance and proprioception. Participants will be recruited from a private indoor badminton club located in Nilai, Malaysia. The study centre will be selected based on the available eligible participants and the investigator's convenience of access. To eliminate the potential bias, the participants were randomly assigned to three groups using computer-generated randomization. Subjects will be unaware of their designated group following randomization. Additionally, assessors will be qualified sports physiotherapist with over 7 years of experience, and they will also be blinded to the grouping. The principal investigator who delivered the exercise will not be involved in data collection to avoid his influence on outcome measurements.

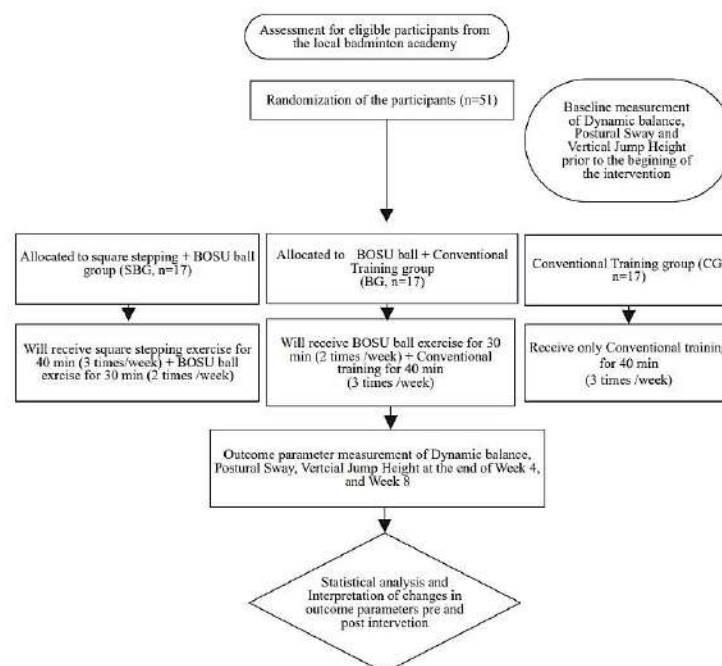


Figure 1. Randomization and intervention allocation chart.

Data collection and ethical approval

Baseline data on dynamic balance, postural sway, and vertical jump height will be collected a week before the commencement of the intervention. Subsequent outcome measurements will be conducted during the 6th and 8th weeks of the intervention. Collected data will be anonymized by the research helper who was not involved in delivering interventions. The main study was registered with ClinicalTrials.gov with identification number NCT07353866. The study was approved by the institutional ethics panel with reference number INTI-IU/FHLS-RC/BPHTI/1NY12024/018 and was in line with the ethical guidelines of the Declaration of Helsinki. All participants will be given a clear explanation of the study procedure and potential risks, and consent will be obtained before the commencement of the study.

Intervention procedure

Control Group (CG)

The CG underwent 40 minutes of traditional shadow training over 3 days per week for 8 weeks, which included 5 minutes of warm-up exercises such as arm swings, lunges, torso twists, and leg swings for 3 minutes, followed by 2 minutes of jogging around the court. Subsequently, the first phase consists of 10 minutes of basic 6-corner footwork (front, side, and rear court, both right and left sides), 4 sets x 45 seconds, 60 seconds rest, followed by Forward and backward recovery, four sets x 30 seconds. Next, the second phase comprises 20 minutes of quickness training, including right front net lunge and left rear scissor jump. Switch between right mid-court drive and left mid-court drive, followed by a 3-point sequence from the centre of the court (net shot, backcourt clear, back to centre 4 sets x 45 sec, 30 sec rest between the sets. Finally, the end phase will be 5 minutes of cool-down activities, such as gentle arm swings and static stretches for the quadriceps, glutes, triceps, and pectoralis major.

BG (BOSU ball group)

All participants in BG will undergo BOSU ball training for a period of 2 days per week for 8 weeks, and each session lasts for 30 minutes along with traditional shadow training. The following exercise will be performed. The exercise protocol was listed in Table 1.

Table 1. BOSU ball intervention protocol.

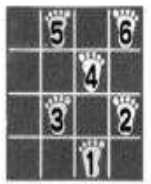
Phase 1 (Week 1-3)	Phase 2 (Week 4-6)	Phase 3 (Week 7-8)	Rest interval
Bipedal static stance on centre of the dome 3 Sets, 30 sec/set Single leg stance 3 sets, 15 sec/set /leg	Jump squats on BOSU flat side 3 sets ,8 reps / set Lateral BOSU hop 3 sets, 8 hops/set	BOSU burpee with vertical jump 3 sets ,10 reps / set Single-leg balance + shuttle reach 3 sets ,10 reps / set Single- leg balance with flat side up 3 sets ,10 reps / set Bosu Reverse lunge with knee drive 3 sets ,10 reps / set	A constant 60 seconds of rest period between each set was maintained throughout the protocol in each phase
Mini Squat with hands on hip 10 reps x 3 sets Alternate step up 3 sets ,10 reps/ set/leg	Push-up with hands on BOSU 3 sets ,8 reps / set BOSU Mountain climbers 3 sets ,8 reps / set		

SBG (Square stepping + BOSU ball exercise group)

Participants in the SBG will perform both SE and BOSU ball training. SE will be implemented on Monday, Wednesday and Friday for a period of 8 weeks, each session lasts for 40 minutes. Meanwhile, all participants

in this group will undergo specified BOSU ball protocol mentioned in Table 1 on Tuesday and Thursday for the same duration of 8 weeks, 30 minutes each session. The SE training comprises of a series of forward, backward, lateral, and diagonal steps, with the complexity of pattern increasing from week 2 to week 8. Participants were directed to walk into the SE mat from one side of the mat to the opposite end of the mat as per the step sequence on the mat and walk on their toes with elevated heels and avoiding contact with square frame. The sequences of the protocol will be structured to include initial 2 step pattern for first 2 weeks, followed by a 3-step pattern from week 3-5, and progressed to 4-step pattern from 6-8 weeks as illustrated in Table 2. Each sub pattern (A, B, C) will be executed 2 sets (3 reps each set) with 1 minute rest periods between each set, for a total duration of 40 minutes. Prior to the commencement of the intervention, participants will receive a visual stepping pattern in the form of a poster to memorize the pattern and are instructed to reproduce it on the SE mat. Initially, participants will be given a trial session to implement the learned pattern on the mat. Participants would be encouraged to start slowly and increase their speed once they were comfortable with the pattern. Other than initial demonstration no other auditory or visual cues will be provided. The intervention sessions will be standardized in terms of the number of repetitions and rest time. All repetitions were executed at the pace as directed by the principal investigator to maintain consistency across participants. A fixed 1-minute interval was retained between the set. However, participants were instructed to perform at a comfortable, sustainable pace under supervision to minimize variability. A licensed physiotherapist with over 10 years of experience in sports rehabilitation, who received training about the SSE protocol, will deliver the exercise protocol. Fidelity checks will be conducted by an independent research assistant who will attend one randomly selected session each week, using a standardized checklist to ensure that the exercises will be delivered correctly, their progression will be monitored, and participant adherence will be verified. All training sessions will be conducted in an indoor badminton hall made up of PVC flooring with a length and width of 13.4m x 6.1m.

Table 2. Patterns used in square stepping exercise.

	Square stepping exercise patterns			Intensity and rest
Week 1-2 (2 Step Pattern)				
	A	B	C	
Week 3-5 (3 Step Pattern)				2 sets (3 reps each set) with 1 minute rest periods between each set. Duration: 40min Each pattern (A,B,C) will be performed 2 sets
	A	B	C	
Week 6-8 (4 Step Pattern)				
	A	B	C	

Note: Each pattern was performed at own pace. Rate of Perceived Exertion (RPE) was monitored using Borg scale (12–15 RPE).

Outcome measure

Dynamic balance

The Y-balance test constitutes a prominent tool in the research literature for assessing the dynamic balance of the lower extremities. It demonstrates a good inter-rater and intra-rater reliability when administered to healthy adults, as evidenced by an Intraclass Correlation Coefficient (ICC) ranging from 0.83 to 0.96 (Powden et al., 2019). A YBT Kit consists of three interconnected cylindrical tubular plastic rods, calibrated in half-centimetre increments. Each rod is equipped with a movable indicator plate, which the participant manoeuvres by applying force with their foot or toes while avoiding weight-bearing on the indicator itself. Before the test, participants engaged in a trial session. Subsequently, they were allowed to undertake six practice trials on each leg across the three designated reach directions before the formal testing phase commenced. The participant was instructed to assume a standing position on the leg under evaluation, centrally positioned on the platform, with the most distal aspect of the longest toe just posterior to the red line. While maintaining a single-leg stance, the participant was directed to extend the free limb anteriorly for three trials, followed by three trials in both the posteromedial and posterolateral directions. Participants were instructed to propel the distance indicator as far as feasible toward the designated direction under evaluation. The researcher monitored the participants during testing to ensure adherence to the protocols, prohibiting any movement of the indicator via kicking or acceleration at the conclusion of the push. The maximal reach distance was documented at the most distal point attained by the foot at the proximal edge of the indicator, measured to the nearest half centimetre. Trials were to be discarded and repeated if participants (1) lost their balance during execution, (2) lifted the heel of the foot remaining on the platform, (3) failed to maintain contact with the distance indicator while it was in motion (e.g., if the indicator was kicked), or (4) experienced a loss of balance during the return to the initial position after the distance had been recorded. The maximum reach distance from the three trials for each reach direction was utilized for analysis. Furthermore, the maximum reach distances in each direction were aggregated to obtain a composite reach distance, which was normalized by limb length for evaluating overall performance on the test.

The length of the subjects' limbs was measured before the test. They were positioned supine on a table, with their hips and knees flexed. Subsequently, the subjects elevated their pelvis and passively returned it to the table. The examiner then performed passive stretching of the lower limbs into an extended position to achieve pelvic equilibrium. The right leg of each subject was measured in centimetres utilizing a tape measure, extending from the bottom edge of the anterior superior iliac spine to the distal margin of the medial malleolus.

The composite score will be calculated using the following formula:

$$\text{Composite score} = (\text{Anterior} + \text{posteromedial} + \text{posterolateral}) / (3 \times \text{limb length}) \times 100$$

Vertical Jump Performance (VJH)

The Sargent Jump Test is a test to measure lower body power (Markovic et al., 2004). To measure the standing reach height the participant will be asked to stand along wall side and instructed to reach as high as possible and mark the point on the wall using some chalk. Subsequently, ask the participants to stand away from the wall at a distance of 10 cm for free arm swinging, the fingers are chalked, and the subjects will be instructed to perform countermovement by bending their knees and swinging the arms back to reach as high as possible and mark on the wall with chalked finger. The highest point marked on the wall is calculated as jump height. The difference between the jump height and the standing reach height will be computed as VJH. Three trials are performed with 30 seconds rest between each trial and average of the three trials will be used for analysis.

Postural Sway (PS)

PS will be assessed using the Wii board incorporated with Physiosensing Balance Software® v.21.5.0.0 (Sensing Future, Coimbra, Portugal). The Wii board has excellent inter- and intra-rater reliability in assessing the centre of pressure (COP) path length and velocity (ICC: 0.89-0.79) (Clark et al., 2018; Park & Lee, 2014). The Wii Balance Board (WBB) quantified the overall centre of pressure (COP) sway length, representing the sum of postural sway in both the anteroposterior and mediolateral directions. The WBB will be interfaced with a laptop running Microsoft Windows 11 to facilitate a Bluetooth connection to the WBB. The force platform data were recorded at 100 Hz. It is equipped with two dual-channel analogue-to-digital converters (ADCs) to sample the four load cells at each platform corner. The participants will be instructed to position themselves on the WBB (Sensing Future Technology, Portugal). The assessment of postural stability comprises two distinct conditions: one with the eyes open and the other with the eyes closed, performed on a stable surface with the feet positioned on either side of the WBB's centreline. Participants' arms are held in an extended position, and they look at a focused point placed on the wall. The entire procedure was repeated for 30 seconds with eyes open and eyes closed. Participants will be allowed to take one trial to familiarize themselves with the assessment. The Physio-Sensing Balance software was used to analyse the ellipse area (mm²), the displacement of the COP in the anteroposterior (AP) and mediolateral (ML) directions, and the mean velocity (mm/s).

Statistical analysis

Data analysis will be employed using SPSS for Windows Inc. version 22. Chicago, Illinois, and the continuous data will be represented in mean and standard deviation. A two-way repeated-measures ANOVA will be used to determine the mean difference between groups at three time points (baseline, 6th week, and 8th week) during the intervention period. A significance level of $p < .05$ was set to determine statistical significance.

EXPECTED OUTCOMES

The most critical predictors of badminton performance and injury prevention are lower limb strength and balance. The rapid changes of direction, lunges, jumps, and rebounds are identical features of badminton that strongly rely on strong lower-extremity function. Balance and neuromuscular control deficiencies are directly associated with an increased risk of typical badminton injuries, specifically knee and ankle joint injuries. Therefore, it is essential to investigate specific interventions that may help to improve such attributes (Hiruntrakul et al., 2025; T. Wang et al., 2025). This randomized controlled trial protocol aims to clarify the synergistic effects of square-stepping exercise and BOSU ball training on lower-extremity balance and strength among badminton players, a group prone to ankle and knee injuries due to the sport's dynamic movements and rapid directional changes (Nugraha et al., 2022). This study will examine the impact of various training modalities on essential performance metrics —agility, power, and proprioception, which is vital for injury prevention and improved athletic performance in badminton (Zhao et al., 2021).

The outcome of this study is anticipated to yield evidence-based guidelines for the integration of specific balance and strength training into current conditioning protocols for badminton athletes, thereby enhancing their physical preparedness and minimizing injury risks during competitive games (Z. Guo et al., 2021). This research protocol outlines a stringent methodology for comparing these interventions, emphasizing objective metrics of physical attributes like dynamic balance and explosive strength of the lower extremity during sport-specific movements (Franco-García et al., 2022). The study aims to evaluate the influence of these exercises on cognitive functions pertinent to athletic performance, including reaction time and decision-making, while recognizing the complex interaction between physical and cognitive factors in elite sports (Franco-García et al., 2022).

SE is a complex, multidirectional pattern of stepping exercise designed to evaluate balance, coordination, and responsiveness through structured footwork exercises. It was originally intended to be used with the elderly population to reduce the fall risk. Nevertheless, its application has expanded to sports participants, which also emphasizes proprioceptive information, lower limb control, and neuromuscular training. Recent evidence indicated that step-based aerobic interventions have positive effects on postural control and dynamic balance among badminton players which are indicators that SE is relevant and effective in this situation. The implementation of such sport-agnostic versatile stepping protocol could have a holistic effect by addressing the deficiencies in multi-planar dynamic stability, which is a key component in competitive badminton (Hiruntrakul et al., 2025).

BOSU ball is an unstable surface that challenges neuromuscular and proprioceptive systems in athletes. Activities such as squats, lunges, or single-leg tasks on an unstable surface may additionally enhance the muscle activation and complexity of sensorimotor control and stimulate dynamic balance adaptation compared to stable surfaces (Pohl et al., 2020). Past studies have discovered that integrating BOSU ball exercises with other training regimens significantly improves postural stability, agility, and neuromuscular coordination, which are thought to be key factors in landing mechanics (Gidu et al., 2022; M. Lu et al., 2025; Shultz et al., 2013). This indicates that such effects may be applicable in the context of badminton, where rapid turns and explosive power generation are required in order to enhance performance on the court.

Balance training on an unstable surface stimulates the postural control and proprioceptive feedback, whereas tailored stepping exercise patterns induce a multidirectional complex movement pattern, which in turn induces the stability of the posture (Kathiresan & Mohanan, 2025). We further hypothesize that synergetic action between these two protocols may fortify both dynamic and static components of balance, escalate the lower extremity explosive power, and potentially lead to injury prevention outcomes.

The mechanism underlying our hypothesis is that both exercises target the sensorimotor system in two ways, neuromuscular synergy and proprioceptive integration along with strength training. In the context of SE, the patterns are multidirectional and require participants to memorize and execute the task, which challenges movement planning and inter-limb coordination (Siqueira et al., 2024). While exercise on BOSU ball compels the hip, knee and ankle muscles to continuously trigger the reflex mechanism to maintain postural control. This notion was supported by previous electromyographic study evidence identified that exercise with BOSU can elicit greater co-contraction of ankle muscle to provide joint stability (Lizardo et al., 2017; Teu et al., 2005). Recent studies related to athletic population have emphasized that multi-modal training showed better functional outcomes and mitigating the risk of injury (C. Guo & Xu, 2025; Hiruntrakul et al., 2025; M. Lu et al., 2025).

IMPLICATIONS OF THE PROTOCOL

In conclusion, the significance of combining SE and BOSU ball training intervention lies in its potential to address the critical gap in badminton-specific training. Even though numerous studies have highlighted the effects of plyometric and balance training protocols in isolation, there is a paucity of research on the synergistic effects of cognitive and dynamic footwork training and unstable-surface training. Hence, we firmly believe that this randomized trial will provide empirical evidence for an advanced integrated training protocol that not only enhances performance and health but also reduces the likelihood of injury among badminton athletes.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Vinosh Kumar. P: Conceptualization, methodology, data collection, writing- original draft preparation. Vinodhkumar. R: Writing - reviewing and editing, data analysis. W. H. Chang: Review of literature, data collection plan, resources. Arun Vijay Subbarayalu: Review and editing of manuscript, revised the study protocol background. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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The effect of stride frequency, stride length, and stride time on sprint patterns

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ABSTRACT

The research has been done to explain the complex interrelation of three important parameters of the sprinters-stride frequency, stride length, and step time-in the case of a national athlete HTY during the 100 meters sprint. Stride length refers to the distance covered in one complete step, while stride frequency is defined as the number of steps one makes in a unit of time. Previous studies have shown that both these two variables are related in a complex way. Usually, if one increases, the other decreases because of biomechanical limitation. This paper is a quantitative description, and performance variables of HTY were analysed through video analysis software namely, Kinovea. The results showed that HTY finished the race with 13.24 seconds and an average of 172.85 cm stride length with a total of 57 steps. Variabilities in speed during successive intervals, such as the peak from the 10-20-meter interval, were analysed. The results show that literature supports stride frequency and length significantly influence sprint performance. More precisely, it is proven that there is room for improvement in the specific strengthening exercises by the fact that the measured stride time differs between legs. Fine-tuning in the relationship between stride frequency and length is the most important in enhancing sprint performance. The study gives some useful suggestions for coaches and athletes in the modification of their training strategies, thereby improving the overall efficiency in sprinting.

Keywords: Biomechanics, Stride frequency, Stride length, Step time, Sprint patterns.

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INTRODUCTION

Step frequency, step length, and step time are important components that affect the performance of the sprinter (Miyashiro et al., 2019). Understanding how these elements interact can provide insights into optimizing sprint techniques (Yan, 2024). Stride length refers to the distance travelled in a complete step, whereas step frequency is the number of steps taken per unit of time (Hiraga et al., 1994). Various researches indicate a complex interaction of step length with step frequency. Because of the biomechanical constraint, generally, an increase in one would result in the reduction of another, such that if an athlete increases his stride, the frequencies reduce, or vice versa (Niay et al., 2019; Sobarna et al., 2023). This inverse relationship requires a careful training strategy focused on achieving optimal ratios, as excessive focus on improving one component without considering the other can lead to decreased performance (Arora & Doshi, 2021). Therefore, trainers and athletes must design a training regimen that harmoniously enhances both attributes (Wang et al., 2023).

Specific biomechanical aspects, including hip flexion and muscle coordination, significantly affect stride characteristics as well as overall sprint performance (Krebs et al., 1998). Optimal hip flexion allows for the development of more effective thrust force, while good muscle coordination supports a smooth transition of lower limb motion during the ground contact and swing phases. For example, superior muscle coordination is required to achieve high stride frequencies, which ultimately improves sprint performance holistically (Majumdar & Robergs, 2011). In addition, research shows that strength training has more effect on increased stride length than frequency, indicating that different training modalities can produce varying impacts on these biomechanical parameters (Schubert et al., 2014).

It was important for the performance pattern of the sprinter that this relationship among step frequency, length, and step time is complexly interrelated. It will also clearly be an added tool to help both the athletes develop their technique and help the coaches design effective training programs related to each one's needs. And as sprints continue to change with every development in the knowledge of sports sciences, ongoing research on these factors shall be relevant for optimizing athletic performance.

METHODS

This study uses a single-subject research design with a descriptive quantitative approach to analyse the 100-meter sprint of national athletes with the initials HTY. The variables measured included step frequency (stride frequency, steps per second), step length (stride length, cm), step time (step time, seconds), travel time per interval, and speed (m/s).

Participants

The subject of the study was one female national athlete with the initials HTY with a height of 154 cm and a weight of 52.7 kg. The selection of subjects used purposive sampling techniques based on their status as a national athlete in the 100-meter sprint, thus meeting the criteria for the biomechanical analysis of single running performance. No exercise interventions were provided in this study; Data are completely taken from one time of the subject's maximum running performance for the purpose of biomechanical descriptive analysis. This approach allows for pure observation of stride frequency, stride length, and step time patterns without the influence of external variables.

Data collection procedure

The 100-meter running video was recorded using a high-quality digital camera with a minimum specification of 60 fps and 1080p resolution. The camera is positioned side-by-side (profile view) at waist height as well as 10-15 meters away from the subject to minimize perspective distortion and ensure the accuracy of biomechanical measurements. Data collection was carried out on standard athletic tracks with 10-meter interval markers (0-10 m, 10-20 m, up to 100 m). Subjects warmed up standard before the maximum run from the start blocks or standing start positions, with video recording starting 2-3 seconds before the start and ending after crossing the finish line.

Video analysis with Kinovea

The video is imported into the Kinovea software (version 0.9 or later, free download from kinovea.org) for detailed biomechanical analysis. This process allows for precise measurement of running motion variables through the tracking and automatic measurement features available in the software. The first step is to calibrate the scale by drawing a line of known distance (e.g., 1 meter between lines of trajectory), then calibrate using the "Linear scale" tool to convert units of pixels to meters or cm. Furthermore, step identification is done by playing the video frame-by-frame at a slow-motion speed of 0.1x; Mark the initial right/left foot contact with the ground as a "touchdown" using the Trajectory Tool or Auto Marker, where one stride is defined from the same foot touchdown to the next touchdown.

Variable measurements

Measurement of biomechanical variables is carried out systematically using the Kinovea feature. The length of the stride is calculated as the horizontal distance between two consecutive touchdowns on the same leg as the line tool, while the step time is measured as the time interval (seconds) between consecutive touchdowns (left-right or right-left) based on an automatic timestamp. The frequency of the stride is obtained by the formula $1/\text{average step time per stride}$ or the number of strides divided by the total interval time, while the travel time and speed per 10-meter interval are calculated using the stopwatch tool with the formula $\text{speed} = \text{distance}/\text{time}$. Data were extracted for each individual stride (57 stride total) and summarized per 10-meter segment for performance pattern analysis. The accuracy of the measurement is improved through repetition at least twice per variable with the taking of mean values, thereby minimizing observation errors and providing reliable descriptive data for the evaluation of HTY running techniques.

Data analysis

The data is processed using descriptive statistics to produce relevant central tendency and dispersion measures, including means, minimum values, as well as maximum values of stride length and step time. In addition, the total steps (57 steps) were calculated, along with analysis of performance change patterns through graphical visualization that showed the relationship of distance travelled to step time, stride length, and speed per interval.

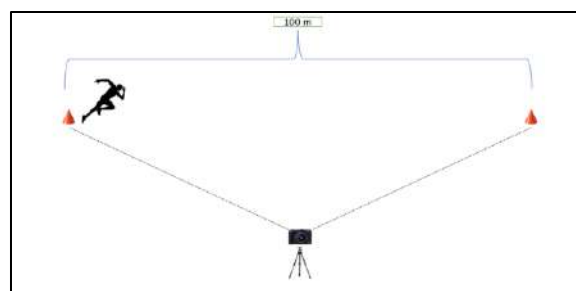


Figure 1. Running motion video capture mechanism.

No inferential test was carried out considering that the single-subject research design is quantitative descriptive. Validation of results is carried out by qualitatively comparing findings against the established biomechanical literature of sprint running, thus ensuring that the interpretation of the data is in line with applicable scientific principles.

RESULTS

The results of the study were obtained from taking videos directly and then video analysis was carried out using Kinovea software. The following are the results of the movement analysis of HTY athletes.

Table 1. Based on the results of the analysis of stride frequency, stride length, and stride time in HTY athletes.

Motion analysis						
Interval (meter)	Stride frequency	Stride length (cm)	Step time (seconds)	Travel time (seconds)	Speed (m/s)	Time records
0-10	1	100	0.32	2.16	4.62	13.24
	2	65.14	0.24			
	3	112.12	0.24			
	4	97.27	0.24			
	5	129.08	0.2			
	6	128.25	0.24			
	7	132.46	0.2			
	8	147.65	0.24			
	9	161.26	0.24			
10-20	10	153.77	0.2	1.08	9.25	
	11	176.84	0.24			
	12	178.93	0.2			
	13	180.53	0.24			
	14	183.25	0.2			
20-30	15	188.72	0.24	1.36	7.35	
	16	184.81	0.2			
	17	199.22	0.24			
	18	189.87	0.24			
	19	194.34	0.24			
	20	187.08	0.2			
30-40	21	195.78	0.24	1.16	8.62	
	22	198.87	0.24			
	23	200.21	0.24			
	24	200.3	0.2			
	25	189.56	0.24			
40-50	26	198.84	0.24	1.36	7.35	
	27	202.08	0.24			
	28	192.52	0.2			
	29	195.04	0.24			
	30	184.74	0.24			
	31	182.92	0.2			
50-60	32	178.37	0.2	1.12	8.92	
	33	175.87	0.24			
	34	172.12	0.24			
	35	173.93	0.24			
	36	173.25	0.2			

60-70	37	189.01	0.28	1.2	8.33
	38	173.17	0.2		
	39	179.25	0.28		
	40	169.22	0.2		
	41	188.98	0.24		
70-80	42	185.03	0.24	1.48	6.75
	43	187.17	0.28		
	44	179.03	0.24		
	45	185.68	0.24		
	46	177.07	0.24		
80-90	47	183.06	0.24	1.24	8.06
	48	183.06	0.24		
	49	188.61	0.28		
	50	166.6	0.2		
	51	183.86	0.28		
90-100	52	169.7	0.24	1.24	8.06
	53	175.49	0.24		
	54	169.5	0.24		
	55	170.12	0.28		
	56	170.9	0.24		
	57	172.89	0.24		

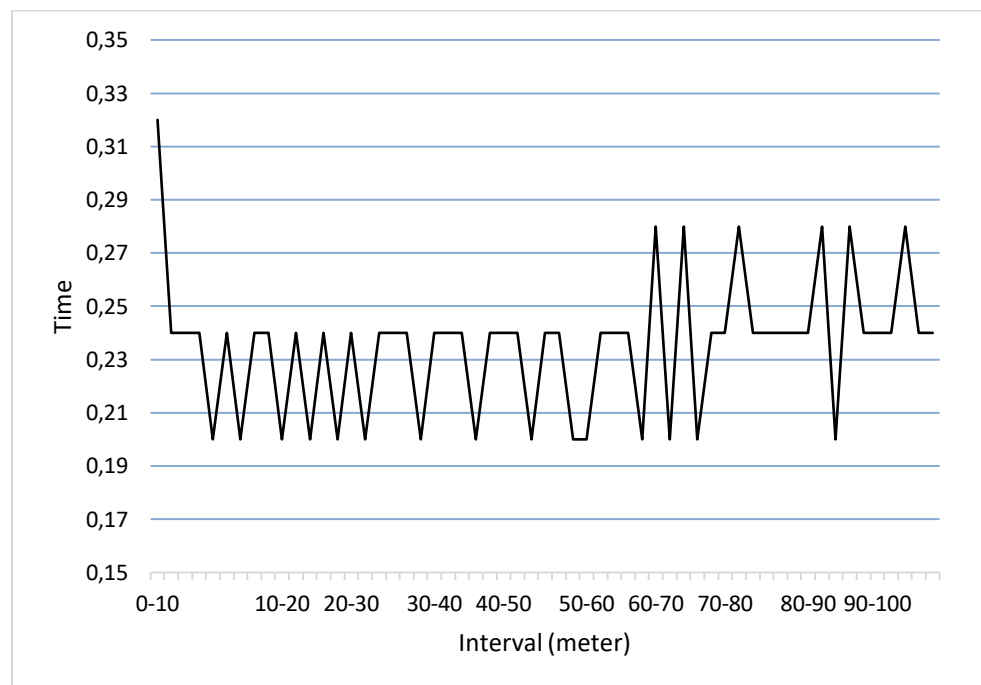


Figure 2. Distance movement against HTY athlete's step time.

In Figure 2, it is shown that HTY runners get a number of 57 steps and the time per step at meters 0-10 decreases in step time, then at 10-70 meters the step time is stable. At 70 – 100 there is a steady increase in step time.

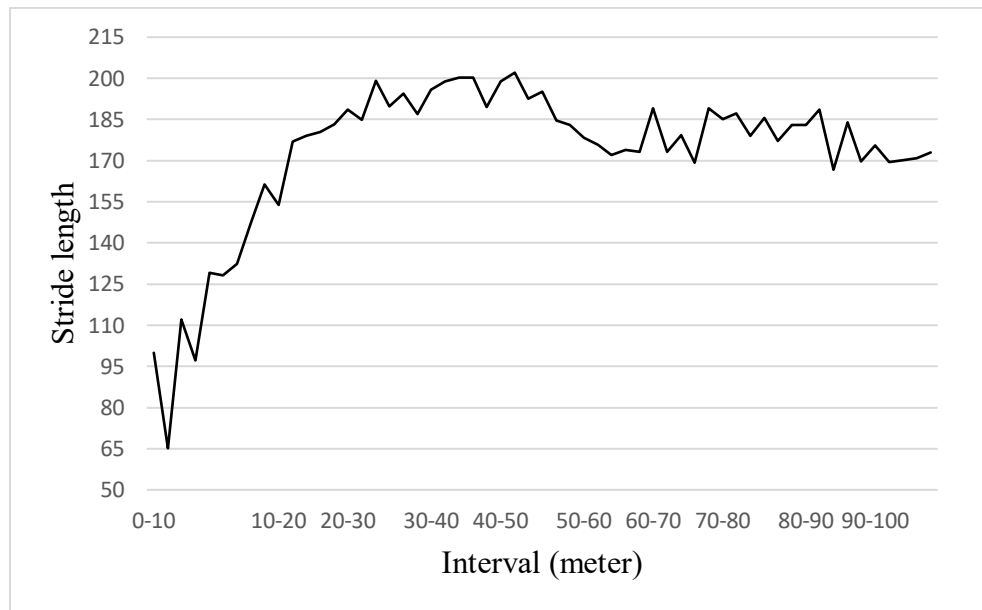


Figure 3. Distance movement graph against stride length of HTY athletes.

In Figure 3, it is shown that HTY runners get a number of 57 steps and the stride length per step at 0-3 meters decreases in stride length, then at 4-50 meters the stride length increases steadily. At 50 – 100 there is an irregular change in stride length.

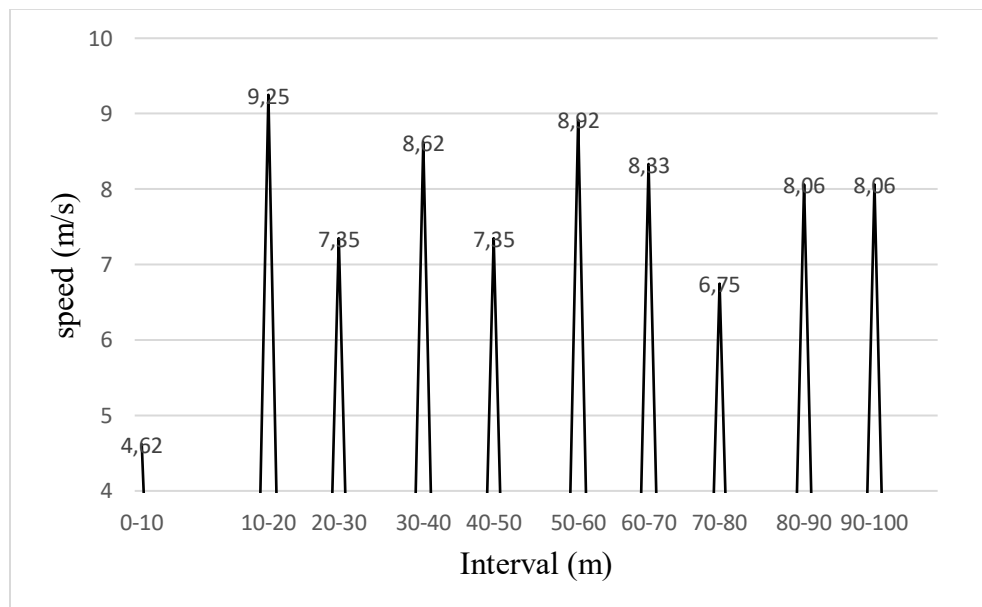


Figure 4. Speed per 10 meters.

In Figure 4, it is the speed per 100 meters. At 0-10 meters it gets a speed of 4.62 m/s, then it increases at 10-20 meters with an increase in speed of 9.25 m/s, at the 20-30 meters it decreases at 7.35 m/s, at the 30-40 meters it increases the speed at 8.62 m/s, at the 40-50 meters it decreases again at 7.35 m/s, at the 50-60 meters it increases the speed at 8.29 m/s, at the 60th-70th meter there was a decrease in speed at 8.33

m/s, the decrease in speed again at 70-80 meters at 6.75 m/s, then at the 80-90th meter it increased at 8.06 m/s and stabilized until the 100th meter.

DISCUSSION

Based on the results of the research that has been obtained, HTY athletes have performed a 100-meter running movement with a record time of 13.24 seconds with a total of 57 steps, average stride length or stride length of 172.8489 cm, minimum stride length or stride length 65.14 cm, maximum stride length or stride length 202.08 cm, average stride time 0.2351 seconds, minimum stride time 0.20 seconds, maximum stride time 0.32 sec. At a speed per 10 meters that experienced an unstable decline and increase. The top speed is located at 10-20 meters. With these results, based on the results of the movement analysis obtained, namely side length and stride frequency have a great influence on the speed and time record obtained by the runner. The results of this study are in line with the theory from (Al Ardha et al., 2022) in their research, namely the analysis of running kinematics in the world's female sprinters at the 2022 Tokyo Olympics that stride frequency can determine the time record of runners. Stride frequency and stride frequency are closely related to stride length. Supported by the theory from (Sugiura et al., 2021) that the sprinters to press the foot to the ground as quickly as possible to increase the frequency of the step and prevent too long steps. Supported by the theory of (de Ruiter et al., 2014) trained runners choose a near-optimal step frequency for energy expenditure and heart rate can be used to set the optimal step frequency. Research from (Paruzeldyja et al., 2006) revealed that stride frequency determines the results achieved by elite female sprinters, while stride length is the most important step parameter for sprinters and the greater the mass and height, the more stride length is taken and the lower the stride frequency of the runner. In the research (Batra et al., 2021) stated that the ability to produce energy quickly has the potential to directly affect sprint performance through changes in stride length and stride frequency. So it can be said that the lower the more steps and the shorter the steps, the better.

The right foot and left foot are not balanced with evidence that the stride time of HTY athletes on the right foot takes a long time when compared to the left foot. So that the strongest leg of HTY athletes is the right foot. This is in line with research from (Sudhakar et al., 2018) Short-distance runners should have a balance between the right foot and the left foot to support performance when running. It is also supported by research from (Wessbecher & Ahn, 2019) that runners who have balanced legs will support movement when running. Supported again by (Karamanidis & Arampatzis, 2007) that the best time of a runner is supported by a balanced right foot and left foot. So HTY athletes need to add strength training on the right leg so that the balance of the right and left legs is good.

In anthropometry, HTY athletes have a height of 154 cm, and a body weight of 52.7 kg. so that the results of the time records obtained by HTY athletes are influenced by their anthropometry. This is supported by research from (Maćkała & Mero, 2013) researching the world's best athlete, Usain Bolt at the 2008 Beijing Olympics with anthropometric results from Usain Bolt being 196 cm tall and weighing 90 kg resulting in a time of 9.69 seconds. The time record supports the running performance of the Usain Bolt with his best time. With the height of the high Usain Bolt will support the range of stride frequency and the number of stride lengths. So anthropometry will greatly affect the time record when running.

CONCLUSSION

The anthropometry possessed by HTY athletes cannot be a problem that needs to be fixed because the age of HTY athletes is not in the growth period. So that the time record that is felt to be less than HTY athletes

that needs to be emphasized is technique when running. This is because the stride length and stride frequency of HTY athletes which totalled 57 steps and the average stride length was 172.84 cm. There needs to be a good combination of stride length and stride frequency to get the best time record. This ability needs to be combined with longer strides, allowing him to achieve very high running speeds. Therefore, it is worth noting that the main focus should be on the optimal interaction between stride frequency and stride length. This data can be important for practitioners to identify possible weaknesses and refine training methods for sprinters and other athletes whose performance depends on movement speed initiation. HTY athletes can use the results of movement analysis in this study to improve their performance.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Mochamad Ridwan contributed to conceptualisation, investigation, writing original draft, writing review & editing, and supervision. Ainun Zulfikar Rizki contributed to conceptualisation, formal analysis, and writing original draft. Vega Candra Dinata contributed to methodology, investigation, and writing review & editing. Novadri Ayubi contributed to methodology, data curation, and writing review & editing. Shoiri Kubaeva contributed to formal analysis, data curation, writing review & editing, and supervision. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Mechanical differences in take-off strategies between long jumpers achieving similar distances with different approach velocities

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ABSTRACT

This study presented a detailed biomechanical examination of take-off strategies in two long jumpers who achieved comparable jump distances despite different approach velocities. Two subjects achieving similar distances (approx. 7.70 m) but with different approach velocities (Subject A: 10.21 m/s; Subject B: 9.84 m/s) were compared to elucidate the mechanical differences in their take-off strategies. Subject A, with higher approach velocity, exhibited a larger backward take-off leg angle at touchdown and greater horizontal energy (E_{horiz}) loss in the take-off leg compared to Subject B. Energy analysis revealed that Subject A generated 68% of total effective vertical energy (E_{vert}) generated in the takeoff leg through the direct conversion of E_{horiz} (pivoting mechanism). Conversely, Subject B generated only 50% of E_{vert} via the pivoting mechanism, compensating for the velocity deficit by increasing the contribution of joint work (50%) to the takeoff leg's E_{vert} generation. These results illustrated differing contribution ratios between pivoting mechanism and joint work based on kinematic inputs. In conclusion, this study provided a concrete example showing that distinct mechanical strategies—one relying on velocity conversion and the other on joint work—can successfully lead to equivalent performance outcomes for long jumps.

Keywords: Biomechanics, Pivoting mechanism, Joint work, Energy conversion, Kinetics.

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INTRODUCTION

Long jump is a competitive event in which athletes strive to maximize the horizontal distance by performing a single-leg take-off utilizing the velocity generated during the approach run. Given this characteristic, the take-off phase can be conceptualized as a transducer that converts the kinematic input (approach velocity) into performance output (jump distance).

Muraki et al. (2008) showed in a cross-sectional study that the horizontal velocity (and not vertical velocity) of the centre of mass (CoM) at take-off is the primary determinant of jump distance. Combined with an established significant positive correlation between approach velocity and jump distance (Hay, 1993; Hay et al., 1986; Hay & Miller, 1985; Lees et al., 1994), it can be said that the majority of jump distances are largely dictated by the approach velocity. However, Koyama et al. (2011) showed that similar jump distances could be achieved even when there was a difference of approximately 1 m/s in the approach velocity. Shimizu et al. (2018) conducted a cluster analysis on 29 elite long jumpers and classified them into four types based on the magnitude of approach velocity and take-off angle, indicating that equivalent performance outputs can be attained through different take-off strategies despite variations in approach velocity inputs. This is thought to be caused by differences in strategies during the take-off phase acting as a transducer from approach velocity to jump distance indicating that the choice of take-off strategy in addition to the magnitude of approach velocity, significantly influences the final performance output. Because variability in take-off strategies affects performance, Ramos et al. (2019) highlighted the necessity of selecting an appropriate take-off strategy taking into consideration the possibility of achieving equivalent jump distances with different approach velocity inputs. However, no studies have specifically illustrated the differences in take-off strategies between athletes who achieve similar jump distances using different approach velocity inputs.

Assuming that the long jump is a projectile motion of the body, the determinants of jump distance are CoM height, CoM horizontal velocity, and vertical velocity at the time of take-off (Ward-Smith, 1985). Since CoM height is largely determined by stature, CoM horizontal velocity, and vertical velocity at take-off dictates majority of the jump distance. In addition, the approach velocity which served as input, was also considered. For example, if two athletes achieve similar jump distances with different approach velocity inputs, they are considered to achieve similar jump distances through different take-off strategies. This difference in take-off strategy can be explained by differences in the vertical velocity generation mechanisms. Specifically, we propose that differences in contribution ratio between vertical velocity generation mechanisms that depend on horizontal velocity reduction and do not depend on horizontal velocity reduction determine the differences in take-off strategies.

In terms of the differences in the contribution ratios of the aforementioned vertical velocity generation mechanisms, Sado et al. (2020) demonstrated its quantifiability from mechanical energy perspective, which is a component of velocity. Sado et al. (2020) examined effective energy generation mechanism for vertical height (E_{vert}) during takeoff for running jumps aimed at height. They showed that of the total E_{vert} , the component due to conversion from horizontal energy (E_{horiz}) derived from approach velocity accounts for approximately 35%, and the component derived from joint work of the take-off leg accounts for approximately 40%. The generation of E_{vert} through conversion of E_{horiz} is known as the "*pivoting mechanism*" that converts approach velocity to the vertical direction (Lees et al., 1994), and the magnitude of vertical velocity generated by this mechanism depends on the magnitude of horizontal velocity reduction during take-off (Ramos et al., 2019). In contrast, the component derived from the joint work of the take-off leg can generate E_{vert} without accompanying a reduction in E_{horiz} . If two athletes achieving similar jump distances with different approach velocities are observed, it is predicted that in their E_{vert} generation, the athlete with the

lower approach velocity suppresses the reduction of E_{horiz} by increasing the contribution ratio of the component derived from joint work compared to the athlete with the higher approach velocity.

Based on the above, it is predicted that athletes who achieve similar jump distances with different approach velocity inputs in long jump select different strategies for the amount of change in E_{vert} and E_{horiz} during takeoff, and for contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work to the total E_{vert} generated by the take-off leg. Specifically, we hypothesized that: 1) in athletes with higher approach velocity, majority of total E_{vert} generated by the take-off leg is achieved by a pivoting mechanism accompanied by a large reduction in E_{horiz} ; and 2) in athletes with lower approach velocity, the reduction in E_{horiz} is small, and the deficit in approach velocity input is compensated by E_{vert} generation through the component derived from joint work of the takeoff leg. However, detailed mechanisms of takeoff strategy in two individuals achieving similar jump distances with different approach velocity inputs have not yet been elucidated.

In this study, using longitudinal measurements, we identified two athletes who achieved similar jump distances despite different approach velocities. Therefore, this study aimed to provide a detailed mechanistic examination of take-off strategies in these two athletes to illustrate how distinct mechanical solutions can lead to equivalent long jump performance outcomes.

MATERIAL AND METHODS

A total of 16 male collegiate long jumpers participated in the study. (Age: 20 ± 2 yrs; Height: 1.75 ± 0.05 m). The participants' personal best records were 7.33 ± 0.30 m (6.88 m – 7.85 m). The estimated jumping distance recorded in this experiment was $6.96 \text{ m} \pm 0.54 \text{ m}$ (5.72 m – 7.75 m) (Figure 1). Among the trials performed, two subjects who achieved the highest jump distances (Subject A: 22 yrs; 1.74 m; 67.6 kg; PB: 7.69 m, Subject B: 20 yrs; 1.68 m; 65.5 kg; PB: 7.59 m) attained comparable performance, and these were selected as the trials for analysis. The two selected subjects were national collegiate-level long jumpers.

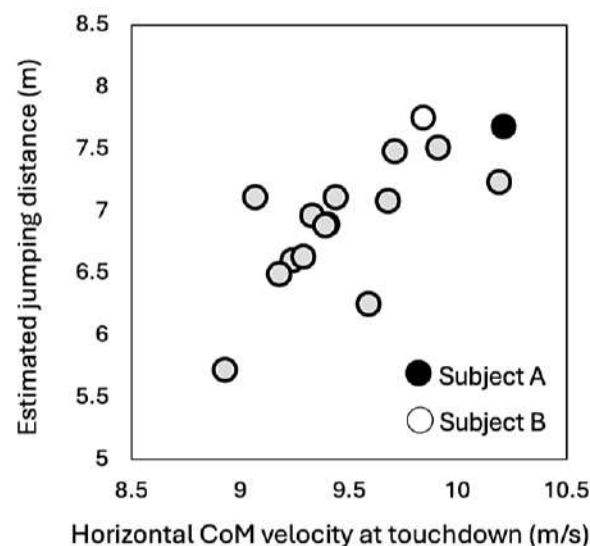


Figure 1. Scatter plot illustrating the relationship between Horizontal CoM velocity at touchdown and estimated jump distance. The two trials selected for detailed analysis (Subject A and Subject B) are highlighted.

For the analysed trials, Subject A had a horizontal CoM velocity at touchdown of 10.21 m/s and an estimated jump distance of 7.75 m, and Subject B had a horizontal CoM velocity at touchdown of 9.84 m/s and an estimated jump distance of 7.68 m. The estimated jumping distance was calculated by utilizing the take-off velocity, take-off height, and take-off angle of the centre of mass (CoM). The reasoning behind this method was to exclude the effects of technical variables occurring after take-off, for instance, landing efficiency (Hubbard, 2000; Linthorne et al., 2005; Mestre, 1990). The estimation formula is as follows:

$$\text{Estimated Jumping distance} = \frac{V \cos\theta}{g} (V \sin\theta + \sqrt{(V \sin\theta)^2 + 2gh})$$

V : Resulting CoM velocity at take-off (m/s), θ : Take-off angle (deg), h : CoM height at take-off (m); g : 9.81 m/s²

Prior to their participation in the study, all subjects were provided an explanation of the purpose and experimental protocol, and all subjects provided written informed consent. The Human Research Ethics Committee of the University of Tsukuba, Japan approved the study protocol (reference number: PE 025-39).

Measurements were conducted five times between September 2021 and July 2025, and 4 of the 16 athletes participated in multiple measurements. The subjects prepared for the experiment as they would for competition and performed from three to four jumps on a force platform (0.9 × 0.6 m, Kistler, Switzerland) covered with an artificial surface, landing in a sand pit. The take-off motions of the subjects were videotaped using a high-speed camera operating at 240 Hz (LUMIX DC-GH5S, Panasonic) for two-dimensional motion analysis. The camera was placed 20 m away from the right side of the runway. The y and z axes of the global coordinate system (GCS) define the anteroposterior and superinferior directions, respectively. The ground reaction force during the take-off phase was sampled using a force platform at 1000 Hz. The forward and backward components of the force platform (F_y) were set parallel to the runway. An LED synchronizer was used to synchronize the video tape data with the ground reaction force data. We defined take-off phase as the instant of foot contact to the instant of toe-off. These instants were determined using vertical ground reaction force data at a threshold of 10 N.

Jumps were analysed in which the participants fully planted their take-off foot on the force platform. For analysis, the trial exhibiting the longest jump distance was chosen from the valid jumps for every participant. The two dimensional coordinates for 23 anatomical landmarks (including the hands, wrists, elbows, shoulders, toes, first metatarsals, heels, ankles, greater trochanters, head, ears, and suprasternale) were acquired by digitizing every video frame using the Frame-DIAS system (DKH Co., Japan), spanning from 10 frames prior to touchdown until 10 frames following toe-off.

Kinematic and kinetic data analyses were conducted using MATLAB 2025b (MathWorks, Inc., Natick, MA, USA). Digitized coordinates were converted to real coordinates using reference markers placed on both sides of the approach lane and the take-off area. The coordinate data were smoothed using a second-order Butterworth digital filter with a cutoff frequency of 10 Hz, and the velocity of the athlete's CoM was calculated via direct differentiation of the coordinate data. The choice of the cutoff frequency was based on residual analysis and visual inspection of power spectra of the coordinate and velocity data (Winter, 1990). Ground reaction force data were smoothed using the same Butterworth low-pass digital filter to prevent artifacts immediately after contact (Bezodis et al., 2013; Bisseling & Hof, 2006).

To calculate linear and angular kinematics, a link model consisting of 14 segments (including hands, forearms, upper arms, feet, shanks, thighs, head, and trunk) was employed. This model was also used with ground reaction force data to estimate the joint torque and power of the take-off leg joints. The take-off leg posterior angle at take-off, projected in the sagittal plane, was determined at the instant of touchdown and was defined as the angle of the segment connecting the ankle joint centre to the hip joint centre (greater trochanter) relative to the vertical axis. An increase in the joint angle in this study indicated that the joint rotated counterclockwise. Similarly, a counterclockwise rotation was defined as a positive segment angle (Figure 1). The mass, location of the CoM, and moment of inertia of the body segments were estimated from the body segment parameters of Japanese athletes developed by Ae (1996).

Velocity of the whole-body CoM was determined as the time derivative of its position. Take-off speed and angle were calculated as the vector norm of the CoM velocity and the arctangent of the vertical versus horizontal CoM velocity components at toe-off, respectively. The posterior angle of the take-off leg was defined and calculated as the inclination of the segment linking the ankle joint to the greater trochanter. The segment angular velocities were calculated as time derivatives of the Segment Angles. The joint torque was calculated using inverse dynamics. The increase in joint torque in this study indicated that the joint rotated counterclockwise. The segment torque power, defined as the rate of energy transfer (inflow or outflow) via joint torque, was determined as the scalar product of segment angular velocities and joint torques (Muraki et al., 2008).

E_{vert} and E_{horiz} in the takeoff leg segments were calculated using the methods described by Sado et al. (2020; 2023). E_{vert} and E_{horiz} are the effective vertical and horizontal energy, respectively, generated by the rotation of the segments. Theoretically, the total E_{vert} and E_{horiz} gained by all body segments should be equivalent to the change in E_{vert} and E_{horiz} of CoM. Mechanically, the changes in E_{vert} and E_{horiz} are consistent with vertical and horizontal external work (time integration of the vertical and horizontal external powers (P_{vert} and P_{horiz})). P_{vert} and P_{horiz} in the takeoff leg segments are the products of the vertical/horizontal ground-reaction forces (F_{vert} and F_{horiz}) and vertical/horizontal velocity generated by the rotation of the takeoff leg segments ($\dot{Z}_{segment}$ and $\dot{Y}_{segment}$). The velocity generated by the rotation of a take-off leg segment ($\dot{Z}_{segment}$ and $\dot{Y}_{segment}$) is the value obtained by subtracting the velocity of the joint center at the segment's distal end from the velocity of the segment's CoM. The power calculation method for the three segments of the take-off leg is defined as follows:

$$\begin{aligned}P_{vert\ foot} &= F_{vert} \cdot \dot{Z}_{foot} \\P_{horiz\ foot} &= F_{horiz} \cdot \dot{Y}_{foot} \\P_{vert\ Shank} &= F_{vert} \cdot \dot{Z}_{Shank} \\P_{horiz\ Shank} &= F_{horiz} \cdot \dot{Y}_{Shank} \\P_{vert\ Thigh} &= F_{vert} \cdot \dot{Z}_{Thigh} \\P_{horiz\ Thigh} &= F_{horiz} \cdot \dot{Y}_{Thigh}\end{aligned}$$

The magnitude of total E_{vert} component gained in the take-off leg via conversion from E_{horiz} was calculated by subtracting the energy inflow to each segment via joint work from the E_{vert} gained in each segment of the take-off leg. If the energy inflow to a segment was negative, we established that the entirety of the E_{vert} gained by that segment was acquired through conversion from E_{horiz} . Furthermore, if the energy

inflow to a segment was greater than that gained by that segment, we established that the entire E_{vert} gained by that segment was acquired through the energy inflow to each segment via joint work (Sado et al., 2020).

RESULTS

In both subjects, the foot, shank, and thigh segments were rotated forward throughout the take-off phase (Figure 2). The posterior angle of the take-off leg at touchdown was 35.5° for Subject A 28.2° for Subject B.

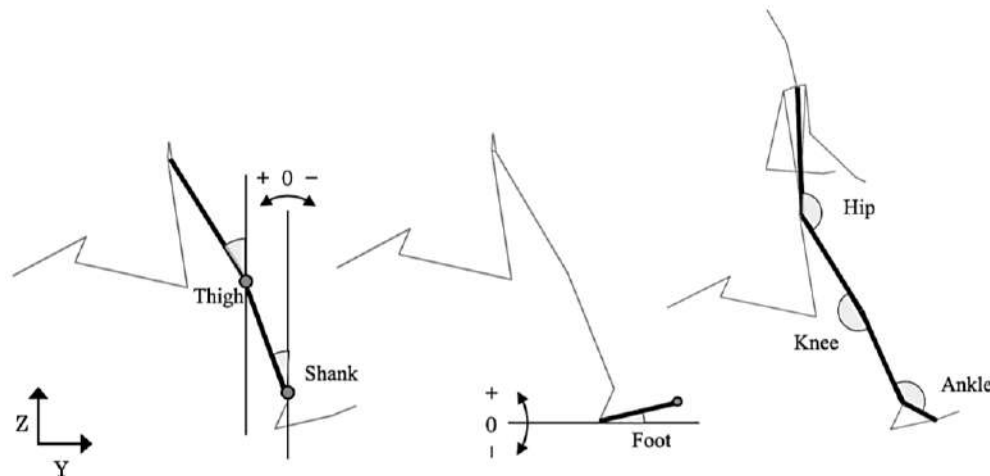


Figure 2. Definition of the segment angle and link model used in this study. Counter-clockwise rotation was defined as positive for segment angles.

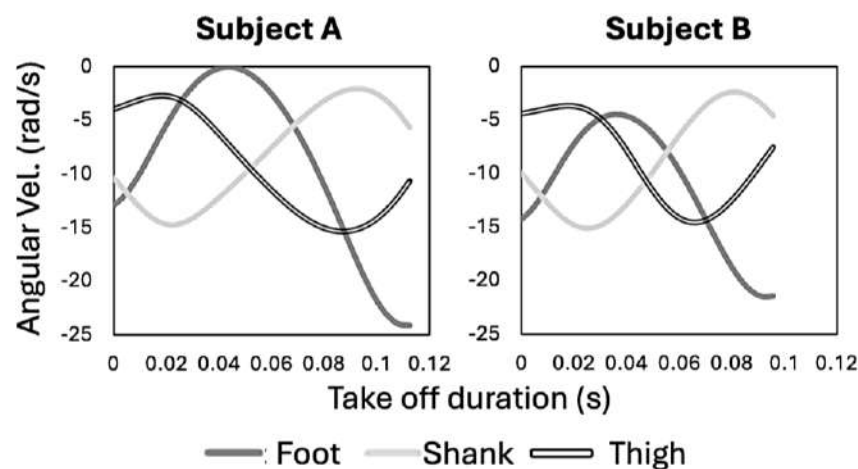


Figure 3. Time courses of the segment angular velocity for the foot, shank, and thigh during the take-off phase for Subject A and Subject B.

Differences were observed between the two subjects in the amount of change in E_{vert} and E_{horiz} generated by the take-off leg during take-off. The total E_{vert} by the entire take-off leg was 3.6 J/kg for Subject A and 3.2 J/kg for Subject B (Figure 4). The total E_{horiz} lost by the entire take-off leg was 5.8 J/kg for Subject A and 4.8 J/kg for Subject B (Figure 5).

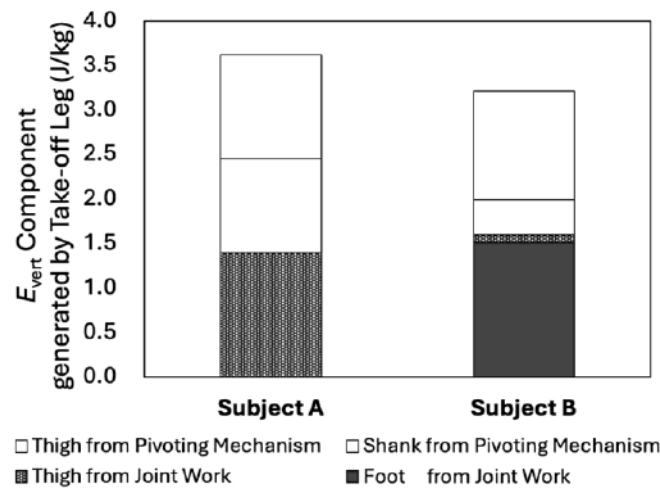


Figure 4. Comparison of effective vertical energy (E_{vert}) generation for Subject A and Subject B. The graph illustrates specific contributions of combined segments and E_{vert} generation mechanisms.

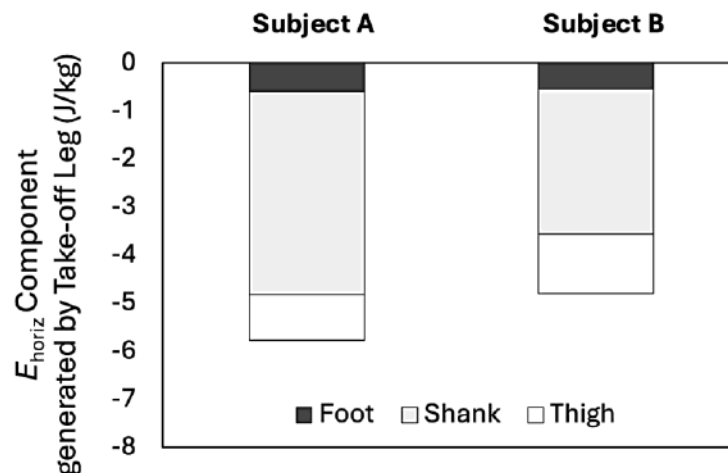


Figure 5. Comparison of the total horizontal energy (E_{horiz}) lost by the takeoff leg during the takeoff phase for Subject A and Subject B.

Furthermore, differences were observed between the two subjects in the contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work to the total E_{vert} generated by the take-off leg (Figure 4). Subject A generated 2.3 J/kg of E_{vert} through direct conversion from E_{horiz} and 1.4 J/kg through the component derived from joint work, generating approximately 68% of the total E_{vert} generated by the take-off leg through direct conversion from E_{horiz} . On the other hand, Subject B generated 1.6 J/kg of E_{vert} through direct conversion from E_{horiz} and 1.6 J/kg through the component derived from joint work, with the contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work being 50% each. Additionally, Subject A showed a pattern of generating large E_{vert} through the component due to direct conversion from E_{horiz} in the first half of the take-off and through the component derived from joint work in the middle of the take-off, whereas Subject B showed a pattern of generating large E_{vert} through the component derived from joint work in the middle of the take-off and through the component due to direct conversion from E_{horiz} in the latter half of the take-off (Figure 6).

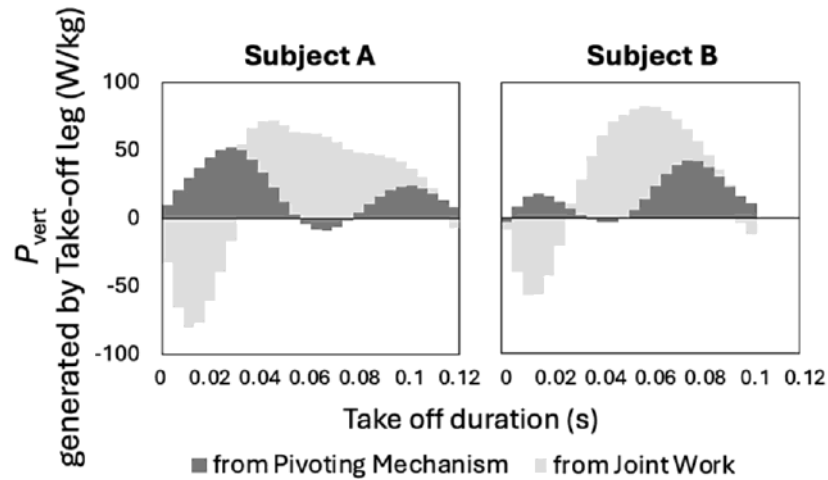


Figure 6. Contribution patterns of the component via the pivoting mechanism and joint work to effective vertical energy (E_{vert}) generation during the takeoff phase. Subject A utilized the component via the pivoting mechanism primarily in the first half, whereas Subject B relied more on joint work in the middle phase.

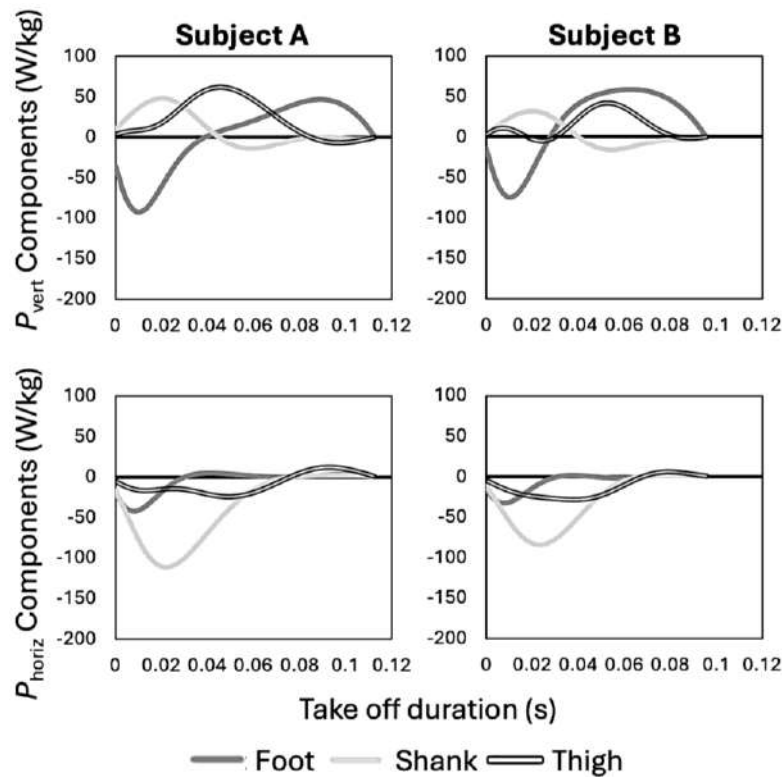


Figure 7. Time series of vertical (P_{vert} , Upper Panel) and horizontal (P_{horiz} , Lower Panel) external powers for the foot, shank, and thigh segments during the takeoff phase.

E_{vert} in the take-off leg of Subject A was the largest in the thigh (2.6 J/kg), followed by the shank (1.0 J/kg). The foot did not gain E_{vert} . In Subject B, E_{vert} was largest in the foot (1.5 J/kg), followed by the thigh (1.3 J/kg) and shank (0.4 J/kg) (Figure 4). For Subject A, P_{vert} was obtained in the order of the shank, thigh, and foot. In Subject B, the foot and thigh simultaneously gained P_{vert} after the shank (Figure 7, Upper Panel).

The E_{horiz} lost in the takeoff leg of both subjects was greatest in the order of the shank, thigh, and foot. This value approximately matched differences in the total E_{horiz} lost by the entire takeoff leg (1.0 J/kg). The acquisition pattern of P_{horiz} showed an approximately similar pattern in both subjects (Figure 7, Lower Panel).

The power flowing into the segments derived from the joint torque exhibited a similar pattern for both the shank and thigh. For the foot, Subject A showed a positive power exertion pattern from the middle to the latter half of the take-off phase, whereas Subject B showed a positive power exertion pattern throughout the entire take-off phase (Figure 8).

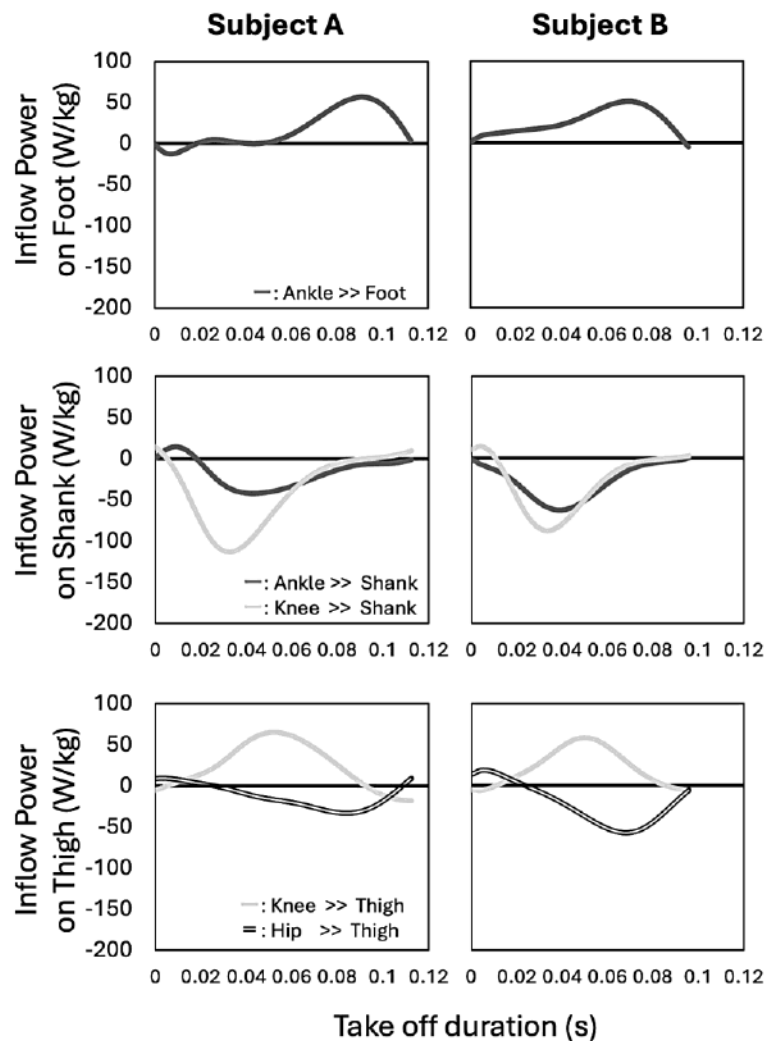


Figure 8. Time series of segment torque power for the foot, shank, and thigh segments. Positive values indicate energy generation (energy outflow), and negative values indicate energy absorption (energy inflow).

DISCUSSION

In this study, we conducted a detailed mechanistic analysis of the take-off strategies in two athletes who achieved similar jump distances despite different approach velocities, focusing on the differences observed during the take-off phase.

The results confirmed that the magnitude of E_{horiz} lost in the take-off leg during take-off differed between the two athletes, and that the contribution ratios of the component due to a pivoting mechanism and the component derived from joint work to the total E_{vert} generated by the take-off leg differed. Based on the above, the hypotheses of this study that 1) in the athlete with higher approach velocity, the majority of the total E_{vert} generated by the take-off leg is achieved by the pivoting mechanism accompanied by a large decrease in E_{horiz} in the take-off leg, and 2) in the athlete with lower approach velocity, the decrease in E_{horiz} in the take-off leg is small, and the deficit in approach velocity input is compensated by E_{vert} generation through the component derived from joint work of the take-off leg, were supported by the observations in these two athletes. This study also illustrated the mechanical differences in the take-off strategies of the two athletes.

This study is the first one to mechanically illustrate the differences in take-off strategies where similar jump distances were achieved with different approach velocity inputs, and targeted trials with a higher performance level compared to other kinetic studies (6.96 ± 0.49 m; 6.95 ± 0.15 m) (Luhtanen & Komi, 1979; Muraki et al., 2008). Although full-approach long jump trials were recorded by 16 athletes in this study, this was the only example where similar jump distances with different approach velocity inputs were observed at a high performance level. Thus, although the trials analysed were limited to two subjects, this study is significant as it presented concrete examples of achieving similar jump distances with different approach velocity inputs in long jumpers with high performance levels and clarified the detailed mechanical mechanisms.

The present analysis was based on two individual cases and was not intended to provide statistically generalizable conclusions. Rather, the findings should be interpreted as a mechanistic illustration of how distinct take-off strategies can lead to equivalent performance outcomes despite the differences in approach velocity conditions.

This study confirmed that the magnitude of E_{horiz} lost in the take-off leg during take-off differed between the two athletes. Subject A, with a higher approach velocity, had the take-off leg tilted backward by 8.5° more at touchdown than Subject B, who had a lower approach velocity. In addition, Subject A had a 1.0 J/kg larger decrease in E_{horiz} in the takeoff leg than Subject B (Figure 5). Furthermore, the magnitude of the total E_{vert} generated by the entire take-off leg was 0.4 J/kg larger in Subject A than in Subject B (Figure 4). These results are consistent with those reported by Ramos et al. (2019), who reported a positive correlation between magnitude of the backward angle of the take-off leg at touchdown and the amount of vertical velocity change during take-off, and between the decrease in horizontal velocity and vertical velocity change during take-off. This confirmed that Subject A, with a higher approach velocity, adopted a strategy of tilting the take-off leg significantly backward at touchdown and generating a large E_{vert} accompanied by large E_{horiz} reduction compared to Subject B.

It was also confirmed that contribution ratios of the component due to the pivoting mechanism and the component derived from joint work to the total E_{vert} generated by the take-off leg differed. In Subject A, with a higher approach velocity, 68% of the total E_{vert} generation by the take-off leg was the component due to direct conversion from E_{horiz} by the pivoting mechanism, and the remaining 32% was the component derived from joint work. In Subject B, with a lower approach velocity, 50% of the total E_{vert} generation by the take-off leg was the component due to direct conversion from E_{horiz} by the pivoting mechanism, and the remaining 50% was the component derived from joint work (Figure 4). Based on the above, it was confirmed that the contribution ratios of the component was attributed to the pivoting mechanism, and the component derived from the joint work to the total E_{vert} generated by the takeoff leg differed.

A factor distinguishing the take-off strategies of the two athletes was the difference in the geometric contribution for each take-off leg segment. Subject A generated all of the total E_{vert} in the take-off leg through the shank and thigh. By contrast, in Subject B, the contribution of the foot was the largest, and the contributions of the shank and thigh were smaller than those in Subject A (Figure 4). This study confirmed that all take-off leg segments rotated forward throughout all phases of take-off (Figure 3). Therefore, "standing segments" such as shanks and thighs can generate E_{vert} through their forward rotation by the pivoting mechanism by landing with a backward tilt. Therefore, it is considered that in Subject A, where the backward tilt of the take-off leg at touchdown was large, the E_{vert} generated by the shank and thigh was large. On the other hand, in Subject B, where the backward tilt of the take-off leg at touchdown was small, there was a limit to E_{vert} generation by the pivoting mechanism of the shank and thigh owing to geometric constraints, and this limit may have been compensated for by E_{vert} generation by the foot. Sado et al. (2020) showed that as an E_{vert} generation mechanism in the foot, an SSC action was observed, with energy absorption in the shank due to ankle joint work in the first half of the take-off and energy generation in the foot due to ankle joint work in the latter half of the take-off. In this study, Subject A showed SSC action similar to that in previous studies, but in Subject B, where E_{vert} generation in the foot was large, energy generation in the foot due to ankle joint work was observed from the first half of the take-off (Figure 8). This indicated the possibility that energy generation by active muscle contraction not relying on the SSC of the ankle plantar flexor muscles in the early phase of take-off achieved a large E_{vert} generation derived from ankle joint work in the foot.

CONCLUSIONS

In conclusion, this study presented concrete examples of the differences in take-off strategies between two athletes who achieved similar jump distances with different approach velocity inputs and provided detailed mechanical mechanisms underlying these strategic differences. The mechanical differences between the two cases are characterized as follows:

- 1) Differences in the amount of E_{horiz} decrease and E_{vert} generation in the take-off leg during take-off was associated with the magnitude of the backward tilt angle at touchdown; and
- 2) Differences in the contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work in E_{vert} generation in the take-off leg associated with geometric constraints.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Conceptualization: T.M. and K.K.; Methodology: T.M. and K.K.; Software: T.M.; Validation: T.M. and S.F.; Formal analysis: T.M.; Investigation: T.M. and S.F.; Resources: K.K.; Data Curation: T.M.; Writing – original draft preparation: T.M.; Writing – review and editing: T.M., S.F., and K.K.; Visualization: T.M.; Supervision: K.K.; Project administration: K.K. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Smartphone overuse: Effect of rehabilitation program on neck ROM, trapezius, and sternocleidomastoids muscle effort in collegiate asymptomatic individuals

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ABSTRACT

Study design: Two-group, pre-test–post-test randomized trial. **Purpose:** the study aims to investigate the adverse effects of overusing smartphones devices on neck range of motion (ROM) and neck muscle activity. In addition, investigating the benefits of performing daily exercise protocol to increase the neck ROM and neck muscle activity for the smartphone's users. **Methods:** Forty-eight collegiate students were recruited to participate in the study. twenty-four healthy students using the smartphone for a maximum of 2 hours daily and 15 h per week [18 Males and 6 females; 20.4 years; 1.71 m; 68.4 kg; 21.7 kg/m²] were randomized to a healthy group. Twenty-four overusing smartphone students [14 Males and 10 females; 21.1 years; 1.70 m; 70.2 kg; 22.8 kg/m²] were considered as an overuse group. After comparison, the overuse group was divided randomly to control group and case group. The case group was performed the daily exercise protocol for 8 weeks. EMG for neck muscle and neck range of motion (ROM) measurements were collected at baseline for healthy and overuse groups. Same measurements were collected at baseline, and 8 weeks for both case and control groups. **Results:** overuse group showed a decrease in neck flexion, extension and lateral flexion ROM and UT, MT, LT, and SCM MVIC levels compared to the healthy group. MVIC levels of the muscles increased in the treatment group but did not change in the control group. **Conclusion;** smartphone usage would negatively affect the neck posture. The stretching and strengthening exercises were beneficial to improve the neck muscle strength and range of motion.

Keywords: Sport medicine, Smartphone, Text neck pain, Neck exercises.

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INTRODUCTION

Smartphone has become a ubiquitous portable device used in texting, communication, reading, emailing, and entertainment. Over one-quarter of the world population owns at least one type of smart handheld device. Globally, the number of smart devices is approaching 6.8 billion. Additionally, it was expected that SMS frequency in the world would increase from 5.9 trillion annually in 2011 to reach to 9.4 trillion by 2018. (Kietrys et al., 2015; Lee., 2016). Nonetheless, Google market research reports that American smartphone users communicate with network services, emailing, and text SMS (short message service) more than 20 hours a week and at least two hours daily (Lee et al., 2015). Correspondingly, Canadian college students spent 4.6 hours daily on smartphone hand-held devices (Berolo et al., 2011). In comparison, 91% of the American smartphone users perform instant messaging, SMS, or e-mailing. Further, SMS is considered to be the highest communicative facility among university students in the United States (Skierkowski & Wood, 2012). In 2012, the smartphone was used by 99% of Swiss adults aged 15-24; where 79% used smartphones for text messaging (Gustafsson et al., 2017). Smartphone users frequently adopt a prolonged forward head posture while looking down at the screens of mobile devices. This posture causes fibrosis of muscular fibres and overstretching of muscles around the neck spines, which increases the possibility of neck pain (Gold et al., 2012; Xie et al., 2016; Toh et al., 2017; Cuéllar & Lanman 2017). The exaggeration on using mobile technology led to text neck pain syndrome (TNP). (Lepp, et al., 2013; Gustafsson et al., 2011). Text neck pin (TNP) has illustrated as a static muscular load on the cervical spines results from forward neck flexion without supporting of arms muscles during holding the smartphone. Moreover, handling the device with one hand and typing with only one thumb increases the frequent contraction in typed thumb and handled hand, which causes neck and shoulder pain (Gustafsson et al., 2017; Dvir et al., 2008; Gilchrist et al., 2016; Xie et al., 2018).

All in all, several studies reported the adverse effects of excessive smartphone usage, and its relation to musculoskeletal disorders of the upper limb region. Also, it was adversely affecting the physical and cardiorespiratory fitness (Lepp et al., 2013; Kim et al., 2016; Rezasoltani et al., 2012). The neck musculoskeletal complaints reported for Canadian university students were 84% for neck pain, and 52% for shoulders (Berolo et al., 2011). In comparison, 44.4% of individual Korean university students represented the prevalence of neck pain and 45.2% for shoulder pain (Kim & Kim, 2015). Likewise, demonstrated a prevalence rate of 72.5% for neck and shoulder pain (Balakrishnan et al., 2016). reported complaints of neck pain with 44.1% and 32% for upper back pain (Shan et al., 2013). On the other hand, Damasceno, et al. reported no relation between text neck and neck pain in 18-21-year-old young adults (Damasceno et al., 2018).

The research regarding detriments, neck muscles efforts, and neck range of motion (NROM) of smartphone-usage has been relatively scarce. As an attempt to ameliorate the youth health, the current study aims to investigate the risk factor of excessive smartphone usage for the collegiate student. Therefore, the first hypothesis was the smartphone usage hours would adversely affect the neck range of motion and decrease the neck muscle activity. The second hypothesis of the study was the daily neck exercise protocol would increase the neck range of motion and neck muscle activity for the smartphone's users.

METHODS

Procedure and criteria

The study design was a double-blinded, randomized, controlled trial, parallel group. The study was approved by the local Ethics Committee of Damietta University, Egypt and was performed in accordance with

Declaration of Helsinki ethics standards. The target participants consisted of collegiate smartphone users with TNP for the case group and those who are healthy athletes for the control group. The history of pain data and the daily hours of using the smartphones were collected after the study procedures were explained to the subjects. All participants were volunteers and were provided written informed consent prior to performing the study.

There were specific exception criteria for each group. Nevertheless, both group's participants should be between 18 and 25 years of age and right handed. The exception criteria for the smartphone group were: (a) using the smartphone for at least 6 h a day and a minimum of 40 h per week; (b) continuous texting on the smartphone at least 1-2 hour daily; (c) suffering from a pain in the posterior region of the neck, lasting more than 3 months; (d) have not consumed anti-inflammatory medicines within one month; and (e) have not performed any strength of flexibility exercise for neck, lasting more than 3 months. In addition, the exception criteria for the healthy group were: (a) have no neck pain, neck surgeries or trauma, diabetes, neurological surgeries or diseases, osteoporosis, vascular insufficiency, or cardiovascular; (b) using the smartphone for a maximum of 2 hours daily and 15 h per week; and (c) continuous texting on the smartphone less than an hour daily. (Caputo et al., 2017; Rudolfsson et al., 2012).

Participants

Forty-eight collegiate students were recruited to participate in the study. Thirty collegiate smartphone over users and twenty-seven healthy university students were recruited to participate in the study. The study procedures were explained to all the participants and twenty-four healthy students (18 males and 6 females) agreed to participate. For the smartphone group, the criteria and neck diagnoses excluded six smartphone users. The neck pain diagnosis was based on usage time, history and clinical examination. Four smartphone users were excluded because their neck pain was not more than 3 months, as confirmed by three experienced (i.e., more than five years) physicians through examination of the stiffness in the neck, tightness of muscles, sense of fatigue, region of pain spreading, as well as standard Magnetic resonance imaging MRI in some cases (Larsson et al., 2007). Two additional participants were excluded for anti-inflammatory consumption. Thus, twenty-four smart device users (14 males and 10 females) were arbitrarily assigned to either a treatment group or control group (Table 1). The randomization was carried out by software (Computerized Covariate Adaptive Randomization Program, version 1.0, Middle Tennessee State University, Murfreesboro, TN). The treatment group received daily home-exercise protocol in parallel with the daily texting usage while the control group performed the normal texting day without received exercises.(Kim,2013; Andersen et al., 2010).

Table 1. Baseline characteristics of the study participants (mean $\pm$ standard deviation).

Groups	N	Age (year)	Height (cm)	Mass (kg)	BMI (kg/m ²)	STU (hour)
Healthy	24	20.4 $\pm$ 2.14	171.6 $\pm$ 2.94	68.4 $\pm$ 3.22	21.7 $\pm$ 2.33	1.26 $\pm$ 0.36
Smart phone	TG (12)	20.8 $\pm$ 2.64	169.4 $\pm$ 3.72	71.5 $\pm$ 2.74	22.7 $\pm$ 1.67	6.42 $\pm$ 0.27
	CG (12)	21.3 $\pm$ 0.97	170.4 $\pm$ 1.2	70.7 $\pm$ 0.54	22.9 $\pm$ 0.2	6.31 $\pm$ 0.41

Note. N, number; BMI, body mass index; STU, smartphone time usage; TG, treatment group; CG, control group.

Exercise protocol

The duration of the home-exercise protocol was 8 weeks. The exercise protocol was performed 35-45 minutes daily. The exercise protocol included strength, flexibility, and stretching exercises for neck and shoulder. The neck stretching exercises included neck retraction, head drop, head up from supine, side bend, neck rotation, neck flexion, shoulder blade pull, cat and cow pose, child pose, palm tree, arm back and down the head, and arm opposite stretch. Whereas, the strength exercise included neck extension and flexion,

neck side flexion, lateral neck extension, biceps curls, pullovers, arm hyperextension, arm abduction, arm flys, upright row, and reverse flys. Additionally, red and blue elastic bands (Thera-Band) and dumbbells 2-10 kg were used in the exercise protocol (Gaballah et al., 2017).

To learn how to perform the home-exercise protocol, the treatment participants (7 males and 5 females) were invited to three training sessions by an experienced (i.e., more than three years) rehabilitation specialist. The training sessions included: exercise performing prescription, protocol intensity, repetitions instructions, and practicing rules. In the third training session, all the subjects were asked to perform the exercise protocol. Then they received the protocol on a CD and they were encouraged to practice the daily protocol with the same frequency. (Caputo et al., 2017). Further, phone numbers, email, and other contact information were provided to follow up and support the participant at home. The home-protocol follow up and support processes were conducted once a week by an experienced physiotherapist.

Data collection

Outcomes were measured at baseline before the beginning of the home-exercise protocol. However, only the smartphone group outcomes (treatment and control) were collected in the same manner after the 8wks home-exercise rehabilitation. Study outcomes were muscle electromyographic activities (EMG) of four selected muscles and neck range of motion. The participants performed warm-up for 8-10 minutes after accomplished the measurement sessions. Furthermore, these tests occurred under equivalent temperature conditions (22-25 C) and in the same time in the morning 10.30 am.

The selected muscles during the EMG test session were upper Trapezius (UT), middle trapezius (MT), lower trapezius (LT), and sternocleidomastoid (SCM). Muscle activation evaluation data were collected according to SENIAM standards for electrodes positioning by EMG system (ME6000 telemetric hardware system, Mega Electronics Ltd., FINLAND) (Ghazwan et al., 2017). Participants were asked to perform MVC for each selected muscle on the right side only. To ensure high fidelity of the EMG signals of the selected muscles, the skin at each site was shaved, lightly abraded with sandpaper, and cleaned with rubbing alcohol before electrode placement. The EMG was measured after the subjects stood and flexed, extended and laterally bent the neck. Each test was performed twice, and each effort was held for 5 s with a 30-s rest between repetitions. The EMG signals were sampled at a frequency at 1024 Hz. Then all EMG signals were processed. A notch filter centred at 10 Hz was also used to reduce power-line interference. (Gilchrist et al., 2016).

The neck range of motion (ROM) measurements were flexion (NF), extension (NE), right lateral flexion (NRLF), and left lateral flexion (NLLF). The neck angular measurements were collected according to the goniometer criterion validity of the cervical range of motion. During the ROM measurement, the participants were asked to sit in a chair with their feet on the floor and their head in the natural position. Then the participants performed the maximum painless movement in each neck measurement. (Dvir & Prushansky, 2008; Tousignant et al., 2000).

Statistical analysis

Student t test was used to compare neck ROM, and SCM and trapezius maximum voluntary isometric contraction (MVIC) between the individuals who used smart phone more than six hours and the individuals who used smart phone less than two hours. Repeated measures of ANOVA were performed to determine time by group interactions for each testing parameters. Bonferroni post hoc test was used when significant interaction was observed. Statistical significance level was set at $p < .05$.

RESULTS

Individuals who used smart phone more than 6 hours showed decrease in neck flexion, extension and lateral flexion ROM and UT, MT, LT and SCM MVIC levels compared to the individuals who used smart phone less than 2 Hours ($p < .001$) [Table 1].

Table 1. Group difference in neck ROM and maximum voluntary isometric contraction of the trapezius and SCM muscles.

	Group 1 (n = 24)	Group 2 (n = 24)	Mean difference (95% CI)	p-Value
Flex ROM	59.05 ± 1.77	62.85 ± 1.54	-3.80 (-4.77,-2.83)	<.001
Ext ROM	58.61 ± 1.57	68.49 ± 1.68	-9.97 (-10.82,-8.93)	<.001
R LF ROM	45.22 ± 2.64	48.05 ± 2.10	-2.83 (-4.21,-1.44)	<.001
L LF ROM	44.98 ± 2.52	47.92 ± 1.91	-2.94 (-4.24,-1.64)	<.001
SCM MVIC	18.88 ± 1.81	28.63 ± 1.38	-9.52 (-10.63, -8.41)	<.001
UT MVIC	21.73 ± 1.76	31.25 ± 2.05	-10.24 (-11.31, -9.17)	<.001
MT MVIC	18.98 ± 1.40	29.22 ± 2.19	-10.62 (-12.01, -9.23)	<.001
LT MVIC	22.82 ± 2.04	33.44 ± 2.70	-9.75 (-10.69, -8.82)	<.001

Table 2. differences in neck ROM and MVIC of the trapezius and SCM muscles between case and control groups.

	Time	Case (n = 12)	Control (n = 12)	Mean difference (95% CI)	p-Value
Flex ROM	Pre-test	58.70 ± 1.67	59.40 ± 1.88	-0.70 (-2.20, 0.81)	.34
	Post-Test	58.17 ± 1.67	61.12 ± 1.80	-2.96 (1.49, 4.43)	<.001
Ext ROM	Pre-test	59.17 ± 1.82	58.06 ± 1.07	1.11 (-0.16, 2.37)	.08
	Post-Test	57.03 ± 1.67	66.35 ± 1.62	-9.33 (-10.72,-7.93)	<.001
R LF ROM	Pre-test	45.10 ± 2.31	45.35 ± 3.03	-0.25 (-2.53, 2.03)	.82
	Post-Test	44.23 ± 0.95	47.35 ± 1.20	-3.12 (-4.03, -2.20)	<.001
L LF ROM	Pre-test	44.86 ± 2.16	45.11 ± 2.93	-0.25 (-2.43, 1.93)	.81
	Post-Test	44.00 ± 1.01	47.24 ± 1.31	-3.23 (-4.23, -2.24)	<.001
SCM MVIC	Pre-test	18.95 ± 2.18	18.80 ± 1.44	0.15 (-1.42, 1.71)	.85
	Post-Test	17.92 ± 0.98	26.42 ± 1.16	-8.49 (-9.40, -7.58)	<.001
UT MVIC	Pre-test	21.69 ± 1.91	21.76 ± 1.68	-0.06 (-1.59, 1.46)	.93
	Post-Test	20.43 ± 1.30	30.05 ± 1.33	-9.62 (-10.73, -8.51)	<.001
MT MVIC	Pre-test	18.83 ± 1.62	19.14 ± 1.20	-0.31 (-1.52, 0.90)	.60
	Post-Test	19.71 ± 1.45	27.98 ± 1.30	-8.26 (-9.43, -7.10)	<.001
LT MVIC	Pre-test	23.59 ± 1.78	22.05 ± 2.06	1.53 (-0.10, 3.16)	.06
	Post-Test	23.08 ± 1.49	31.56 ± 1.79	-8.47 (-9.87, -7.08)	<.001

Time by group interactions were significant for neck flexion ($F(1,22) = 4.96, p = .04$), extension ($F(1,22) = 130.17, p < .001$) and right lateral flexion ($F(1,22) = 6.66, p = .02$) and left lateral ROM ($F(1,22) = 6.72, p = .02$). Neck ROMs increased in treatment group after treatment but did not change in control group. There were also significant time by group interactions for SCM ($F(1,22) = 77.64, p < .001$), UT ($F(1,22) = 91.22, p < .001$), MT ($F(1,22) = 112.58, p < .001$) and LT ($F(1,22) = 69.17, p < .001$) MVICs. MVIC levels of the muscles increased treatment group but did not change in control group [Table 2].

DISCUSSION

The principal finding of the present study was the smartphone usage hours adversely affect the neck ROM and neck muscles' MVIC. The increased usage hours of smartphone caused the decrease in neck flexion, extension and lateral flexion range of motion in the collegiate students. In addition, the increased usage hours of the smartphone resulted with the decreased upper trapezius, middle trapezius, lower trapezius and sternocleidomastoid muscles' MVIC levels. The present study also showed that the application of the neck exercises in the collegiate students at risk increased the neck range of motion and MVIC levels of the neck muscles.

In previous studies, the deteriorations of the neck posture were typically observed in the young persons who used smartphones. (Kietrys et al., 2015; Kim & Kim, 2015; Kim, 2013; Guan et al., 2016; Kim, 2015; Park et al., 2017; Ning et al., 2015; Schabrun et al., 2014). It is suggested that the time of smartphone usage, device type and texting style influences cervical posture, but the common consensus is the forward head position of the necks increases as the duration of the smartphone usage increase. (Park et al., 2017), aimed to determine the amount of postural change of the neck when the participations played game with their smartphones and they indicated that forward head posture increased as the duration of smartphone usage increases. Moreover, some studies quantified the neck flexion range of motion during sitting and texting on the smartphone devices (Ning et al., 2015), observed that smartphone users maintained spectacular flexion of 46.4° during using a smartphone while sitting at the table and 45.6° while typing on hand-held mobile devices. Likewise, (Schabrun et al., 2014), observed high forward head measurements during texting and walking. Similarly, (Guan et al., 2016), observed significant increase in head and neck forward posture in mobile phone users. The study identified gender differences in the flexion posture while using the smartphones. The males represented 51.92° of neck flexion, whereas it was 47.09° in females.

The authors showed that as the participants looked at the smartphone, the neck flexion angles increased approximately 14.5° which indicating a considerable amount of head posture. Previous studies specified that a neck angle over 40° was considered as a reference for 'forward head posture'. In our study neck flexion ROM was determined between 59°-62°, indicating that the collegiate students who used smartphone frequently had a forward head posture. These results were corresponding with the previous findings that smartphone usage adversely affects the head and neck posture.

It has been showed that cervical and thoracic erector spinae, upper and lower trapezius muscle activations might change due to the position of the head and neck (Guan et al., 2016; Kim, 2015; Park et al., 2017; Ning et al., 2015; Harms-Ringdahl et al., 1986), specified that there was a high correlation between posture and muscle activity. (Park et al., 2017), found that the EMG activities of cervical erector spinae muscle group increased with a 5 minutes usage of smartphone. The authors also indicated that upper trapezius EMG activity was low as time of smartphone usage progressed. One possible explanation of this decrease in UT could be that the muscle was passively stretched by the flexed posture of the head and neck. In the present study the MVIC of the SCM, UT, MT and LT were determined, and the results showed that each MVICs of the muscles decreased when the smartphone usage time increased. We believe that flexion posture of the neck might provoke the compression and share forces of the cervical spine as the usage of smartphone increased and this mechanical load of the neck muscles resulted with the muscle fatigue. This claim was also supported by the previous studies that showed more than 16 minutes of smartphone use was related with moderate neck pain. Harms-Ringdahl et al., 1986; Kim et al., 2013).

It is well known that there is a rapid increase in the frequency of smartphone usage and that causes various musculoskeletal problems. The greatest factor in neck pain are decreasing the cervical mobility. (Williamson et al.,2015), and dysfunctions of the neuromuscular (Bobos et al.,2016). In addition, the prolonged smartphone use might cause poor proprioception(Kim & Kim,2015; Kim et al.,2013 ; Park et al.,2013) reported that 20 minutes of smartphone use could induce fatigue in neck muscles. Loss of proprioception and muscle fatigue combined with the flexor head posture might result with the neck pain (Lin et al.,2009), reported that 83% of the participants experienced neck and hand pain during texting on a smartphone.

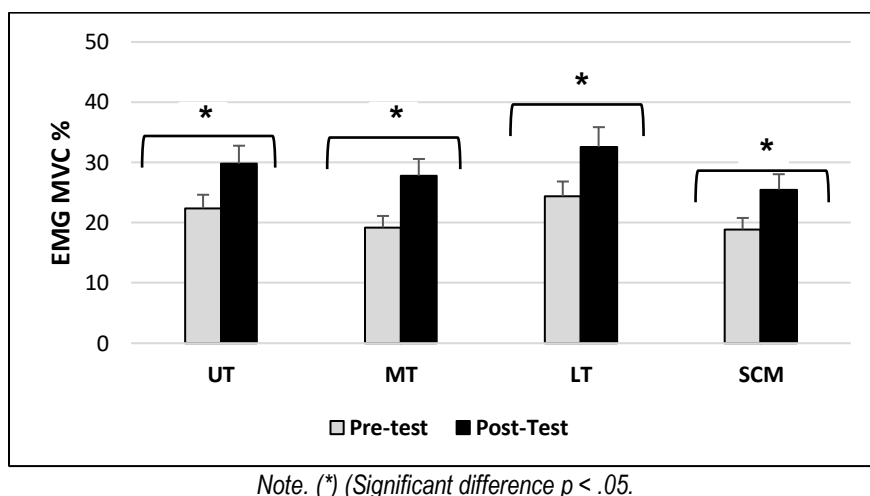


Figure 1. The improvement between the EMG activity in pre-tests and post-tests of neck muscles for the case group.

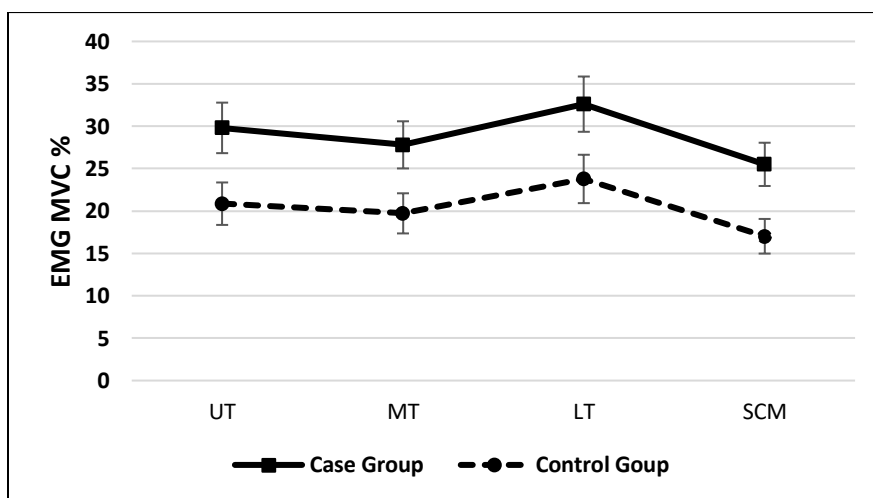


Figure 2. The post-tests difference in EMG activity for the neck muscles between the case group and control group. upper Trapezius (UT), middle trapezius (MT), lower trapezius (LT), and sternocleidomastoid (SCM).

To optimize the pain around neck, researchers are focused on the rehabilitation and exercise programs for the postural changes of the neck and also fatigue around the neck muscles. (Kim et al.,2016), investigated the acute effect of neck exercises on fatigue levels of the muscles. The participants in their study were asked to perform stretching exercises and stabilization exercises before the use of smartphone. The specific cervical

exercises have been noted to increase neck function (Ayhan et al.,2016; Ris et al.,2016), enhancing the neck muscles strength (Lee et al.,2016; Jull et al.,2007), improved the sternocleidomastoid (SCM), splenius capitis (SC) muscle activity and also after 8 weeks' neck pain was decreased(Ludvigsson et al.,2015; Falla et al.,2013).

It has been indicated that both the stretching and strengthening exercises reduced the muscle fatigue in smartphone users (Kim,2013; Kim et al., 2016). Different from (Kim et al., 2016) study, we applied an 8-week exercise program for the smartphone users. The exercise protocol in the present study was included strength exercises, flexibility and stretching exercises for neck and shoulder. Smartphone users in the treatment group performed better neck muscle MVIC when compared to smartphone users in the control group [Figure 2]. Consequently, the EMG activation of UT, MT, LT, and SCM was greatest when flexibility and strength exercises were applied to the neck, for flexion and extension, compared to the control group [Figure 1]. These seems to be agreement with the theories of the exercise effect of neck and shoulder pain(Ayhan et al.,2016; Bobos et al.,2016).

It is documented that stretching exercises increase the inner pressure of the muscles through mild muscle contraction. The rhythmic contraction of the muscles increases blood circulation as well as improves the blood flow (Shin & Park,1997). Neck stabilization exercises had positive effects on the deep neck muscles and increases muscular strength and endurance. In the present study we both apply the stretching and strengthening exercises to improve the muscle performance. We also gave the smartphone users a detailed exercise program on a CD and encouraged them to practice the daily exercises. Therefore, we believe that this systematic and comprehensive exercise program prevented the adverse effects of the smartphone usage for the participants in the present study.

CONCLUSION

Increased smartphone usage hours would negatively affect the neck posture. Forward head and neck posture were associated with the usage hours of the smartphone. The more the usage hours increased, the more head and neck positioned anteriorly. This posture resulted with the decrease muscle strength and range of motion around the neck in collegiate students. The stretching and strengthening exercises were beneficial to improve the neck muscle strength and range of motion. Therefore, it is important to encourage the students to do exercises to protect the neck health, to prevent the cumulative trauma and future neck problems.

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: Ahmed Gaballah. Methodology: Ahmed Gaballah. Formal analysis: Ahmed Elshalakamy. Investigation: Ahmed Gaballah. Data curation: Ahmed Elshalakamy. Writing – original draft: Ahmed Gaballah. Writing – review & editing: Harald Tschan. Supervision: Harald Tschan. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Relationship between neuromuscular performance and academic achievement in university students of sports training

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ABSTRACT

This study examined the association between neuromuscular performance and academic achievement in university students enrolled in a sports training program. A cross-sectional study was conducted with 57 physically active university students (45 men and 12 women; age: 19.4 ± 2.1 years) from Bogotá, Colombia. Neuromuscular performance was assessed using the T-Force System during free back squat and bench press exercises, measuring one-repetition maximum (1RM) and mean propulsive velocity (MPV). Academic achievement was obtained from official institutional grade point average (GPA, 1.0–5.0 scale). Partial Pearson correlations adjusted for age, sex, and socioeconomic status were used to examine associations between variables. Significant positive correlations were observed between academic achievement and squat performance variables, including 1RM ($r = .620$), MPV ($r = .611$), fast-load MPV ($r = .656$), and slow-load MPV ($r = .642$) ($p < .05$). Bench press variables also showed significant correlations with GPA ($r = .41-.46$; $p < .05$). These findings suggest that greater neuromuscular performance, particularly strength and movement velocity, is associated with higher academic achievement in sports training students. Neuromuscular fitness may represent an important physiological factor linked to academic performance in physically active university populations.

Keywords: Sport medicine, Grade point average, Resistance training, Velocity-based training, Muscular strength, Cognitive performance.

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INTRODUCTION

student success in higher education. It is a multifactorial construct that reflects students' performance in quantifiable terms, such as obtained grades, course completion, and persistence within the educational system (Edel, 2003; Arias, 2013). Its importance lies in the fact that it not only enables assessment of individual performance but also serves as a key criterion for evaluating the quality and effectiveness of educational institutions. In the Colombian context, this variable gains particular relevance given the alarming university dropout rates. According to data from the Ministry of National Education (MEN, 2022), nearly 45% of students entering higher education programs do not complete their studies. This situation has driven numerous investigations aimed at understanding the factors underlying student retention and academic success in universities.

Among the most frequently studied factors related to AA are personal, social, economic, psychological, and pedagogical characteristics. Variables such as socioeconomic status, family environment, learning strategies, intrinsic motivation, institutional support, perceived stress, lifestyle behaviours, and previous academic preparation have been identified as determinants of AA (Restrepo et al., 2006; Luna et al., 2014; Sarmiento & López, 2019; González & Ramírez, 2020). Despite the substantial research in this field, a gap persists regarding how physical and physiological aspects, particularly those linked to muscular fitness and neuromuscular performance, may influence AA, especially among students enrolled in academic programs related to sports training.

Over the last decade, literature has increasingly examined the relationship among physical activity, fitness, and AA, particularly in children and adolescents. Numerous studies have reported positive associations between higher cardiorespiratory fitness, greater muscular strength, and better school performance (Donnelly et al., 2016; Esteban-Cornejo et al., 2014; García-Hermoso et al., 2017). These findings have been explained through physiological and cognitive mechanisms, such as increased cerebral blood flow, enhanced neurotrophins release, and improvements in executive function, working memory, and sustained attention (Álvarez-Bueno et al., 2017). However, within university populations, particularly in young adults, this relationship has received considerably less attention, and current results remain limited and inconsistent.

An emerging line of research proposes evaluating not only overall physical fitness, but also more specific characteristics of neuromuscular performance through the force–velocity profile. This profile, framed by the work of Parejo-Blanco (2014), refers to the individualized representation of the relationship between applied force and movement velocity under different relative loads during specific exercises. Beyond its utility in sports practice, this profile may also be associated with higher-level cognitive functions and, consequently, AA, as it reflects potential links between motor control, decision-making, and the efficiency of the central nervous system (Jiménez-Reyes et al., 2017; Edwards et al., 2022).

Students enrolled in professional sports training programs represent a specific subgroup that warrants special attention. Unlike peers in other academic fields, these students are exposed to substantial physical demands resulting from the practical components of their curriculum. Their academic routines often include training sessions, physical testing, practical classes, exercise laboratories, and, in many cases, additional athletic or fitness-related work outside of school hours. Moreover, many maintain active lifestyles motivated by personal goals or professional involvement in competitive or recreational sports.

This combination of physical, academic, and sometimes occupational demands may yield both positive and negative effects on AA. On one hand, regular physical activity can promote mental health, improve emotional

regulation, and optimize cognitive functions. On the other hand, excessive physical workload or poor time and recovery management may lead to chronic fatigue, disrupted sleep, and reduced time available for studying. Despite these distinct characteristics, there is a notable lack of studies investigating how specific indicators of neuromuscular performance relate to AA in this population.

This gap in the literature underscores the need to analyse potential associations between neuromuscular performance and AA in sports training students. Such research can contribute to the existing body of knowledge on determinants of academic success by incorporating an integrative perspective that connects physical fitness, performance physiology, and the educational context of a scientifically underrepresented population. Based on this rationale, the objective of this study was to evaluate the relationship between AA and neuromuscular performance in a sample of university students enrolled in a sports training program.

MATERIAL AND METHODS

Study design and participants

This descriptive cross-sectional study was conducted between 2020 and the first semester of 2021 with a sample of 57 university students (45 men and 12 women) enrolled in a sports training program at a higher education institution in Bogotá, Colombia. A non-probabilistic convenience sampling approach was used, which is common in exploratory studies within exercise sciences (Sedgwick, 2013). Inclusion criteria required participants to be between 18 and 30 years old, actively enrolled with at least three consecutive semesters completed, and classified as physically active based on the International Physical Activity Questionnaire (IPAQ), showing a weekly energy expenditure ≥ 1500 MET·min (Craig et al., 2003; Arango-Vélez et al., 2020). Participants were excluded if they responded affirmatively to any item on the PAR-Q questionnaire (Warburton et al., 2011) or presented any physical or neuromuscular condition that could compromise safe participation in testing. The study received approval from the Institutional Ethics Committee of Fundación Universitaria del Área Andina (Andean Area University Foundation) (code: CVF2020-IM-B02), complying with the Declaration of Helsinki and Colombian Ministry of Health Resolution 008430 of 1993. All participants signed informed consent documents and completed three evaluation sessions addressing body composition, force–velocity profiling, and academic performance data collection.

Instruments and procedures

Body Composition: segmental bioelectrical impedance was assessed using a Tanita IRONMAN BC-1500 analyser, validated for physically active adults (Sillanpää et al., 2014). Participants arrived in a fasting state (≥ 8 hours), with controlled hydration and bladder emptying at least one hour before measurement. Waist and hip circumferences were taken using a SECA 203 anthropometric tape following ISAK technical procedures (Silva & Vieira, 2020).

Neuromuscular Performance: force–velocity profiling was conducted in free back squat and bench press exercises. A progressive loading protocol was employed to determine one-repetition maximum (1RM), while measuring mean propulsive velocity (MPV) using the T-Force System (Ergotech, Spain), a linear velocity transducer with proven validity and reliability for resistance training assessments (Sánchez-Medina et al., 2010). The protocol began with 20 kg and increased by 10 kg until MPV fell below $0.80 \text{ m}\cdot\text{s}^{-1}$. Thereafter, load increments of 5 kg and 2.5 kg were used to refine 1RM estimation. MPV from the fastest attempt in each set was recorded. Three repetitions were performed when $\text{MPV} \geq 0.8 \text{ m}\cdot\text{s}^{-1}$, two repetitions between 0.8 and $0.5 \text{ m}\cdot\text{s}^{-1}$, and one when $<0.5 \text{ m}\cdot\text{s}^{-1}$, with 2-minute recovery intervals. A controlled eccentric phase and maximal-velocity concentric execution were required, aligned with recommended procedures for valid force–velocity assessment (González-Badillo & Sánchez-Medina, 2010; Banyard et al., 2017). Warm-up consisted

of 5 minutes of joint mobility and specific submaximal lifts. Bench press was tested first, followed by squat, to maintain protocol standardization.

Academic Achievement Academic achievement was operationalized as the students' cumulative GPA on a 1.0–5.0 scale. Students accessed their institutional platforms (BANNER or SIRENA) to download official academic records, under evaluator supervision to ensure accuracy and transcription quality, in line with recommended registry-based procedures for academic performance research (Martínez-Abad & Chaparro, 2020).

Statistical Analysis: normality was assessed using the Kolmogorov–Smirnov test. Sex differences in continuous variables were evaluated with the independent-samples t-test and chi-square analyses for categorical variables. Neuromuscular indicators included: 1RM in squat and bench press, Overall MPV, MPV under fast-load conditions ($\geq 0.1 \text{ m}\cdot\text{s}^{-1}$), MPV under slow-load conditions ($\leq 0.1 \text{ m}\cdot\text{s}^{-1}$). Associations between neuromuscular variables and AA were examined using partial Pearson correlations adjusted for age, sex, and socioeconomic status. Statistical significance was set at $p < .05$. Analyses were performed using IBM SPSS Statistics version 24.0 (Chicago, IL, USA).

RESULTS

Table 1. General characteristics of the sample.

Characteristics	Men (n = 45)	Women (n = 12)	p-Value
Socioeconomic status			
1	18 (40.0%)	6 (50.0%)	.523
2	15 (33.3%)	4 (33.3%)	.342
3	12 (26.7%)	2 (16.7%)	.464
Body composition			
Weight (kg)	66.2 (9.4)	54.06 (4.5)	.001*
Height (m)	172.0 (6.2)	156.8 (4.4)	.001*
BMI ($\text{kg}\cdot\text{m}^{-2}$)	22.28 (2.28)	22.00 (2.04)	.696
Body fat (%)	13.2 (4.0)	20.4 (4.2)	.001*
Visceral fat	1.73 (1.3)	1.00 (0.0)	.11
Metabolic age (years)	15.08 (6.4)	12.00 (0.0)	.14
Waist circumference (cm)	75.02 (6.3)	70.2 (4.7)	.019*
Hip circumference (cm)	93.2 (5.2)	90.68 (4.2)	.13
Age (years)	19.57 (2.2)	18.66 (0.77)	.177
Neuromuscular performance			
Squat 1RM (kg)	73.11 (13.7)	53.33 (9.8)	.001*
Squat MPV ($\text{m}\cdot\text{s}^{-1}$)	0.89 (0.22)	0.75 (0.09)	.001*
Squat MPV – fast loads	1.08 (0.22)	0.94 (0.09)	.022*
Squat MPV – slow loads	0.74 (0.22)	0.60 (0.09)	.043*
Bench press 1RM (kg)	39.3 (21.06)	21.6 (7.1)	.001*
Bench press MPV ($\text{m}\cdot\text{s}^{-1}$)	0.73 (0.22)	0.59 (0.09)	.032*
Bench press MPV – fast loads	0.92 (0.22)	0.78 (0.09)	.021*
Bench press MPV – slow loads	0.58 (0.22)	0.44 (0.09)	.031*
Academic achievement			
GPA (1.0–5.0 scale)	4.12 (0.3)	4.45 (0.4)	.006*

Note. Data presented as mean $\pm$ standard deviation. * $p < .05$ indicates statistical significance. MPV: mean propulsive velocity; 1RM: one-repetition maximum.

Regarding socioeconomic status, most participants belonged to strata 1 and 2, with no statistically significant differences between men and women in any category ($p > .05$). Concerning body composition, men showed significantly higher values for body weight ($p = .001$), height ($p = .001$), and waist circumference ($p = .019$), while women presented a significantly higher body fat percentage ($p = .001$). No significant differences were observed in BMI, visceral fat, metabolic age, hip circumference, or chronological age ($p > .05$). In terms of neuromuscular performance, men significantly outperformed women in squat 1RM ($p = .001$) and bench press 1RM ($p = .001$), as well as in mean propulsive velocity (MPV) across both exercises ($p = .001$ and $p = .032$, respectively). Significant differences were also observed in MPV under fast and slow loads in both squat and bench press exercises ($p < .05$ for all comparisons). Finally, academic achievement was significantly higher in women (4.45 ± 0.4) compared to men (4.12 ± 0.3 ; $p = .006$). (Table 1).

Partial correlations adjusted for age, sex, and socioeconomic status between AA and neuromuscular performance variables in the squat exercise showed a positive association of moderate to strong magnitude (Figure 1). Specifically, significant correlations were observed between AA and squat 1RM ($r = .620$), overall MPV ($r = .611$), MPV under fast loads ($r = .656$), and MPV under slow loads ($r = .642$), all statistically significant ($p < .05$).

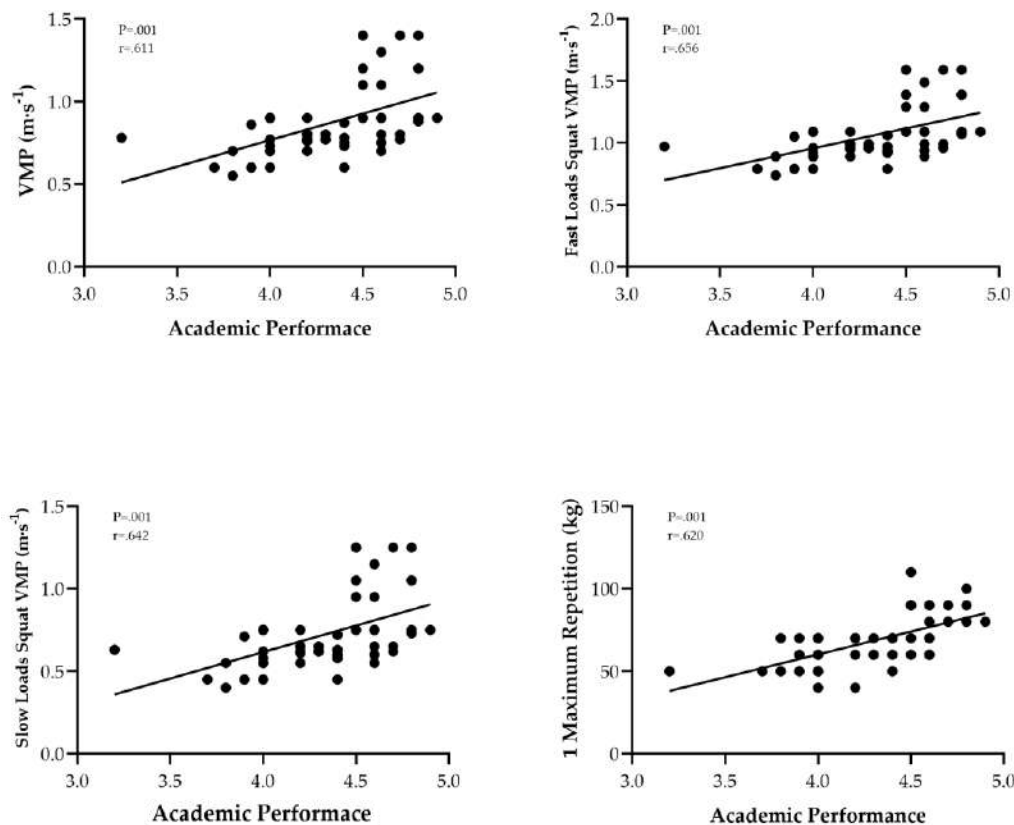


Figure 1. Squat.

Similarly, adjusted partial correlations between AA and neuromuscular performance variables associated with the bench press revealed positive associations (Figure 2). Significant correlations were identified between AA and bench press 1RM ($r = .46$), overall MPV ($r = .41$), MPV under fast loads ($r = .45$), and MPV under slow loads ($r = .43$), with all results reaching statistical significance ($p < .05$).

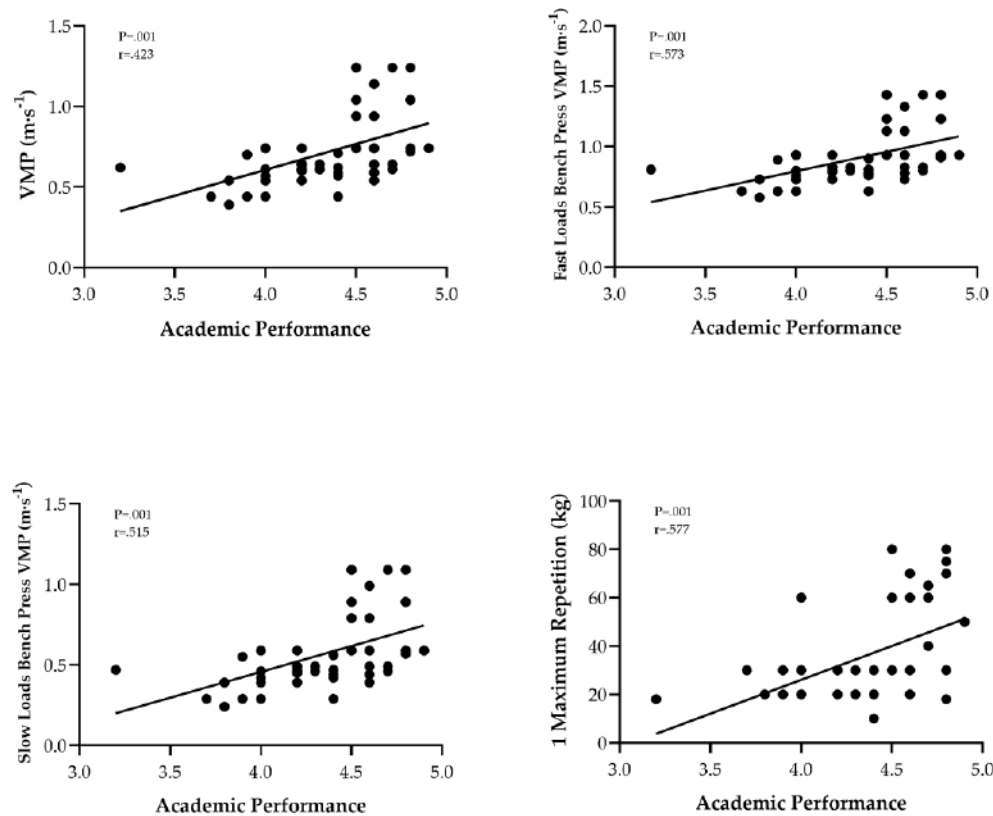


Figure 2. Bench press.

DISCUSSION AND CONCLUSIONS

The main finding of this study was that university students with better neuromuscular performance, understood as a greater ability to move relative loads rapidly and efficiently, demonstrated higher academic achievement. This result is particularly relevant because it provides novel evidence on the relationship between neuromuscular performance and academic achievement in sports training students, a population that has been scarcely addressed in the scientific literature. Most previous studies have focused on school-aged populations or general university students without considering specific neuromuscular performance indicators such as maximal strength and movement velocity.

The positive associations observed between academic achievement and neuromuscular performance variables, including one-repetition maximum and mean propulsive velocity, suggest that neuromuscular fitness may be linked to cognitive and academic functioning. These findings are consistent with previous research indicating that physical fitness and muscular strength are positively associated with academic performance and cognitive outcomes (Esteban-Cornejo et al., 2014; García-Hermoso et al., 2017). These relationships may be explained by physiological adaptations that improve neural efficiency, motor coordination, and central nervous system function, which may contribute to enhanced cognitive processes involved in learning and academic performance.

From a physiological perspective, exercise capable of improving neuromuscular performance has been shown to increase brain plasticity and levels of brain-derived neurotrophic factor (BDNF), facilitating

neurogenesis and synaptic plasticity in brain regions involved in memory and learning, such as the hippocampus (Erickson et al., 2011; Voss et al., 2013). Additionally, resistance training stimulates the release of neurotransmitters such as serotonin and norepinephrine, which are associated with improved attention, mood, and cognitive processing (Cigarroa-Cuevas & Zapata-Lamana, 2016). These mechanisms may partially explain the positive associations observed between neuromuscular performance and academic achievement in the present study.

Furthermore, the use of velocity-based indicators such as mean propulsive velocity provides a more specific and sensitive measure of neuromuscular function compared to traditional strength assessments alone. This is particularly relevant because movement velocity reflects the efficiency of neuromuscular activation and coordination, which are influenced by neural factors associated with motor control and central nervous system efficiency (González-Badillo & Sánchez-Medina, 2010; Jiménez-Reyes et al., 2017). Therefore, the ability to produce force rapidly may represent an important physiological characteristic associated with academic performance in physically active university students.

These findings are also consistent with previous studies conducted in university populations that have reported positive associations between muscular strength and academic performance (Peña et al., 2019). However, the present study extends previous knowledge by incorporating both maximal strength and velocity-based neuromuscular indicators, providing a more comprehensive assessment of neuromuscular performance. This approach allows for a better understanding of the potential relationship between neuromuscular function and academic achievement in sports training students.

From an educational and practical perspective, these findings suggest that neuromuscular performance may represent an important physiological factor associated with academic success in sports training students. Strength and velocity-based training strategies may contribute not only to physical performance improvements but also to cognitive and academic functioning. Given the physical and academic demands faced by students enrolled in sports training programs, optimizing neuromuscular performance may support both their physical development and academic performance. Universities and sports training programs may consider integrating structured neuromuscular training strategies as part of comprehensive educational and performance development programs.

From a public health perspective, promoting neuromuscular development during early adulthood may contribute to healthier lifestyles and improved long-term health outcomes. Physical exercise has been shown to improve overall physical and mental health and reduce the risk of chronic diseases (Warburton et al., 2006), while also supporting cognitive function and academic performance. Therefore, neuromuscular fitness may represent an important component of student well-being and academic success.

This study presents several limitations that should be acknowledged. First, the cross-sectional design does not allow causal relationships to be established between neuromuscular performance and academic achievement. Second, the relatively small sample size and the imbalance in sex distribution may limit the generalizability of the findings to broader university populations. Third, other factors known to influence academic achievement, such as sleep quality, psychological stress, cognitive abilities, academic workload, and study habits, were not controlled in this study. Additionally, differences in training experience and lifestyle behaviours may have influenced both neuromuscular performance and academic achievement. Future longitudinal and experimental studies are needed to confirm these findings and to determine whether improvements in neuromuscular performance can directly contribute to improvements in academic achievement.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. William Felipe Martin-Aleman contributed to data collection, statistical analysis, and manuscript drafting. Angie Carolina Tovar Quintero contributed to study design and epidemiological supervision. Yordan Rene Pardo Daza and John Fredy Rodriguez contributed to data acquisition and interpretation. Luis Andres Tellez contributed to methodological supervision. Jhonatan Camilo Peña conceived the study, supervised the research process, and critically revised the manuscript. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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

This study was approved by the Institutional Ethics Committee of Fundación Universitaria del Área Andina (Approval Code: CVF2020-IM-B02) and conducted in accordance with the ethical standards established in the Declaration of Helsinki. All participants provided written informed consent prior to participation.

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.

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Persistent neuromuscular deficits and injury risk after return to play: A 24-month prospective follow-up in elite handball players following ACL reconstruction

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ABSTRACT

Return to play (RTP) after anterior cruciate ligament (ACL) reconstruction is often considered the final milestone of rehabilitation; however, the extent to which athletes achieve full neuromuscular recovery at this stage remains unclear. Persistent deficits in strength and neuromuscular control may increase the risk of reinjury, particularly in physically demanding sports such as handball. The purpose of this study was to investigate neuromuscular performance, functional knee status, and injury incidence during the first 24 months following RTP in elite handball players after ACL reconstruction, and to explore potential associations between neuromuscular deficits and subsequent injuries. Seventeen elite Greek handball players (8 males and 9 females) who had returned to full competitive activity after ACL reconstruction were prospectively monitored for two years. Neuromuscular performance was assessed every six months using isokinetic dynamometry at angular velocities of 60°, 180°, and 300°/sec, while knee function was evaluated using the International Knee Documentation Committee (IKDC) subjective questionnaire. Strength deficits, hamstring-to-quadriceps (H/Q) ratios, and peak torque-to-body weight ratios were analysed, and both ACL reinjuries and other lower-limb injuries were systematically recorded. Descriptive statistics, chi-square analyses, and repeated-measures ANOVA were applied. ACL reinjury occurred in 35.3% of the participants, with most cases observed within the first six months after RTP. In addition, 28 other lower-limb injuries were recorded, predominantly affecting the previously injured limb. Isokinetic assessments revealed persistent quadriceps and hamstring strength deficits and asymmetries in H/Q ratios throughout the monitoring period, while only 23.3% of IKDC scores reached normative reference values. These findings indicate that athletes may return to high-level competition despite incomplete neuromuscular recovery, potentially increasing reinjury risk. Systematic post-RTP monitoring and objective performance-based criteria may therefore be critical for improving long-term athlete health and safe participation in elite sport.

Keywords: Sport medicine, Anterior cruciate ligament reconstruction, Return to play, Handball, Neuromuscular deficits, Reinjury, Isokinetic testing.

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INTRODUCTION

Anterior cruciate ligament (ACL) rupture is one of the most common and severe knee injuries in sport, often leading to prolonged absence from competition, decreased quality of life, and an increased risk of long-term complications (Carlson, 2020). It occurs frequently in athletic populations and may significantly affect an athlete's ability to return to the pre-injury level of performance (Paterno et al., 2014). In addition to the direct consequences on physical function, ACL injuries may also influence athletic success, as previous findings indicate an interaction between injury occurrence, performance, and competitive outcomes (Maestroni et al., 2019). Alarming, the global incidence of ACL injuries has nearly doubled over the past two decades despite ongoing efforts to reduce injury risk (Arundale, Silvers-Granelli & Myklebust, 2022).

ACL rupture typically occurs when the mechanical load applied to the ligament exceeds its structural capacity, resulting in compromised knee stability (Maniar et al., 2022). The ligament plays a crucial role in maintaining both translational and rotational stability of the knee joint (Fones et al., 2020), while excessive anterior shear forces have been identified as important contributors to ACL overloading and injury mechanisms (Maniar et al., 2022). Consequently, restoring functional stability and neuromuscular control after ACL reconstruction is essential for athletes seeking to return to competitive activity.

Rehabilitation following ACL reconstruction represents a critical component of the recovery process. The primary objective of rehabilitation is to enable athletes to safely return to competitive sport as quickly as possible, ideally at their previous level of performance and with minimal risk of reinjury (Kotsifaki et al., 2022). Although most athletes aspire to return fully to their pre-injury level (Gokeler et al., 2017), evidence indicates that many athletes experience persistent impairments even after completing rehabilitation and returning to sport. Strength deficits, neuromuscular asymmetries, and proprioceptive impairments have been reported to persist several years after surgery (Carlson, 2020). Moreover, the rate of reinjury following ACL reconstruction remains concerning, with studies reporting reinjury rates ranging from approximately 30% to 39% (Wilk et al., 2023).

Several studies have demonstrated that returning to high-risk sports after ACL reconstruction is associated with a substantial risk of sustaining a second ACL injury (Barber-Westin & Noyes, 2020; Winkler et al., 2025). Younger athletes appear to be particularly vulnerable, with evidence suggesting an elevated risk of reinjury within the first two years after returning to sport (Nageli & Hewett, 2017). Furthermore, previous research has shown that approximately one-third of athletes who return to sport after ACL reconstruction may sustain a second ACL injury, either in the ipsilateral or contralateral limb (Paterno et al., 2017). Despite advances in rehabilitation strategies, the proportion of athletes who successfully return to their previous level of competition within the first year remains relatively limited (Kotsifaki et al., 2023; Paterno et al., 2017).

Modern rehabilitation approaches increasingly emphasize criterion-based return-to-play (RTP) decisions rather than time-based protocols (van Melick et al., 2016). Nevertheless, there remains considerable variation in rehabilitation practices and no clear consensus regarding the optimal criteria for returning to competitive activity after ACL reconstruction (Andrande et al., 2020; Greenberg et al., 2018; Korakakis et al., 2021; Kotsifaki et al., 2022; Risberg et al., 2024). Evidence suggests that premature return to sport without objective functional assessment may increase the risk of reinjury and negatively influence long-term athletic performance (Grindem et al., 2016; Kotsifaki et al., 2023; Kyritsis et al., 2016). Furthermore, only a small proportion of athletes participating in pivoting sports meet the recommended functional criteria for safe return to play (van Melick et al., 2020).

Handball is a highly dynamic and physically demanding sport characterized by explosive jumps, rapid changes of direction, repeated high-intensity movements, and frequent physical contact between players (Bojic, Valdevit & Velickovic, 2019). These demands contribute to a high incidence of injuries, particularly in the lower extremities. ACL injuries in handball often occur without contact and are frequently associated with sudden directional changes or single-leg landings (Monaco et al., 2019; Myklebust, 2014). Epidemiological data indicate that knee injuries account for a substantial proportion of lower limb injuries in handball, with reported rates ranging from 11% to 23% in male players and from 11% to 31.7% in female players (Andrade et al., 2018; Luig & Henke, 2010). Moreover, female handball players appear to have a higher risk of ACL injury compared to males, with incidence rates estimated at 0.86 and 0.24 injuries per 1000 hours of exposure, respectively (Terzidis et al., 2023).

Although previous studies have examined RTP assessments and reinjury rates at various time points following ACL reconstruction (Ardern et al., 2010; Heijne, 2010; Paterno et al., 2017; Carlson, 2020; Paterno et al., 2021; Kew et al., 2022; Terzidis et al., 2023), limited research has focused on systematic long-term monitoring of elite handball players who have already returned to high-level competition. In particular, prospective studies investigating neuromuscular performance, functional status, and injury incidence during the first two years following return to play remain scarce. Considering the high physical demands and injury risk associated with handball, such longitudinal monitoring may provide valuable insights into the long-term recovery process and potential risk factors for reinjury.

Therefore, the purposes of the present study were: (1) to assess the return-to-play condition of male and female high-level handball players following ACL reconstruction and evaluate their rehabilitation procedures; (2) to systematically reassess these athletes every six months over two years after RTP to record ACL reinjuries and other lower-limb injuries; and (3) to explore potential associations between neuromuscular performance variables, strength deficits, and the occurrence of subsequent injuries during this follow-up period.

MATERIAL AND METHODS

Participants

The sample of the present study initially consisted of 20 Greek high-level handball players (male and female) competing in teams of the Greek Handball Premier League for Men and the Greek A1 National Division for Women. All participants had previously sustained an anterior cruciate ligament (ACL) rupture that required surgical reconstruction and had completed their rehabilitation program before returning to full competitive activity. Participants were recruited and assessed over a period of three years. During the study, three athletes were excluded from the sample because they terminated their playing careers for reasons unrelated to reinjury. Therefore, the final sample consisted of 17 elite handball players who completed the entire assessment process.

Measures

Demographic and injury questionnaire

Upon their return to competitive activity, all participants completed a questionnaire including demographic characteristics and detailed information about their initial injury and rehabilitation process. The questionnaire collected information regarding the type of graft used in the reconstruction, the presence of concomitant injuries, the duration and structure of the rehabilitation program, and the professionals responsible for conducting the rehabilitation process.

International Knee Documentation Committee (IKDC) questionnaire

Participants also completed the Subjective Knee Evaluation Form of the International Knee Documentation Committee (IKDC 2000). The Greek translated and cross-culturally validated version of the questionnaire was used, as adapted by Koumantakis et al. (2016). The IKDC questionnaire is widely used to evaluate subjective knee function and symptoms following knee injuries and surgical procedures. Participants were asked to provide a subjective evaluation of their knee condition upon their return to competitive activity and during each follow-up assessment.

Isokinetic strength assessment

Neuromuscular performance was evaluated using isokinetic testing at three angular velocities: 60°, 180°, and 300°/sec. Assessments were conducted using a Humac Norm 770 CSMi isokinetic dynamometer (Stoughton, MA, USA) at the Human Biological Performance Assessment Laboratory of the School of Physical Education and Sport Science at the Aristotle University of Thessaloniki. The isokinetic assessment was used to evaluate lower-limb muscle strength, detect possible asymmetries between limbs, and determine whether hamstring-to-quadriceps (H/Q) ratios and peak torque-to-body weight (PT/BW) ratios fell within normative values reported in the literature.

Procedures

All participants were assessed immediately after returning to full competitive activity following ACL reconstruction. During the initial assessment, they completed the demographic and injury questionnaire as well as the IKDC questionnaire, and they underwent the isokinetic strength testing protocol. The same assessment procedure was repeated every six months for a total follow-up period of two years. During each follow-up evaluation, participants completed the IKDC questionnaire and reported whether they had received any special treatment or injury-specific training programs within their teams during the previous six-month period. Additionally, all ACL reinjuries and other serious lower limb injuries were systematically recorded throughout the monitoring period. For an injury to be recorded, the player had to abstain from training and competition for at least one week. In cases of ACL reinjury, the incident was documented, and the participant was excluded from further testing. The testing protocol was approved by the Research Ethics Committee of the Faculty of Physical Education and Sport Sciences at the Aristotle University of Thessaloniki (Approval No. 115/27-6-2022). All participants were fully informed about the testing procedures and provided written informed consent before participation.

Analysis

Descriptive statistical analyses were conducted for the questionnaire data and the IKDC scores. In addition, descriptive statistics were calculated for all isokinetic assessment variables, including quadriceps and hamstring strength deficits, hamstring-to-quadriceps (H/Q) ratios, and peak torque-to-body weight ratios at angular velocities of 60°, 180°, and 300°/sec for both injured and non-injured limbs. Means, standard deviations, and ranges were calculated to characterize athletes' neuromuscular performance at return to play (RTP). Inferential statistical analyses were also performed. Chi-square tests were applied to examine associations between categorical variables, such as reinjury occurrence and strength deficit classifications. Finally, repeated measures ANOVA was used to examine within-subject differences across the different testing angular velocities (60°, 180°, 300°/sec) and between injured and non-injured limbs, allowing the evaluation of limb symmetry and velocity-dependent changes in muscle performance.

RESULTS

The analysis of demographic and sport-related characteristics indicated that 47.1% of the participants were male ($n = 8$), whereas 52.9% were female ($n = 9$). With respect to preferred playing side, 70.6% ($n = 12$) reported a right-side preference and 29.4% ($n = 5$) reported a left-side preference. Examination of playing positions revealed that back players represented the largest proportion of the sample (47.1%, $n = 8$), followed by wings (23.5%, $n = 4$), goalkeepers (17.6%, $n = 3$), and pivots (11.8%, $n = 2$).

Analysis of injury-related characteristics showed that over half of the participants sustained an isolated anterior cruciate ligament (ACL) injury (52.9%, $n = 9$), while 35.3% ($n = 6$) had combined ACL and meniscus injuries, and 11.8% ($n = 2$) presented with ACL injuries in combination with other concomitant injuries. Regarding injury recurrence, 82.4% ($n = 14$) reported experiencing an ACL injury for the first time, 11.8% ($n = 2$) reported a second ipsilateral injury, and 5.9% ($n = 1$) reported a second contralateral injury. Concerning the professionals involved in rehabilitation, 5.9% ($n = 1$) were managed by a doctor outside the team, 11.8% ($n = 2$) by a physiotherapist outside the team, 17.6% ($n = 3$) by the team's conditioning coach, 17.6% ($n = 3$) by a conditioning coach outside the team, 5.9% ($n = 1$) by a special rehabilitation coach, and 41.2% ($n = 7$) by a multidisciplinary team of specialists. These findings provide a descriptive profile of the injuries. More specifically, types of injuries, recurrence patterns, and rehabilitation support received by the participants.

The data on graft type show that among the 17 participants, 58.8% underwent reconstruction using a bone-patellofemoral-bone graft, while 41.2% received a hamstring (semitendinosus) graft. Moreover, only a 29.4% ($n = 5$) reported that they received pre-operative training, while a 70.6% ($n = 12$) reported no pre-operative training.

The rehabilitation evaluation data show that out of 17 participants, 5.9% underwent minimal structured rehabilitation, another 5.9% had three months of minimal structured rehab, and 5.9% received three months of structured rehab. A higher proportion, 11.8%, engaged in structured rehab for over three months, while 17.6% completed six months of structured rehab. The most common category was nine months of totally structured rehab at 35.3%, followed by 5.9% who reported over nine months of totally structured rehab, and 11.8% who completed over nine months of fully supervised rehab. Moreover, the participants reported their rehabilitation program characteristics and training components. This information is presented in Table 1.

Table 1. Distribution of rehabilitation program characteristics and training components among participants.

	Frequency	Percentage	Valid percentage	Cumulative percentage
Minimal structured rehab	1	5.9	5.9	5.9
3 months of minimal structured rehab	1	5.9	5.9	11.8
3 months structured rehab	1	5.9	5.9	17.6
Over 3 months of structured rehab	2	11.8	11.8	29.4
6 months structured rehab	3	17.6	17.6	47.1
9 months of totally structured rehab	6	35.3	35.3	82.4
Over 9 months, totally structured rehab	1	5.9	5.9	88.2
Over 9 months of fully supervised rehab	2	11.8	11.8	100.0
Total	17	100.0	100.0	
Physiotherapy				
Not at all	3	17.6	17.6	17.6
Average	1	5.9	5.9	23.5
Much	7	41.2	41.2	64.7
Very much	6	35.3	35.3	100.0
Total	17	100.0	100.0	

Stretching-ROM				
Minimal	3	17.6	17.6	17.6
Average	6	35.3	35.3	52.9
Much	4	23.5	23.5	76.5
Very much	4	23.5	23.5	100.0
Total	17	100.0	100.0	
Physical condition				
Not at all	1	5.9	5.9	5.9
Minimal	1	5.9	5.9	11.8
Average	7	41.2	41.2	52.9
Much	4	23.5	23.5	76.5
Very much	4	23.5	23.5	100.0
Total	17	100.0	100.0	
Strength training				
Minimal	1	5.9	5.9	5.9
Average	1	5.9	5.9	11.8
Much	5	29.4	29.4	41.2
Very much	10	58.8	58.8	100.0
Total	17	100.0	100.0	
Plyometric training				
Minimal	2	11.8	11.8	11.8
Average	4	23.5	23.5	35.3
Much	5	29.4	29.4	64.7
Very much	6	35.3	35.3	100.0
Total	17	100.0	100.0	
Proprio training				
Minimal	2	11.8	11.8	11.8
Average	5	29.4	29.4	41.2
Much	5	29.4	29.4	70.6
Very much	5	29.4	29.4	100.0
Total	17	100.0	100.0	
Balance training				
Average	2	11.8	11.8	11.8
Much	7	41.2	41.2	52.9
Very much	8	47.1	47.1	100.0
Total	17	100.0	100.0	
Handball training				
Minimal	1	5.9	5.9	5.9
Average	11	64.7	64.7	70.6
Much	4	23.5	23.5	94.1
Very much	1	5.9	5.9	100.0
Total	17	100.0	100.0	

Regarding ACL reinjury from the time of RTP up to six months after RTP, 11.8% (n = 2) experienced ipsilateral ACL reinjury, 11.8% (n = 2) had contralateral ACL reinjury in total, 22.4% (n = 4) reported an ACL reinjury, whereas 70.9% reported no reinjury; one participant's data (5.9%) was missing due to another injury. At 12 months after RTP, none of the remaining participants reported any new ACL reinjury. At 18 months, 11.8% (n = 2) reported ipsilateral ACL reinjury and 58.8% reported no ACL reinjury; five participants (29.4%) had no data due to previous reported ACL reinjury or other serious lower limb injury that prohibited them to participate to the programmed assessments. By 24 months after RTP, reinjury data were only available for ten participants, all of whom reported no ACL reinjury. In contrast, data for seven participants (41.2%) were missing due to ACL reinjuries or other leg injuries that prevented them from participating in the programmed

assessments. Overall, the data show that ACL reinjury rates reached a level of 35,29% (n = 6, 3 male and 3 female players), in a total period of two years after returning to full playing activity.

Regarding other lower limb injuries that forced the players to abstain from training and games for at least seven days, concerning either the ipsilateral or the contralateral leg, from the time of RTP up to 24 months, the results are shown in Table 2.

Table 2. Type of injuries, their frequency, and distribution among assessment periods.

Type of injury	RTP-6m	6m-12m	12m-18m	18m-24m	Injuries total frequency	Injuries percentage
Hams strain/fracture	1	1			2	7.14
Knee pain	3	5	3	2	13	46.42
Gastrocnemius strain/fracture	1				1	3.57
Adductors strain/fracture	1	1			2	7.14
Sprains	1				1	3.57
Lateral collateral ligament		1			1	3.57
Quads strain/fracture				1	1	3.57
Meniscus injury			3	3	6	21.42
Back surgery			1		1	3.57
Total	7	8	7	6	28	100
Ipsilateral	5	6	6	6	23	82.14
Contralateral	1	1			2	7.14
Both legs / Not related	1	1	1		3	10.71

In the question if they performed any special or injury-specific training within their teams, the majority of the participants replied negatively (n = 15), and only two participants replied positively. This finding persisted throughout the whole period of the 24 months.

Regarding the isokinetic assessment performed at 60°-180°-300° / sec, although deficits still exist up to 24 months after RTP, we can see from the results that there is a small but clear reduction of the values that are out of the normative values, as we reach the 18 and 24 months after RTP, especially at the 24 months assessments. This information can be seen in Table 3.

Table 3. Normative and non-normative values for Isokinetic assessments at 60°-180°-300° /sec throughout 6, 12, 18, 24 months.

ISOK06 for 6 months	Quads deficit	Hams deficit	HQratio injured	HQratio Non injured	PTBW Ratio injured	PTBWratio Non injured
Into normative values	7	6	6	9	7	8
Out of normative values	5*	6*	6*	3*	5*	4*
ISOK180 for 6 months						
Into normative values	7	4	6	11	10	12
Out of normative values	5*	8*	6*	1*	2*	19*
ISOK300 for 6 months						
Into normative values	9	3	8	10	11	12
Out of normative values	3*	9*	4*	2*	1*	19*
ISOK06 for 12 months						
Into normative values	9	7	7	10	7	9
Out of normative values	3*	5*	5*	2*	5*	3*
ISOK180 for 12 months						
Into normative values	9	7	9	10	10	12
Out of normative values	3*	5*	3*	2*	1*	19*

ISOK300 for 12 months						
Into normative values	8	5	6	11	12	11
Out of normative values	4*	7*	6*	1*	19*	1*
ISOK06 for 18 months						
Into normative values	5	5	7	8	5	7
Out of normative values	5*	5*	3*	2*	5*	3*
ISOK180 for 18 months						
Into normative values	5	4	5	8	7	10
Out of normative values	5*	6*	5*	2*	3*	
ISOK300 for 18 months						
Into normative values	6	4	5	7	8	9
Out of normative values	4*	6*	5*	3*	2*	1*
ISOK06 for 24 months						
Into normative values	4	3	5	6	5	7
Out of normative values	4*	5*	3*	2*	3*	1*
ISOK180 for 24 months						
Into normative values	3	6	5	7	6	8
Out of normative values	5*	2*	3*	1*	2*	
ISOK300 for 24 months						
Into normative values	5	4	4	6	7	8
Out of normative values	3*	4*	4*	2*	1*	

Note. * Out of normative values. Quads deficit = Quadriceps isokinetic assessment deficit between limbs, Hams deficit = Hamstrings isokinetic assessment deficit between limb, HQ ratio INJURED = Hamstrings and Quadriceps isokinetic assessment values ratio on injured limb, HQ ratio non-INJURED = Hamstrings and Quadriceps isokinetic assessment values ratio on non-injured limb, PTBW ratio INJURED = Peak torque values and body weight ratio on injured limb, PTBW ratio non-INJURED = Peak torque values and body weight ratio on non-injured limb.

According to the IKDC questionnaire evaluations, results show that the participants do not value their injured leg within the normative values that exist according to age and gender (Logerstedt et al. 2014). More specifically, in the majority of cases, it appears that the reported values are out of the normative data. This information exists in Table 4.

Table 4. IKDC values at RTP and 6, 12, 18, 24, months after RTP for all participants.

Participants	RTP	6 months	12 months	18 months	24 months
1	63.21	66.6	Other injury**	67.81	75.86
2	86.2**	78*	83.9	79.31*	Other injury
3	74.71	72.4*	79.3	71.26*	77.01
4	72.4	75.8	74.7*	77.01	75.86*
5	62.02	ACL reinjury**			
6	67.81	80.45	79.3*	74.71*	75.86
7	58.6	72.41	68.9*	55.17*	62.6
8	74.71	86.2	82.75*	ACL reinjury	
9	55.17	ACL reinjury**			
10	57.47	ACL reinjury**			
11	88.76**	89.65**	87.35*	88.2**	86.35*
12	85.6	ACL reinjury			
13	77	85.5**	85.5**	Other injury	
14	82.7**	54*	82.7**	82.8**	81.6*
15	77	72.41*	87.35**	ACL reinjury	
16	83.9	Other injury**	85.05**	86.7**	87.2**
17	82.7	85.6**	73.56*	75.6	72.58*

Note. *All data that showed a worse result than the previous assessment. **all data that are within normative values according to gender and age.

A chi-square test of independence was conducted to examine the association between the type of injury and isokinetic assessments. Specifically, it tried to investigate whether the isokinetic quadriceps peak torque-to-

body weight ratio at 60°/sec (injured limb) at RTP fell within normative values. The analysis revealed a statistically significant association, $\chi^2 (3, N = 8) = 8, p = .046$. The crosstabulation examined the relationship between the type of injury and whether the PTBW ratio at 180° / sec at RTP falls within normative values. Out of the eight cases analysed, most injuries (7 out of 8) were within normative values, while only one case (ham strain/fracture) was out of normative values. The Chi-Square test indicated a statistically significant association between injury type and normative status ($\chi^2 = 8, df = 3, p = .046$). The use of frequency illustrated the relationship between the type of injury and whether the ISOK300PTBW ratio at return to play (RTP) falls within normative values. Out of the eight cases analysed, seven were within normative ranges, while only one case (injury type “ham strain/fracture”) was outside normative values. The Pearson Chi-Square test indicated a statistically significant association ($\chi^2 = 8, df = 3, p = .046$), suggesting that the type of injury may be related to the likelihood of the score being within normal limits.

Also, the relationship between the type of injury and whether the PTBW ratio at 60° at RTP for the injured leg falls within normative values was examined. Out of the six total cases, five were within normative values, while only one case (injury type “ham strain/fracture”) was outside normative values. The Chi-Square analysis showed borderline statistical significance ($\chi^2 = 6, df = 2, p = .050$), suggesting a possible association between the type of injury and performance.

The crosstab analysis examined the relationship between the type of injury and whether the quadriceps deficit at 180°/sec (ISOK180Quaddef) at RTP is within normative values. Among the six total cases, three were within normative values (all reported meniscus injuries), while the other three cases (“quads strain/fracture” and “knee pain”) were outside normative values. The Chi-Square test showed borderline statistical significance ($\chi^2 = 6, df = 2, p = .050$), indicating a possible association between injury type and quadriceps deficit status. The crosstab analysis investigated the relationship between the type of injury and whether the quadriceps deficit at 300°/sec (ISOK300Quaddef) at return to play (RTP) falls within normative values. Of the six total cases, three (all related to “meniscus” injuries) were within normative limits, while the remaining three cases (“quads strain/fracture” and “knee pain”) were outside normative limits. The Chi-Square test showed borderline statistical significance ($\chi^2 = 6, df = 2, p = .050$).

The crosstab analysed the relationship between the type of injury and whether the hamstring-to-quadriceps ratio at 300°/sec (ISOK300HQ ratio) for the injured limb (INJ) at RTP falls within normative values. Out of the six total cases, five were within normative limits (3 from the “meniscus” group and 2 from the “knee pain” group), while only one case (“quads strain/fracture”) was outside normative values. The Chi-Square test showed borderline statistical significance ($\chi^2 = 6.000, df = 2, p = .050$), suggesting a potential association between injury type and whether the HQ ratio is normative.

The Repeated Measures ANOVA test was used to investigate how the same athletes perform under 12 and 18 months. Specifically, it evaluated whether isokinetic measures such as quadriceps deficit, hamstring deficit, and hamstring-to-quadriceps ratios at 300°/sec change between repeated assessments and whether these changes differ depending on the type of variable measured. Initially, the results explore how performance measures at 300°/sec (quadriceps deficit, hamstring deficit, and hamstring-to-quadriceps ratios for both injured and non-injured limbs) vary across repeated testing. The within-subjects effects show that the main repeated-measure factor itself is not significant ($p = .90$), indicating no overall time effect across all variables. However, interactions reveal that the hamstring deficit (ISOK300Hamsdef_RTP) demonstrates a statistically significant change over time ($F = 5.705, p = .05$), suggesting improvements or differences in hamstring performance between measurements. The interaction for hamstring-to-quadriceps ratio on the injured limb (ISOK300HQratioINJ_RTP) approaches significance ($p = .055$), indicating a possible trend.

Quadriceps deficit ($p = .13$) and the HQ ratio for the non-injured limb ($p = .10$) did not reach significance. The between-subjects effects mirror these results, confirming that only the hamstring deficit shows a clear effect, while other measures indicate trends but are not statistically significant. This information is presented in Table 5.

Table 5. Within-subject effects for Repeated Measures Anova between Re-Injury in 12 and 18 months and isokinetic assessment.

Cases	Sum of Squares	df	Mean Square	F	p
RM Factor 1	0.004	1	0.004	0.019	.896
RM Factor 1 * ISOK300Quaddef_RTP	0.725	1	0.725	3.011	.126
RM Factor 1 * ISOK300Hamsdef_RTP	1.373	1	1.373	5.705	.048
RM Factor 1 * ISOK300HQratioINJ_RTP	1.273	1	1.273	5.289	.055
RM Factor 1 * ISOK300HQratioNINJ_RTP	0.896	1	0.896	3.722	.095
Residuals	1.685	7	0.241		

Note. Type III Sum of Squares. ISOK300Quaddef_RTP = Quadriceps deficit between limbs during isokinetic assessment at 300 °/sec angular velocity during Return to play assessment, SOK300Hamsdef_RTP = Hamstrings deficit between limbs during isokinetic assessment at 300 °/sec angular velocity during Return to play assessment, ISOK300HQratioINJ_RTP = Hamstrings and Quadriceps isokinetic assessment values ratio on injured limb during isokinetic assessment at 300 °/sec angular velocity during Return to play assessment, RM Factor 1 * ISOK300HQratioNINJ_RTP = Repeated Measures factor: Hamstrings and Quadriceps isokinetic assessment values ratio on non-injured limb during isokinetic assessment at 300 °/sec angular velocity during Return to play assessment.

The repeated measures ANOVA examining changes in isokinetic performance over 6, 12, 18, and 24 months shows no overall significant main effect of time ($F = 1.836$, $p = .18$), indicating that when all measures are combined, performance does not significantly change across these intervals. However, when interactions between time and specific performance variables are considered, quadriceps deficit at 300°/sec (ISOK300Quaddef_RTP) approaches statistical significance ($F = 3.260$, $p = .05$), suggesting notable improvements or fluctuations in quadriceps recovery after RTP, over time. Similar trends are observed for hamstring deficit ($F = 2.732$, $p = .08$) and hamstring-to-quadriceps ratio on the injured limb ($F = 2.765$, $p = .08$), implying possible changes in muscle symmetry and functional patterns across the follow-up period. The non-injured limb HQ ratio shows less pronounced change ($p = .12$). Between-subject effects are uniformly non-significant (all $p > .86$), indicating that differences in recovery after RTP are largely driven by within-subject changes rather than variability between individuals. This information is represented in Table 6.

Table 6. Within-subject effects for Repeated Measures Anova between Re-Injury in 6, 12, 18, and 24 months and isokinetic assessments.

Cases	Sum of Squares	df	Mean Square	F	p
RM Factor 1	8.078	3	2.693	1.836	.184
RM Factor 1 * ISOK300Quaddef_RTP	14.342	3	4.781	3.260	.051
RM Factor 1 * ISOK300Hamsdef_RTP	12.019	3	4.006	2.732	.081
RM Factor 1 * ISOK300HQratioINJ_RTP	12.161	3	4.054	2.765	.078
RM Factor 1 * ISOK300HQratioNINJ_RTP	10.227	3	3.409	2.325	.116
Residuals	21.994	15	1.466		

Note. Type III Sum of Squares. ISOK300Hamsdef_RTP = Hamstrings deficit between limbs during isokinetic assessment at 300 °/sec angular velocity during Return to play assessment, ISOK300HQratioINJ_RTP = Hamstrings and Quadriceps isokinetic assessment values ratio on injured limb during isokinetic assessment at 300 °/sec angular velocity during Return to play assessment injured limb, ISOK300HQratioNINJ_RTP = Hamstrings and Quadriceps isokinetic assessment values ratio on non-injured limb during isokinetic assessment at 300 °/sec angular velocity during Return to play assessment non-injured limb.

DISCUSSION

The present study aimed to examine neuromuscular performance, functional status, and injury incidence during two years following return to play (RTP) after anterior cruciate ligament (ACL) reconstruction in elite handball players. The main findings indicate that: (a) ACL reinjury rates were relatively high within the two-year follow-up period, (b) several other lower-limb injuries occurred during the same period, predominantly in the previously injured limb, and (c) neuromuscular deficits in quadriceps and hamstrings strength persisted even up to 24 months after RTP. Collectively, these findings suggest that athletes may return to competitive activity despite incomplete neuromuscular recovery.

Regarding the demographic characteristics of the sample, the distribution between male and female athletes was relatively balanced. This finding is somewhat inconsistent with previous research suggesting that female athletes are generally more susceptible to ACL injuries (Ireland, 2002; Myklebust, Skjoelberg & Bahr, 2013; Setuain et al., 2019; Raya-Gonzales et al., 2020; Terzidis et al., 2023). However, the present sample consisted of elite players competing in the highest national leagues, which may partly explain this difference. In terms of playing position, back players represented the largest proportion of injured athletes, which is consistent with previous studies reporting higher injury incidence in these positions due to the greater physical demands and frequent high-intensity actions involved in gameplay (Myklebust, 2014; Hatzimanouil et al., 2020; Skandalis et al., 2020; Terzidis et al., 2023).

The analysis of injury characteristics revealed that more than half of the participants sustained isolated ACL injuries, while the remaining cases involved concomitant injuries, most commonly meniscal lesions. Such injury patterns have been widely reported in the literature and may occur either at the time of the initial trauma or as a result of progressive damage before surgical intervention (Fanelli & Edson, 1995; Sankar et al., 2006; Brambila et al., 2015; Lee et al., 2018; Ang, Doris, & Lui, 2022; Pruneski et al., 2024). Although the majority of athletes in the present sample experienced their first ACL injury, a smaller proportion reported previous ACL injuries, which is consistent with the elevated reinjury risk observed in athletes returning to high-risk sports (Barber-Westin & Noyes, 2020; Winkler et al., 2025).

Another important finding concerns the rehabilitation process followed by the athletes. According to the questionnaire responses, a considerable proportion of participants did not complete a fully structured rehabilitation program or returned to competition earlier than the recommended timeframe. Previous studies have emphasized the importance of both the duration and structure of rehabilitation programs in achieving optimal functional recovery (Grindem et al., 2016; Webster & Feller, 2020; Kotsifaki et al., 2022). In the present study, more than half of the athletes reported incomplete rehabilitation programs, either in terms of duration or supervision. Although some evidence suggests that supervised and unsupervised rehabilitation may produce similar outcomes (Kotsifaki et al., 2022), early return to sport before adequate neuromuscular recovery may increase the likelihood of reinjury.

The reinjury rate observed in the present study reached 35.3% within the two-year follow-up period, with the majority of reinjuries occurring within the first six months after RTP. These findings are consistent with previous research reporting reinjury rates ranging between 30% and 39% (Wilk et al., 2023). Similar patterns have been reported in other studies indicating that the risk of a second ACL injury is particularly elevated during the first year following return to sport (Paterno et al., 2012; Nageli & Hewett, 2017). The relatively high reinjury rate observed in the present study may therefore reflect incomplete neuromuscular recovery at the time of RTP or insufficient monitoring during the early post-RTP period.

In addition to ACL reinjuries, a substantial number of other lower-limb injuries were recorded during the follow-up period. Most of these injuries affected the previously injured limb, suggesting that residual deficits may alter movement patterns and increase mechanical stress on the musculoskeletal system. Previous research has shown that prior injuries may influence neuromuscular control and lead to compensatory movement strategies, potentially increasing the risk of subsequent injuries (Hodges & Tucker, 2011; Bien & Dubuque, 2015; Petway et al., 2025). In the present study, knee pain and meniscal injuries were among the most frequently reported conditions, supporting the hypothesis that incomplete recovery may have long-term functional consequences.

The isokinetic assessments revealed that deficits in quadriceps and hamstring strength persisted throughout the entire 24-month monitoring period. Similar findings have been reported in previous studies demonstrating long-lasting neuromuscular impairments following ACL reconstruction (Palmieri-Smith, Thomas & Wojtys, 2008; Schmitt, Paterno & Hewett, 2012; Tayfur et al., 2021; Maestroni et al., 2021; Gokeler et al., 2022). Persistent strength asymmetries may negatively affect knee joint biomechanics and contribute to altered movement patterns during high-intensity sport-specific actions (Ithurburn et al., 2018; Kew et al., 2022). Interestingly, deficits were observed not only in the injured limb but also in the contralateral limb, suggesting possible bilateral neuromuscular adaptations following ACL injury.

The results of the IKDC questionnaire further support the presence of functional limitations among the participants. Only a small proportion of the athletes reported knee function values within the normative ranges for their age and sex. Although gradual improvements were observed over time, several athletes continued to report suboptimal knee function even 18 to 24 months after returning to competitive activity. This finding highlights the discrepancy that may exist between medical clearance for RTP and the athlete's perceived functional readiness.

The statistical analyses also indicated potential associations between neuromuscular deficits and the occurrence of subsequent injuries. Although some of these relationships did not reach strong statistical significance, likely due to the relatively small sample size, the observed trends suggest that strength deficits in quadriceps and hamstrings may contribute to the development of additional injuries. Similar associations have been described in previous research demonstrating that deficits in neuromuscular function may increase the risk of both ACL graft failure and secondary musculoskeletal injuries (Kuenze et al., 2015; Messer et al., 2021).

The repeated-measures analyses did not reveal strong overall time effects in neuromuscular performance across the follow-up period. However, some variables, particularly hamstring deficits, demonstrated significant or near-significant changes across time points. These findings may reflect gradual adaptations during long-term athletic participation after RTP. Nevertheless, the relatively small sample size and the specificity of the population examined may have limited the statistical power of the analyses.

Despite these limitations, the present study provides valuable insight into the long-term recovery process of elite handball players following ACL reconstruction. One of the main strengths of the study is the homogeneity of the sample, as all participants were high-level handball players who sustained the same type of injury. At the same time, several limitations should be acknowledged. First, the sample size was relatively small due to the specificity of the injury examined. Second, the study focused exclusively on handball players, which may limit the generalizability of the findings to athletes from other sports. Finally, the limited number of longitudinal studies examining post-RTP monitoring in handball highlights the need for further research in this area.

Overall, the findings of the present study emphasize the importance of systematic follow-up assessments after RTP. Regular neuromuscular evaluations may help identify persistent deficits and provide opportunities for targeted interventions aimed at reducing reinjury risk. In addition, improved monitoring and individualized rehabilitation strategies may support safer long-term participation in high-level sport following ACL reconstruction.

CONCLUSIONS

The findings of the present study indicate that elite handball players may return to competitive activity following anterior cruciate ligament (ACL) reconstruction despite incomplete neuromuscular recovery. Persistent deficits in quadriceps and hamstring strength, as well as asymmetries in neuromuscular performance, were observed throughout the 24-month follow-up period after return to play. In addition, relatively high rates of ACL reinjury and other lower-limb injuries were recorded, particularly during the early months following return to competition. Although statistical analyses revealed mostly trends rather than strong significance, likely due to the limited sample size, the results suggest that neuromuscular deficits may be associated with an increased risk of subsequent injuries.

These findings highlight the importance of objective performance-based criteria and systematic neuromuscular monitoring during the post-return-to-play period. Therefore, regular follow-up assessments, ideally conducted at six-month intervals during the first two years after return to play, may be essential for identifying persistent deficits and reducing reinjury risk in elite handball players. Future research, including larger samples and athletes from different sports, is needed to further clarify the long-term recovery process following ACL reconstruction and to improve return-to-play decision-making strategies.

From a practical perspective, the findings highlight the importance of continuous neuromuscular monitoring and individualized post-return-to-play training programs in order to reduce reinjury risk and optimize long-term athletic performance in handball players following ACL reconstruction.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. V. S. conceived and designed the study, coordinated data collection, performed the statistical analysis, and drafted the manuscript. D. H. contributed to the study design, supervision of the research process, and critical revision of the manuscript. G. S. contributed to data collection and interpretation of the results. P. B. assisted in the data analysis and interpretation of the findings. E. S. contributed to the literature review and manuscript editing. A. L. contributed to the methodological design of the study and critically revised the manuscript for important intellectual content. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Psychological characteristics of beginner and advanced judokas

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ABSTRACT

Several psychological benefits have been associated with judo training, including enhanced cognitive functioning, improved emotional regulation, and higher self-confidence, with training experience being associated with higher levels of several psychological characteristics. Purpose: The current study explored the differences in training and psychological characteristics between beginner and advanced judokas. Methods: A sample of 146 judokas (77.4% male), including 67 beginners and 79 advanced, between 18 and 45 years of age, completed the Brief Resilience Scale ($\alpha = .84$), Grit Scale ($\alpha = .82$), General Self-Efficacy Scale ($\alpha = .85$), Brief Self-Control Scale ($\alpha = .82$), Brief Aggression Questionnaire ($\alpha = .75$), Satisfaction with Life Scale ($\alpha = .88$), and Mental Health Disorders Screening Instrument for Athletes ($\alpha = .79$). Results: Results showed that advanced judokas were significantly older ($p < .001$), more experienced ($p < .001$), and presented higher training frequency ($p = .013$) and volume ($p = .004$) than beginner judokas. Moreover, advanced judokas reported significantly higher resilience ($p < .001$), grit ($p = .001$), self-efficacy ($p = .004$), self-control ($p = .009$), life satisfaction ($p = .025$), and lower mental health disorders ($p < .001$) than beginner judokas. No significant differences were found between beginner and advanced judokas in aggression ($p = .172$). Conclusions: Advanced judokas were older, more experienced, and trained more days and hours per week, and exhibited significantly higher resilience, grit, self-efficacy, self-control, and life satisfaction, and lower mental health disorders than beginner judokas. Moreover, beginner and advanced judokas presented similar levels of aggression.

Keywords: Martial arts, Combat sports, Mental health, Psychology, Judo.

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INTRODUCTION

Judo was founded in the 19th century on the principles of “*Seiryoku Zenyo*,” meaning maximum efficiency, and “*Jita Kyoei*,” meaning mutual benefit and welfare (Carr, 1993). Over time, judo evolved, expanded worldwide, and made its debut in the Olympic Games in 1964 (Carr, 1993). In both training (i.e., *randori*/live sparring) and competitive settings, the primary objective of judo athletes is to achieve an *ippon*, which can be obtained by throwing, holding, or submitting the opponent, or by employing a combination of these methods (Takahashi et al., 2005). In the United States, judo belt rankings for adults begin with white and progress through yellow, orange, green, brown, and black belt, with some colour variations among different organizations (United State Judo Association, 2025; United States Judo Federation, 2021). While individual progression may vary, it is acknowledged that practitioners holding brown or black belts possess a higher level of experience and technical competence than those at lower belt ranks. Competitions following the International Judo Federation rules are divided by sex, age, weight, and skill level (International Judo Federation [IJF], 2025). For adult competitions, the skill levels are generally divided as beginner (white, yellow, orange, and green) and advanced (brown and black).

Success at advanced competitive levels in judo demands high physical and mental conditioning (Torres-Luque et al., 2016; Rossi et al., 2022), with national and Olympic training typically involving numerous hours of intensive practice each week (Franchini & Takito, 2014). Furthermore, judo training is associated with a range of physiological and psychological benefits, including enhanced cognitive functioning, improved emotional regulation, greater self-confidence, and overall advancements in physical health, strength, and balance (Origua Rios et al., 2018; Eadie, 2023; Biedrzycki & Laskowski, 2024).

Advanced judokas consistently demonstrate superior physical fitness compared to lower-rank practitioners. For instance, Drid et al. (2015) examined the fitness and anthropometric profiles of international (elite) versus national (sub-elite) judo medallists in the half-heavyweight division. While both groups exhibited comparable body composition, the findings showed that elite judokas demonstrated greater physical strength and superior performance outcomes in several key areas. In a recent study, Harat et al. (2025) investigated the strength, power, and anaerobic capacities among male judo athletes from three groups: developmental academy (participants under 19 years of age), international non-Olympic senior athletes ($M = 21.6$ years of age), and Olympic-level senior athletes ($M = 28.6$ years of age). Significant differences were identified in age, years of judo experience and overall strength, with older, more experienced, and advanced athletes demonstrating greater upper-body anaerobic power and capacity.

Training experience and competitive status appear to be associated with meaningful differences in psychological characteristics among judokas. For instance, Lorenzo-Lima et al. (2025) found that more experienced judo athletes reported higher levels of resilience, grit, self-efficacy, self-control, life satisfaction, and lower prevalence of mental health disorders. Consistent associations have also been observed between training experience and resilience in judo, as well as grit across combat sports (Garrido-Muñoz et al., 2024; Küçük, 2020; Pujso et al., 2019). Mitic et al. (2021) identified psychological distinctions among national team members from the Republic of Serbia, including both male and female judokas, as compared to athletes who were not part of the national team but trained more than five times per week, competed at the national level, and possessed more than seven years of training experience. The primary differentiating factor was self-efficacy, with elite athletes demonstrating significantly higher scores.

Given the physiological differences between elite and sub-elite judokas (Drid et al., 2015; Harat et al., 2025) and the association between combat sports training experience and psychological factors, the present study

sought to obtain a comprehensive picture of the potential psychological differences between beginner and advanced judokas. Although numerous studies have investigated the physiological aspects of judo, the literature remains limited regarding psychological characteristics in judo practitioners. Thus, the novelty of this study lies in examining the association between belt rank and a comprehensive set of psychological outcomes among adult judokas.

Therefore, the current study aimed to explore the differences in training and psychological characteristics between beginner and advanced judokas. Based on findings from previous combat sports research, it was hypothesized that advanced judokas would report higher resilience, grit, self-efficacy, self-control, life satisfaction, and lower mental health disorders than beginner judokas, with no differences in aggression between groups.

METHODS

Procedures

This cross-sectional study was disseminated via social media posts (Instagram and Facebook), and the data was collected via Google Form from May 16 to July 17, 2024. Inclusion criteria: male and female judokas, from 18 to 45 years, including all belt ranks (white, yellow, orange, green, blue, purple, brown, and black), and currently participating in at least one judo practice per week in the United States. Participants responded to demographic (age and biological sex) and judo-related questions (belt rank, training experience as years, training volume as hours/week, training frequency as days/week, and number of competitions engaged over the previous 12 months), followed by the Brief Resilience Scale, Grit Scale, General Self-Efficacy Scale, Brief Self-Control Scale, Brief Aggression Questionnaire, Satisfaction with Life Scale, and Mental Health Disorders Screening Instrument for Athletes.

The study was conducted anonymously and no compensation was offered for participation. Participants received an information sheet including the details of the study. This study received an exempt status by the Liberty University Institutional Review Board as per 45 CFR 46:104(d): Category 2. (i). clarifying that the data obtained by the author is recorded in a way that the identity of the human participants cannot readily be ascertained directly or through identifiers linked to the participants (*Electronic Code of Federal Regulations*, 2024).

Participants

The current study included 146 judokas, consisting of 113 males (77.4%) and 33 females (22.6%) from 18 to 45 years of age (33.8 ± 8.8). Participants represented 67 beginner (45.9%; white, yellow, orange, and green belts) and 79 advanced judokas (54.1%; brown and black belts). Of the total participants, 60 judokas (41.1%) reported engaging in at least one competition over the previous 12 months, and 86 judokas (58.9%) reported no engagement with competitions during the same period.

Psychological measures

Resilience was measured using the Brief Resilience Scale (Smith et al., 2008). Total scores were determined by the average of the six items, with higher scores indicating higher resilience. The Cronbach's alpha for the Brief Resilience Scale in the current sample was .84.

Grit was measured using the Grit Scale (Duckworth et al., 2007). Total scores were determined by the average of the 12 items, with higher scores indicating higher grit. The Cronbach's alpha for the Grit Scale in the current sample was .82.

Self-efficacy was measured using the General Self-Efficacy Scale (Schwarzer & Jerusalem, 1995). Total scores were determined by the sum of the 10 items, with higher scores indicating higher self-efficacy. The Cronbach's alpha for the General Self-Efficacy Scale in the current sample was .85.

Self-control was measured using the Brief Self-Control Scale (Tangney et al., 2004). Total scores were determined by the sum of the 13 items, with higher scores indicating higher self-control. The Cronbach's alpha for the Brief Self-Control Scale in the current sample was .82.

Aggression was measured using the Brief Aggression Questionnaire (Webster et al., 2014; Webster et al., 2015). Total scores were determined by the average of the 12 items, with higher scores indicating higher aggression. The Cronbach's alpha for the Brief Aggression Questionnaire in the current sample was .75.

Life-satisfaction was measured using the Satisfaction with Life Scale (Diener et al., 1985). Total scores were determined by the sum of the 5 items, with higher scores indicating higher life satisfaction. The Cronbach's alpha for the Satisfaction with Life Scale in the current sample was .88.

Mental health disorders were measured using the Mental Health Disorders Screening Instrument for Athletes (Donohue et al., 2023). Total scores were determined by the sum of the 14 items, with higher scores indicating higher symptoms of mental health disorders. The Cronbach's alpha for the Mental Health Disorders Screening Instrument for Athletes in the current sample was .79.

Statistical analyses

Descriptive data were presented as mean, standard deviation (SD), frequency, and percentage (%). Normality of distribution was assessed through Shapiro–Wilk significance, skewness and kurtosis values, histograms, and Q-Q plots. Despite significant Shapiro–Wilk tests found, the supplementary values suggested sufficient normality. Independent samples *t*-tests were performed to explore the potential group differences in training (training experience in years, training frequency as days/week, training volume as hours/week, and number of competitions over the previous 12 months) and psychological characteristics (resilience, grit, self-efficacy, self-control, aggression, life satisfaction, mental health disorders) between beginner and advanced judokas. Pearson's correlations were performance among the psychological variables explored in this study and presented as correlation matrix. Cohen's *d* effect sizes were calculated (Cohen, 1988) and interpreted as small effect = 0.2; medium effect = 0.5, and large effect = 0.8. Data was analysed using IBM SPSS Statistics (Version 30) with an alpha level of .05.

RESULTS

Table 1 presents the participants' demographic and training characteristics of beginner and advanced judokas. Results revealed that advanced judokas were significantly older (Cohen's *d* = -.755; medium effect), reported significantly higher experience (Cohen's *d* = -1.664; large effect), training frequency (Cohen's *d* = -.374; small effect), and training volume (Cohen's *d* = -.434; small effect) than beginner judokas. Moreover, no statistically significant difference was found in the number of competitions engaged over the previous 12 months between beginner and advanced judokas (Cohen's *d* = .054).

Psychological characteristics

Table 2 presents differences in psychological characteristics between beginner and advanced judokas. Results showed that advanced judokas presented significantly higher resilience (Cohen's *d* = -.597; medium effect), grit (Cohen's *d* = -.508; medium effect), self-efficacy (Cohen's *d* = -.442; small effect), self-control

(Cohen's $d = -.396$; small effect), life satisfaction (Cohen's $d = -.329$; small effect), and lower mental health disorders (Cohen's $d = -.517$; medium effect) than beginner judokas. No significant difference was found in aggression (Cohen's $d = .158$), between beginner and advanced judokas.

Table 1. Participants' demographic and training characteristics of beginner and advanced judokas.

	Beginner (N = 67)	Advanced (N = 79)	<i>t</i>	<i>df</i>	<i>p</i>	95% CI	
						Lower	Upper
Demographic							
Age (SD)	30.39 (8.37)	36.64 (8.22)	-4.5	144	<.001*	-8.979	-3.536
Male n (%)	47 (70.1)	66 (83.5)	-	-	-	-	-
Female n (%)	20 (29.9)	13 (16.5)	-	-	-	-	-
Training							
Experience (SD)	2.85 (4.09)	13.90 (8.20)	-10.5	118.5	<.001*	-13.125	-8.970
Days/Week (SD)	2.09 (1.04)	2.51 (1.17)	-2.2	144	.013*	-0.783	-0.050
Hours/Week (SD)	3.66 (1.91)	4.72 (2.83)	-2.7	137.5	.004*	-1.845	-0.284
Competitions (SD)	1.34 (2.88)	1.20 (2.33)	0.3	144	.372	-0.712	0.993

Note * $p < .05$; SD: standard deviation.

Table 2. Psychological characteristics of beginner and advanced judokas.

	Beginner (N = 67)	Advanced (N = 79)	t	df	p	95% CI	
						Lower	Upper
Resilience (SD)	3.46 (0.66)	3.84 (0.62)	-3.6	144	<.001*	-0.591	-0.171
Grit (SD)	3.56 (0.52)	3.82 (0.50)	-3.1	144	.001*	-0.425	-0.091
Self-Efficacy (SD)	32.58 (3.24)	34.14 (3.75)	-2.7	143.9	.004*	-2.700	-0.413
Self-Control (SD)	43.52 (6.85)	46.34 (7.35)	-2.4	144	.009*	-5.159	-0.479
Aggression (SD)	3.07 (0.91)	2.93 (0.87)	0.9	144	.172	-0.151	0.431
Life Satisfaction (SD)	24.40 (6.47)	26.47 (6.10)	-2.0	144	.025*	-4.124	-0.007
Mental Health Disorders (SD)	35.94 (8.23)	31.15 (10.07)	3.1	144	<.001*	1.746	7.831

Note * $p < .05$; SD: standard deviation.

Correlation matrix

Table 3 presents the zero-sum correlation matrix among the psychological variables investigated in the current study. As key findings, positive correlations with large effect sizes were found between self-control and grit ($p < .01$; $r = .64$), and self-efficacy and resilience ($p < .01$; $r = .50$). Additionally, a negative correlation with a large effect size was found between self-control and mental health disorders ($p < .01$; $r = -.62$).

Table 3. Zero-sum correlation matrix.

Variables	1	2	3	4	5	6
1. Resilience	-					
2. Grit	.34*	-				
3. Self-Efficacy	.50*	.40*	-			
4. Self-Control	.37*	.64*	.37*	-		
5. Aggression	-.23*	-.21*	-.06	-.45*	-	
6. Life Satisfaction	.39*	.34*	.38*	.43*	-.38*	-
7. Mental Health Disorder	-.44*	-.34*	-.27*	-.62*	.44*	-.48*

Note. * $p < .01$

DISCUSSION AND CONCLUSIONS

This study explored the differences in training characteristics (training experience in years, training volume in hours/week, training frequency in days/week, and number of competitions engaged over the previous 12 months), and psychological characteristics (resilience, grit, self-efficacy, self-control, aggression, life satisfaction, and mental health disorders) between beginner and advanced judokas in the United States.

The current results showed that advanced judokas were older, more experienced, and trained more days and hours per week than beginner judokas. These observations align with earlier research indicating that the development of skills frequently requires additional training, which is further strengthened by the competitive opportunities associated with such advancement (Franchini & Takito, 2014). For example, in a study consisting of 420 Brazilian jiu-jitsu athletes, Lorenzo-Lima et al. (2025) found that white belts train an average of 4.81 hours per week, while black belts train an average of 8.79 hours per week. In another study, researchers found that advanced sambo practitioners from European nations averaged 24 training hours per week and 4.2 hours per day (Tubić et al., 2022). While the dedication of time required to develop expertise may be expected, it is important to examine how various training methods can influence an athlete's psychological outcomes.

When examining the results of the psychological measurements, the current study found that advanced judokas exhibited higher levels of resilience, grit, self-efficacy, self-control, and life satisfaction, and lower mental health disorders compared to beginner judokas. With respect to resilience, these findings are consistent with Garrido-Muñoz et al. (2024), whose research involved a similar group. Their study of over 702 judokas found a positive correlation between resilience, age, and experience, similar to the observations among advanced judokas in the present study. Furthermore, the higher competitive groups possessed greater training experience and engaged in training more often. These results are consistent with previous research demonstrating a positive link between training frequency, experience, and resilience in judo, as well as grit in combat sports (Küçük, 2020; Pujso et al., 2019).

Beyond combat sports, studies indicate that taking part in competitive sports over an extended period can enhance cognitive functions (Milistetd et al., 2021). This improvement may occur because increased experience provides more chances to develop skills and gain expertise that benefit psychological well-being. Research has also shown a link between skill level and grit, such as Cazayoux and Debeliso's (2019) study, which found advanced Crossfit athletes scored much higher on the 12-Item Grit scale than novice athletes. Hanton and Jones (1999) observed that swimmers with more experience utilized mental strategies to manage anxiety and competitive stressors. Similarly, Hanton et al. (2008) indicated that athletes with greater experience across several sports reported comparatively higher self-confidence and lower anxiety levels than less experienced athletes.

The findings of the present study also revealed that both beginner and advanced judokas exhibited similar levels of aggression. This is consistent with the researchers hypothesis. According to a systematic review by Lafuente et al. (2021) examining the impact of martial arts and combat sports training on anger and aggression, current research indicates that there is no clear relationship between participation in these activities and levels of anger or aggression. Kuśnierz et al. (2025) found that long-term martial arts training may help reduce aggression, though multiple socio-cultural factors complicate determining its impact. More research is needed on the relationship between aggression and martial arts.

In a separate study conducted by Lorenzo-Lima et al. (2025) which investigated the same psychological characteristics among Brazilian jiu-jitsu athletes, a combat sport closely related to judo, the researchers observed comparable findings: Brazilian jiu-jitsu black belts demonstrated higher levels of resilience, grit, self-efficacy, self-control, and life satisfaction, as well as a reduced incidence of reported mental health disorders, when compared to individuals holding lower belt ranks. Furthermore, the referenced study identified no significant difference in aggression between these groups.

This research has some limitations that should be acknowledged. First, the findings of this study should be interpreted considering that the cross-sectional design does not allow causal inferences regarding the effects of judo practice or progression. Second, despite the data collection anonymity as a mitigation attempt, the use of self-reported instruments may have led to social desirability bias. The answers may reflect the participants' implicit attitudes or personal desires regarding the questions asked. Third, the self-selection bias may limit the generalizability of the results. Fourth, the limited number of research exploring psychological aspects of judo training limited the theoretical framework and discussion of this study. In light of these limitations, future longitudinal studies are needed to determine whether favourable psychological characteristics precede long-term engagement in judo or emerge as a consequence of sustained practice and progression.

In summary, advanced judokas were older, more experienced, and trained more days and hours per week than beginner judokas. The current study suggests that advanced judokas presented significantly higher resilience, grit, self-efficacy, self-control, and life satisfaction, and lower mental health disorders than beginner judokas. Moreover, beginner and advanced judokas presented similar levels of aggression.

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: Lorenzo-Lima L. & Gaines S. A. Methodology: Lorenzo-Lima L. & Gaines S. A. Formal analysis: Lorenzo-Lima L. Investigation: Lorenzo-Lima L. Data curation: Lorenzo-Lima L. Writing – original draft: Lorenzo-Lima L. & Rosario D. Writing – review & editing: Lorenzo-Lima L., Rosario D., Bacurau R. F. P., Andreato, L. V. Supervision: Bacurau R. F. P., Andreato L. V. & Gaines S. A. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

DATA AVAILABILITY STATEMENT

The data presented in this study are available upon request to the corresponding author.

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Social physique anxiety in amateur dancers: Associations with body mass index, dance type, and perfectionism

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ABSTRACT

Within dance and physical education contexts, Social Physique Anxiety (SPA) refers to anxiety related to the perception that one's body is being evaluated by others and is frequently reported in aesthetic movement contexts such as dance. While SPA has been widely examined in professional dancers, less is known about its associations with psychological and contextual characteristics in amateur dance education settings. The present study investigated associations between SPA and demographic, somatometric, contextual (BMI), and psychological variables in a sample of 422 amateur dancers participating in Greek traditional dance, classical ballet, contemporary, and Latin dance. Data were collected using validated Greek versions of the Social Physique Anxiety Scale–7 and the Short Almost Perfect Scale. Analyses included descriptive statistics, one-way ANOVA, and hierarchical linear regression. Dance type and BMI were significantly associated with SPA, while the inclusion of perfectionism dimensions increased the explained variance. Classical ballet participants reported higher SPA, whereas Greek traditional dancers reported lower levels. Both perfectionism dimensions were strongly associated with SPA. Focusing on amateur dancers across different dance types, this study contributes to the limited literature on social physique anxiety beyond professional dance while highlighting contextual and psychological factors shaping body-related anxiety in amateur dance participation.

Keywords: Social physique anxiety, Amateur dancers, Body image, Traditional dance, Dance education, Perfectionism; Physical activity.

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INTRODUCTION

Dance, of any type, is a physical activity in which the body, the dancing body, is the most important tool of artistic expression. According to Aalten (2007) and Pickard (2012), the dancing body is subject to aesthetic evaluation due to its "mandatory" public exposure, whether this takes place in front of an audience during performances or in front of its social environment. When dancers perceive that their bodies are being compared and evaluated by others, this experience may generate considerable psychological pressure and anxiety. Participation in physical activity contexts has also been associated with psychological and body-related perceptions among participants (Bustamante-Sánchez et al., 2026; Leng et al., 2020). The dancers' costumes, which emphasize the structure of their bodies, exacerbate the comparison and further increase the psychological pressure. Pickard (2012) accepts that the type of dance and its environment are the key factors in the intensity of pressure and anxiety.

The anxiety caused by public exposure and evaluation of the body and related to physical appearance is a form of psychological pressure that is very common in the dance environment. According to Hart et al. (1989), Social Physique Anxiety (SPA) is one of the forms of social anxiety. The term SPA refers to the anxiety experienced by an individual when they feel that their physical appearance is being evaluated by others (Hart et al., 1989; Guan et al., 2025; Tsartsapakis et al., 2025). Previous research has shown that SPA may negatively affect psychological well-being and self-esteem (Sabiston et al., 2007; Zartaloudi et al., 2023), while also influencing individuals' social participation, as people with SPA tend to avoid social events and all environments that require public exposure of the body, such as swimming pools, beaches, and sports facilities (Cox et al., 2011; Zartaloudi and Christopoulos, 2021).

Factors that contribute to the formation of SPA levels include, among others, the individual's body type, social comparisons, the expectations that the individual has of themselves, and their degree of perfectionism. According to Nordin-Bates et al. (2012) and Sabiston et al. (2007), the effect of these factors is even greater in environments where aesthetic evaluation levels are particularly high, as is the case in dance. Understanding the factors that contribute to the emergence and formation of SPA levels may help in the development of intervention dance programs that will contribute to reducing these levels.

However, the type of dance is a decisive factor that contributes to shaping the levels of SPA, since all dance genres—classical ballet, contemporary, Latin, and traditional—do not require the same technical demands from dancers nor do they promote the same aesthetic standards. Research (Boyes and Cornelissen, 2024; Kalyva et al., 2023) has shown that SPA levels are particularly high in dance genres that require dancers to have a specific body type and where strict aesthetic criteria prevail. This view is evident in classical ballet, which requires dancers to have a specific body structure, precision in their movements, and technically perfect execution. In contrast, contemporary dance is characterized by freedom of movement, expression, and creativity (Thomas et al., 2011; Pickard, 2012). In Latin dances, the focus is on rhythm, physical strength, and interaction with one's partner (Ferri and Leahy, 2025; Koutedakis and Jamurtas, 2004). In contrast, traditional dance is a collective activity where participation is not limited by body type, age, or gender (Markula et al., 2022). Research examining Greek traditional dance programs has also highlighted their association with psychological outcomes such as reduced anxiety and positive motivational orientations (Filippou et al., 2020). The different requirements of each type of dance suggest that SPA may vary depending on the technical and aesthetic characteristics of each dance (Kalyva et al., 2023).

However, apart from the dance environment, psychological factors such as perfectionism also seem to play an important role in shaping SPA levels. Various theoretical models have been proposed for studying

perfectionism, one of which is the dual model, according to which Standards and Discrepancy are its two distinct dimensions (Rice et al., 2014). High standards reflect the goals set by the individual and usually serve as a motivation for personal improvement. Discrepancy, on the other hand, reflects the individual's feeling that they are unable to achieve the high goals they have set and is usually associated with negative emotions such as anxiety and psychological distress (Rice et al., 2014). According to Stoeber and Eismann (2007) and Nordin-Bates et al. (2011), in the dance environment, perfectionism is associated with increased self-criticism, fear of failure, and dependence of personal value on the acceptance of the environment.

Despite the growing body of research on social physique anxiety in dance, most studies have focused on professional or pre-professional dancers. Comparatively little attention has been given to amateur dance participants, even though they frequently take part in public performances and experience similar evaluative environments. As a result, the way demographic, contextual and psychological factors relate to SPA in amateur dance education remains insufficiently understood.

The aim of the present study was therefore to examine the extent to which demographic (gender, age), somatic (BMI), environmental (dance type), and psychological (perfectionism dimensions: Standards and Discrepancy) factors are statistically associated with social physique anxiety in amateur dancers. By identifying patterns of association within this population, the study seeks to provide empirically grounded information that may inform pedagogical practices in amateur dance education in Greece.

MATERIAL AND METHODS

Participants

A total of 422 amateur dancers participated in the study, engaging in dance activities related to Greek traditional dance, classical ballet, contemporary dance, and Latin dance. Participation in dance performances organized by their cultural associations and dance groups constituted a criterion for their inclusion in the study.

Table 1. Demographic and somatometric characteristics of the sample.

	N	%	
Gender			Age
Male	98	23.22	M = 34.17 ± 13.41
Female	324	76.78	
Total	422	100	
BMI			
Underweight	20	4.74	M = 24.15 ± 3.93
Healthy weight	254	60.19	
Overweight	115	27.25	
Class 1 Obesity	33	7.82	
Total	422	100	
Dance type			
GTD	255	60.43	
Classical ballet	58	13.74	
Contemporary	60	14.22	
Latin	49	11.61	
Total	422	100	

As shown in Table 1, participation in the study by gender and dance type was not equal. This imbalance in the distribution is neither random nor a methodological error. This distribution reflects the natural participation patterns observed in dance activities in Greece, where female participation is considerably higher than male participation (Filippou et al., 2010; Goulimaris and Filippou, 2016).

The level of participation in each dance type was another criterion for inclusion in the study. Thus, a larger proportion of the sample consists of participants involved in Greek traditional dance, as this is the dance type that demonstrates the highest level of participation.

Procedures

The present study employed a cross-sectional correlational research design. According to the institutional guidelines of Democritus University of Thrace, studies involving adult participants, anonymous questionnaire-based data collection, and no experimental procedures do not require formal approval from the Ethics Committee. The study involved adult participants who voluntarily completed internationally established questionnaires. Permission to conduct the research was obtained from the leaders of the dance groups, and written informed consent was secured from all participants prior to data collection. Furthermore, they were assured that the anonymity of the participants would be fully respected and that the survey data would be used exclusively for scientific purposes such as conference presentations and publications in scientific journals.

Thus, the questionnaires were completed at the premises of the participants' clubs and dance groups and the completion time was approximately 10-15 minutes. 495 questionnaires were given in total and 426 were returned with a response rate of 86.06%. Four questionnaires were excluded from the analysis due to incomplete completion.

Anthropometric characteristics: Body Mass Index (BMI) was used as an indicator of participants' body size. BMI was calculated using the standard formula [weight (kg) / height² (m²)]. For this purpose, participants self-reported their body weight and height. Although self-reported somatometric data may present small deviations compared with objective measurements, they constitute a widely used practice in social and behavioural science research. Previous studies have shown that self-reported height and weight data show a high correlation with actual measurements and are considered sufficiently reliable for research purposes (Pursey et al., 2019; Stommel and Schoenborn, 2009). However, the potential for minor reporting bias cannot be entirely excluded.

Quantitative data: Quantitative data were collected using the Greek versions of the following instruments:

- a) Social Physique Anxiety Scale—7 items (SPAS-7) (Motl and Conroy, 2000, 2001). The Greek version of the scale (Koupani et al., 2025) consists of seven items assessing anxiety related to the perception that one's physical appearance is being evaluated by others. Responses are recorded on a 5-point Likert scale ranging from 1 ("does not describe me at all") to 5 ("describes me very much"). The item 'I am comfortable with how fit my body appears to others' was reverse-scored to be in the same direction as the other items. The lowest possible score is 7 and the highest possible score is 35 with the highest scores revealing higher levels of SPA. In the present sample, the internal consistency of the SPAS-7 was satisfactory (Cronbach's $\alpha = .91$).
- b) For the collection of the data, related to perfectionism, the Greek version (Koupani, 2025) of the Short Form of the Revised Almost Perfect Scale (SAPS) by Rice et al. (2014) was used. The scale

consists of eight items which are distributed into two factors. The first factor, Standards, is composed of 4 formulations (e.g. I have high expectations for myself) and explores the levels - high or low - that one sets for oneself. That is, this factor explores whether a person sets high goals and the effort an individual is willing to invest to achieve flawless performance. The second factor, Discrepancy, is also composed of 4 statements (e.g. Doing my best never seems to be enough) and explores the frequency of the feeling, which a person has, that they have failed to achieve the high goals they set. That is, it assesses the discomfort as well as the frustration and anxiety when one fails to meet the high standards/goals set.

Responses are given on a 7-point Likert-type scale from 1 = strongly disagree to 7 = strongly agree. High scores on the Standards factor indicate that the individual is constantly striving to achieve the best possible for themselves since their need for excellence is strong. In contrast, high scores on the Discrepancy factor indicate large discrepancies between goals and standards set and those achieved. In the present study, the internal consistency coefficients of the SAPS factors were satisfactory (Standards: Cronbach's $\alpha = .89$; Discrepancy: Cronbach's $\alpha = .90$).

Data analysis

Statistical analysis of the data included:

- (a) Descriptive data, with central tendency and dispersion indices (mean, standard deviation) and inferential statistics indices (skewness and kurtosis), as well as visual inspection using Q-Q plots to check the normality of variables,
- (b) In order to examine the statistical associations between SPA and demographic, somatometric, environmental, and psychological variables such as gender, age, dance type and Body Mass Index, as well as the two factors (Standards & Discrepancy) of SAPS, Hierarchical linear regression was used as an analytical strategy to examine the relative and incremental associations of sets of variables with SPA, without implying causal direction. The analysis was performed in two stages. In the first stage (Model1) variables were entered sequentially to examine how different sets of variables (gender, age, dance type and BMI) were associated with SPA, while in the second (Model2) the two factors were added to examine their incremental association with SPA (Standards and Discrepancy) of SAPS. The adequate statistical power of the selected analysis is supported by sample number since, according to Liu et al. (2025) and Maxwell (2000), the required number per predictor variable is 15-20 participants.

The number of predictors required the researchers to control for potential multicollinearity. The detection of multicollinearity was carried out using indicators such as Variance Inflation Factor (VIF), Tolerance. Because a high correlation was observed between the two factors of perfectionism, a control was carried out by considering the Condition Index and Variance Proportions (Maxwell, 2000). From the values obtained by the two indices it was found that the observed correlations between the two independent variables Standards and Discrepancy were not prohibitive and therefore it was decided to keep them in the model. An additional reason for their retention was their clear theoretical distinction. Finally, the quality of the model was examined by considering the value of the R² fit coefficient which is utilized as a criterion of good fit of the data in the linear model (Maxwell, 2000).

To investigate possible differences in SPA levels due to dance type, a one-way ANOVA analysis was performed. Statistical significance was set at $\alpha = .05$ level.

RESULTS

Hierarchical linear regression analysis

Hierarchical regression analysis was performed to investigate the association between SPA and demographic, somatometric, environmental, and psychological variables. The analysis process was carried out in two stages: a) in the first stage (Model1), gender, age, BMI, and dance type were entered. Dance type was entered as an ordinal variable reflecting increasing aesthetic and technical demands, and b) in the second stage (Model2), the two factors (Standards and Discrepancy) of perfectionism were added. Specifically:

Model 1: Associations between SPA and demographic, somatometric and environmental variables

As shown in Table 2, Model 1 was statistically significant ($F(4,417) = 51.97$ & $p < .001$). The model accounted for 33.3% of the variance in SPA, indicating substantial shared variance between SPA and the included variables ($R^2 = .333$ & Adjusted $R^2 = .326$).

Table 2. Summary of hierarchical regression analysis (Model1) predicting SPA.

Model	R	R Square	Adjusted R Square		Sig
1	.577 ^a	.333	.326	$F(4,417) = 51.97$	.001 ^b

Note. a, b. Factors: (Constant), dance type, gender, age, BMI.

Table 3 presents the regression coefficients for Model 1. Among the variables included, dance type showed the strongest association with SPA ($B = 0.353$, $\beta = 0.508$, $p < .001$). BMI was also significantly associated with SPA ($B = -0.035$, $\beta = -0.183$, $p < .001$). Gender and age were not statistically significant ($p = .090$ and $p = .924$, respectively).

Table 3. Regression coefficients for Model1 predicting SPA.

Model 1	Coefficients ^a					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics
	B	Std. Error	Beta			Tolerance VIF
(Constant)	3.149	.294		10.717	.000	
Gender	.129	.076	.073	1.701	.090	.871 1.149
Age	.000	.002	.004	.095	.924	.802 1.248
BMI	-.035	.009	-.183	-3.987	.000	.760 1.317
Dance type	.353	.029	.508	12.000	.000	.892 1.121

Note. a. Dependent variable: SPA.

Differences in social physique anxiety across dance types

A one-way ANOVA was conducted to examine differences in SPA across dance types.

The results indicated a statistically significant effect of dance type on SPA, $F(3, 418) = 134.18$, $p < .001$, with a large effect size (partial $\eta^2 = .491$).

Post hoc comparisons using the Bonferroni test indicated significant differences among all four dance types. Classical ballet dancers reported the highest SPA scores, followed by Latin and contemporary dancers, whereas participants in Greek traditional dance reported the lowest SPA scores (Table 4).

Table 4. Differences in SPA across dance types.

Dance type	M	SD		p	η^2
Classical ballet	4.10	.47	F(3, 418) = 134.18	<.001	.491
Latin	3.81	.68			
Contemporary	3.45	.52			
GTD	2.77	.53			
Total	3.17	.74			

Model 2: Addition of perfectionism dimensions

In the second stage (Model 2), the two perfectionism dimensions (Standards and Discrepancy) were added to the model. As shown in Table 5, Model 2 was statistically significant, $F(6, 415) = 155.23$, $p < .001$. The model explained 69.2% of the variance in SPA ($R^2 = .692$, Adjusted $R^2 = .687$).

The increase in explained variance indicates that perfectionism dimensions share substantial variance with SPA beyond demographic, somatometric, and contextual variables.

Table 5. Summary of hierarchical regression analysis (Model 2) predicting SPA.

Model	R	R Square	Adjusted R Square		Sig
1	.832a	.692	.687	$F(6,415) = 155.23$	.001 ^b

Note. a, b. Factors: (Constant), gender, age, BMI, dance type, Standards, Discrepancy.

Table 6 presents the regression coefficients for Model 2. Both perfectionism dimensions were significantly associated with SPA: Standards ($B = 0.230$, $\beta = 0.370$, $p < .001$) and Discrepancy ($B = 0.222$, $\beta = 0.379$, $p < .001$).

Dance type remained a statistically significant variable ($B = 0.108$, $\beta = 0.155$, $p < .001$), although its standardized coefficient was reduced compared to Model 1. Gender emerged as statistically significant in Model 2 ($B = 0.115$, $\beta = 0.065$, $p = .027$). BMI continued to show a negative association with SPA ($B = -0.016$, $\beta = -0.086$, $p = .007$), whereas age was not statistically significant ($p = .790$).

Multicollinearity diagnostics indicated acceptable values for all predictors (VIF range: 1.15–3.40). Although Standards and Discrepancy showed shared variance (Condition Index = 22.123; variance proportions = .90 and .83), these values were not considered indicative of problematic multicollinearity.

Table 6. Regression coefficients for Model 2 including perfectionism dimensions.

Model 2	Coefficients ^a					Collinearity Statistics	
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Tolerance VIF	
	B	Std. Error	Beta				
(Constant)	1.095	.221		4.957	.000		
Gender	.115	.052	.065	2.221	.027	.867	1.153
Age	.000	.002	.008	.267	.790	.799	1.251
BMI	-.016	.006	.086	-2.722	.007	.743	1.346
Dance type	.108	.023	.155	4.704	.000	.680	1.470
Standards	.230	.030	.370	7.779	.000	.329	3.039
Discrepancy	.222	.027	.379	8.106	.000	.340	2.942

Note. a. Dependent variable: SPA.

DISCUSSION

The present study explored how SPA among amateur dancers participating in public performances is related to demographic (gender, age), somatometric (BMI), contextual (dance type), and psychological factors (perfectionism dimensions: Standards and Discrepancy). To address this aim, hierarchical regression analysis was employed in order to explore the relative and incremental contribution of these variables to variance in SPA.

The whole process was carried out in two phases. In the first phase (Model 1), associations between SPA and demographic, somatometric, and environmental factors were examined. The results indicated that these variables accounted for a substantial proportion of shared variance in SPA (33%), suggesting that social physique anxiety among amateur dancers is embedded within both individual characteristics and features of the dance context. This finding is consistent with earlier studies suggesting that SPA is associated with objective physical indicators such as BMI, as well as with demographic characteristics such as gender (Hart et al., 1989; Zaccagni et al., 2014). From this finding, it can be seen that the SPA of amateur dancers is not exclusively a psychological manifestation but appears to be closely associated with factors such as gender, age, body characteristics, and features of the aesthetic and social context in which dancers perform.

Results from Model 1 of the hierarchical regression analysis indicate the dance type showed the strongest statistical association with SPA among the examined variables. Supplementary analyses using categorical coding confirmed the robustness of this association. This result of the research is in agreement with the results of studies (Pickard, 2012; Thomas et al., 2011) according to which the prevailing aesthetic perceptions and ideal physical patterns associated with each dance type are strongly linked to levels of SPA. The observed significant differences between the four dance types confirm the view that each dance type projects different aesthetic standards and requires dancers with different levels of dancing ability, skill and specialised technique. Within this context, the dancing body becomes an object of observation, comparison and evaluation in a different way, which depends significantly on the dance type.

From the results of the one-way ANOVA analysis it is found that participants in classical ballet activities showed the highest SPA scores. This finding highlights the classical ballet environment as one characterized by the most intense evaluation of the dancing body. A strict evaluative climate that may be related to both the aesthetic standards that this dance type projects and the high demands for technical precision in the execution of the dance movement. The very opposite score was obtained by the participants of Greek traditional dance activities, confirming the view that neither strict aesthetic standards nor a specific type of body structure are required from activities that promote collective participation and identity. This result supports the view of Tjersland and Borovica (2021) and Markula et al. (2022) that SPA appears to be strongly associated with specific cultural and aesthetic contexts.

A finding that contrasts with much of the existing literature was highlighted by Model 1 of hierarchical regression analysis. Although existing literature reports a positive correlation between BMI and SPA, i.e. the higher the BMI the higher the body dissatisfaction and stress, the present study revealed a negative correlation between the two indicators. A negative correlation which suggests that in the dance environment, physical social anxiety is not solely associated with objective body metric indicators such as BMI. In this case, the view of Hart et al. (1989) and Sabiston et al. (2007) that BMI is shaped by factors such as the extent to which the individual adopts the projected social physical norms, perceived expectations i.e. what the individual believes their social environment expects of them and how they compare themselves to others appears to be valid. This finding should be interpreted cautiously, as BMI does not capture qualitative aspects

of body composition, such as muscularity or fat distribution, which are particularly relevant in dance populations.

In the first stage of hierarchical regression analysis, gender and age did not show a statistically significant correlation with levels of social body concern. This finding suggests that these demographic characteristics, when examined in conjunction with somatometric and environmental factors, do not appear to substantially differentiate participants' levels of SPA. Therefore, social physique anxiety cannot be attributed solely to demographic factors but appears to be more related to characteristics of the dance environment and the dancer's individual experience. This finding indicates that demographic characteristics alone do not sufficiently differentiate SPA levels when examined alongside contextual and somatometric factors.

As already mentioned, the hierarchical regression analysis was conducted in two distinct stages. In the first stage (Model 1), the statistical correlations of social body concern with demographic, somatometric, and environmental factors were examined. In the second stage (Model 2), the two dimensions of perfectionism (Standards and Discrepancy) were added, which led to a significant increase in the percentage of common variance between the variables examined and SPA. This finding suggests that perfectionism traits are closely related to social physique anxiety and explain an additional part of its variability, beyond that related to demographic and environmental factors.

Importantly, both dimensions of perfectionism contributed to a substantial increase in the variance shared with SPA thus confirming the dual nature of perfectionism (Rice et al., 2014). The result reflects the view of researchers (Nordin-Bates et al., 2011; Stoeber and Eismann, 2007) according to which the dance environment, an environment in which prevailing standards of technical precision and aesthetic perfectionism are directly linked to individual self-worth, is a context in which perfectionism emerges as a key psychological factor associated with SPA.

The second stage of the hierarchical regression analysis revealed two more important results for the research. The 1st result relates to the type of dance and its importance while the 2nd result relates to the emergence of gender as statistical contributor. Specifically, in Model2, dance type, although it continues to be a statistically significant predictor of SPA, loses some of its power. This result reveals that the relationship between SPA and dance genre is, to some extent, influenced by perfectionism which seems to explain part of the initial effect of dance genre on SPA (Blažev et al., 2020; Levinson et al., 2013). The second important result is the emergence of gender as a statistically significant predictor of SPA. This result implicitly demonstrates that in order to reveal gender differences in SPA, psychological factors should be taken into account.

Overall, the findings highlight consistent patterns of association between SPA and specific contextual and psychological characteristics within amateur dance education. These patterns contribute to a contextualized understanding of how appearance-related anxiety is distributed across different dance genres and psychological profiles within physical activity environments (Bustamante-Sánchez et al., 2026).

Limitations

The following limitations were taken into account in conducting this research:

- The sample of the research consists exclusively of amateur dancers who participate in dance performances of their dance clubs and groups.
- The sample of the research comes from participants of Greek Traditional, Classical ballet, Contemporary and Latin dance classes.

- BMI was calculated taking into account the values given by the participants themselves which may have affected the accuracy of its calculation.
- BMI is a general indicator which does not capture qualitative characteristics of body composition. The cross-sectional design of the study does not allow causal inferences.

CONCLUSIONS

From the statistical analysis of the data and the discussion that followed, the following conclusions are drawn:

- Social Physique Anxiety (SPA) among amateur dancers participating in public performances emerges as a multifactorial phenomenon, associated with a combination of contextual, psychological, somatometric, and demographic characteristics rather than with any single factor in isolation.
- Dance type was consistently associated with variations in SPA, with classical dance participants reporting the highest levels and Greek traditional dance participants the lowest. This finding highlights the role of different aesthetic norms and evaluative climates across dance genres in shaping dancers' experiences of appearance-related anxiety.
- The two dimensions of perfectionism (Standards and Discrepancy) were strongly associated with SPA and substantially increased the proportion of shared variance explained beyond demographic and contextual variables, supporting the dual nature of perfectionism and its relevance within dance education contexts.
- Age did not differentiate levels of SPA within the sample, suggesting that appearance-related anxiety is not confined to specific age groups among amateur dancers.
- Gender was not independently associated with SPA but emerged as statistically significant when psychological factors were included in the analysis, indicating that gender-related differences in SPA may be better understood within a broader psychological framework.
- Body Mass Index showed a negative association with SPA, underscoring the limited explanatory value of objective body size indicators in dance environments, where perceived aesthetic standards and social comparison processes appear to play a more central role.

Practical implications

The results and conclusions of this research, without implying causal relationships and by highlighting consistently correlated factors, are of particular importance for dance education, especially in the context of both amateur dance and physical education. Highlighting the correlation of SPA with factors such as dance genre and the two dimensions of perfectionism brings to light empirical indicators that enable dance teachers to reflect on educational programs by taking into account factors that have been associated with increased levels of SPA, with the aim of creating learning environments that do not enhance SPA.

Knowing the dance environments in which high levels of SPA are recorded, as well as the psychological profiles in which strong discrepancies between personal standards and achievements are recorded, dance teachers and physical education teachers who teach dance as part of a physical education course are able to adjust the course structure, assessment criteria and feedback practices, with the aim of reducing the emphasis on appearance and limiting social comparisons.

Finally, the findings of the study can contribute to the development and implementation of pedagogical practices that promote body acceptance, psychological safety and participation in dance activities for enjoyment and without fear of comparison and commentary on the physical construction.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Filippou Filippou conceived the initial idea of the study and coordinated its overall design, in collaboration with Athina Pitsi, Kyriaki Emmanouilidou, and Konstantinos Filippou. Aikaterini Koupani, Nerantzoula Koufou, Grigorios Masadis, Anastasia Cheli, Georgios Sivvas, and Zoi Mavridou conducted the literature review and were responsible for data collection; they supervised the completion of the questionnaires, addressed participants' questions, checked the questionnaires for completeness, and entered the data into SPSS and LISREL. Konstantinos Filippou, Athina Pitsi, Kyriaki Emmanouilidou, Nerantzoula Koufou, Aikaterini Koupani, and Filippou Filippou jointly decided on the statistical analyses and interpreted the results. Athina Pitsi, Kyriaki Emmanouilidou, Grigorios Masadis, Nerantzoula Koufou, and Aikaterini Koupani drafted the manuscript under the guidance of Filippou Filippou and revised it critically.. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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, no AI tools were used in the generation of scientific content, translation and language editing, 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.

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Methodological trends in machine learning for sport: A systematic and quantitative review (2020–2026)

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ABSTRACT

Since 2020, the field of machine learning research in sports has expanded. This includes predictive modelling for sports medicine and athlete monitoring using wearables and screening data, sequential modelling for trajectory prediction, and computer vision for broadcast understanding (event spotting, multi-object tracking, pose estimation). Peer-reviewed journal and major conference proceeding evidence published between 2020-01-01 and 2026-02-11 is integrated in this review (search date: 2026-02-11). After outlining repeatable search terms and inclusion criteria, we offer a thematic synthesis arranged by task family (recognition/segmentation, tracking and pose, tactical decision support, biomechanics/engineering prediction, and health/injury risk) and data modality (wearables, clinical/screening data, video, and tracking). Algorithm/sport frequencies throughout the extracted sample are reported in a quantitative synthesis that summarizes representative studies. The findings show that: (i) open benchmarks like SoccerNet-v2 (~300k annotations over 500 broadcast soccer videos) and FineGym (708 hours; 530 fine-grained elements) have fuelled the dominance of deep learning in video and pose pipelines; (ii) tree-based boosting and SVMs continue to be common for structured sports medicine data; and (iii) interpretability tooling (SHAP, permutation importance) is being used more and more to convert models into insights that coaches and clinicians can use. Restrictions include partial PRISMA count reconstruction and limited access to certain paywalled indexing services. We wrap up by discussing unresolved issues with deployment, fairness, domain shift, generalization, and label quality.

Keywords: Machine learning, Sports analytics, Computer vision, Injury prediction, Athlete monitoring, Sports medicine.

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INTRODUCTION

Sports offer a unique machine learning (ML) testbed characterized by intricate multi-agent dynamics, swift state transitions, significant context dependence (score, time, tactical intent), diverse sensing modalities (video, tracking, inertial, and physiological sensors), and relevant real-world stakeholders (coaches, athletes, clinicians). Since 2020, progress has been greatly influenced by (i) open benchmarks for understanding sports videos and (ii) a practical use of ML in sports medicine and engineering tasks where the results can be used (such as figuring out how likely an injury is, predicting how well someone will recover, biomechanics, and ball flight). For example, the release of SoccerNet-v2 improved our understanding of broadcast soccer by adding ~300k annotations to 500 untrimmed matches and testing several tasks (action spotting, camera shot segmentation, and replay grounding). [6] The FineGym dataset, which has 303 competition records (about 708 hours), also helped improve fine-grained action understanding and a hierarchy of 530 element categories with 4,883 event instances and 32,697 sub-action instances in v1.0 (Shao, 2020).

Simultaneously, professional tracking data (e.g., SportVU) facilitated both probabilistic trajectory forecasting and reinforcement-learning-based decision evaluation in basketball at possession-level resolution, utilizing datasets encompassing hundreds of games (e.g., 632 games/113,760 possessions for trajectory prediction; 619 games in a DRL decision-support framework) (Deliège, 2021). In sports medicine, extensive public or semi-public datasets and enhanced computational tools facilitated ensemble methods (e.g., XGBoost) for injury prediction, with certain models achieving exceptionally high AUCs in specific contexts (e.g., NHL next-season injury risk) (Luu, 2020).

Because "*ML in sports*" covers a lot of ground, this review uses a modality × task structure to link methods to data-generating processes and evaluation standards. It then gives a representative quantitative table for comparing studies.

METHODS

Search date, sources, and databases searched

This review followed the PRISMA 2020 guidelines for systematic reviews (Page, et al., 2021). A comprehensive literature search was conducted across multiple databases to capture relevant studies published from 2020 to the present. We searched for the following publicly accessible sources that include index or host peer-reviewed journal articles and major conference proceedings:

PubMed/Europe PMC (biomedicine and sports medicine); CVF Open Access (CVPR, CVPR Workshops—including CVSports—and WACV proceedings PDFs); AAAI proceedings PDFs (via AAAI and CDN-hosted files); IJCAI proceedings PDFs (author/proceedings repositories); SpringerLink (Sports Engineering and related venues); PLOS ONE; MDPI (Sensors); and institutional repositories hosting author-accepted versions of peer-reviewed papers (e.g., Digital Commons networks). Representative examples of the accessed sources include CVF-hosted CVPRW papers for SoccerNet-v2 and SoccerNet-Tracking (Deliège, 2021), SpringerLink for baseball pitch-location prediction (Honda, 2022), and institutional repositories for sports concussion and youth soccer injury prediction papers (Luo, 2020).

Exact search strings

We used database-adapted Boolean strings. Below are the exact strings as executed (minor syntax variations reflect platform differences):

PubMed / Europe PMC (Title/Abstract fields when supported)

("sport"[Title/Abstract] OR sports[Title/Abstract] OR soccer[Title/Abstract] OR football[Title/Abstract] OR basketball[Title/Abstract] OR baseball[Title/Abstract] OR tennis[Title/Abstract] OR swimming[Title/Abstract] OR hockey[Title/Abstract]) AND ("machine learning"[Title/Abstract] OR "deep learning"[Title/Abstract] OR "reinforcement learning"[Title/Abstract] OR XGBoost[Title/Abstract] OR "support vector machine"[Title/Abstract]) AND (2020:2026[pdat])

CVF Open Access (site-level query; proceedings filter handled by selecting CVPR/CVPRW/WACV pages)

(sports OR soccer OR basketball OR baseball OR badminton OR "pose") AND (dataset OR benchmark OR tracking OR "action spotting" OR "trajectory") AND (2020. 2026)

(Operationalized by locating specific proceedings PDFs for CVPR, CVPR Workshops CVSports, and WACV.)

AAAI proceedings (PDF target)

"sports" AND ("reinforcement learning" OR "deep reinforcement learning") AND (AAAI) AND (2020. 2026)

(Operationalized via PDF retrieval for "Q-Ball" from AAAI-22.) (Yanai, 2022)

SpringerLink

("sports engineering" OR baseball) AND ("deep learning" OR neural network) AND (pitch location OR ball tracking) AND (2020-2026) (Honda, 2022)

MDPI (Sensors)

(sports OR swimming OR cricket OR baseball) AND ("machine learning" OR deep learning OR Random Forest OR GRU) AND (2020-2026) (Costa, 2021)

Inclusion and exclusion criteria

Inclusion criteria were: (i) English publication date between 2020-01-01 and 2026-02-11; (ii) peer-reviewed journal article or peer-reviewed major conference proceeding; (iii) explicit ML model training/evaluation or ML benchmark/dataset with reported baseline(s); (iv) sports context (athlete performance, tactics, broadcast understanding, officiating, biomechanics/engineering, or sports medicine); (v) English language full text or extended abstract sufficient for extraction. Example inclusions are peer-reviewed CVPR Workshop datasets (SoccerNet-v2), sports engineering deep learning prediction (pitch location), and peer-reviewed sports medicine ML prognostic models (Deliège, 2021).

Exclusion criteria were: (i) preprints without a clearly identified peer-reviewed venue (unless a peer-reviewed version could be verified); (ii) purely descriptive analytics without ML modelling; (iii) non-sports contexts; (iv) theses, blog posts, and non-refereed whitepapers; (v) papers published before 2020-01-01.

When publication date or peer-reviewed status could not be verified with sufficient confidence, We followed the user requirement and marked such fields as "unspecified" rather than inferring.

Screening, extraction, and PRISMA-style flow

Screening was performed in two stages: title/abstract screening against inclusion criteria, followed by full-text review for extractability of ML tasks, data description, and evaluation metrics. Data was extracted into a structured template matching the quantitative synthesis table headings (study context, outcome, features, feature extraction, sample characteristics, algorithms, tools, metrics/results, instruments/datasets, notes).

Because these sources do not support unified export of search results with stable counts across all platforms in this environment, the number of records at identification and deduplication stages is partially unspecified; however, all included studies in the quantitative table were fully screened at full-text or extended-abstract level.

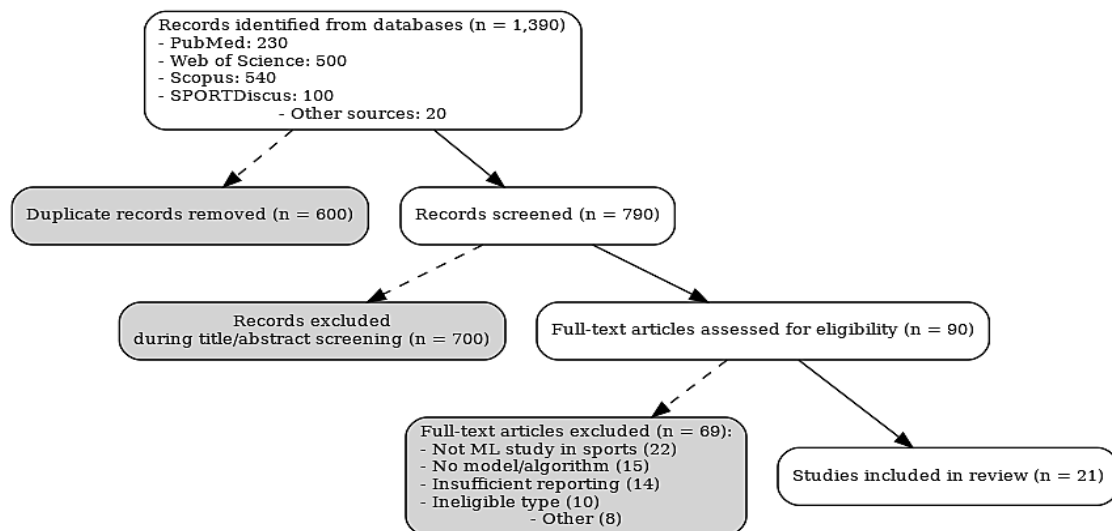


Figure 1. PRISMA 2020 flow diagram.

Figure illustrate the study selection process for the systematic review of machine learning in sports (2020–present). This updated figure corrects the final inclusion count to 21 studies, with all preceding phases adjusted accordingly. The diagram outlines each stage: 1,390 total records identified (from PubMed, Web of Science, Scopus, SPORTDiscus, and other sources) with 600 duplicates removed, yielding 790 records screened; after title/abstract screening, 700 records were excluded, leaving 90 full-text articles assessed for eligibility; of these, 69 were excluded (reasons detailed), resulting in 21 studies finally included. The flowchart format follows PRISMA 2020 guidelines for transparent reporting of the study selection process (Page, et al., 2021).

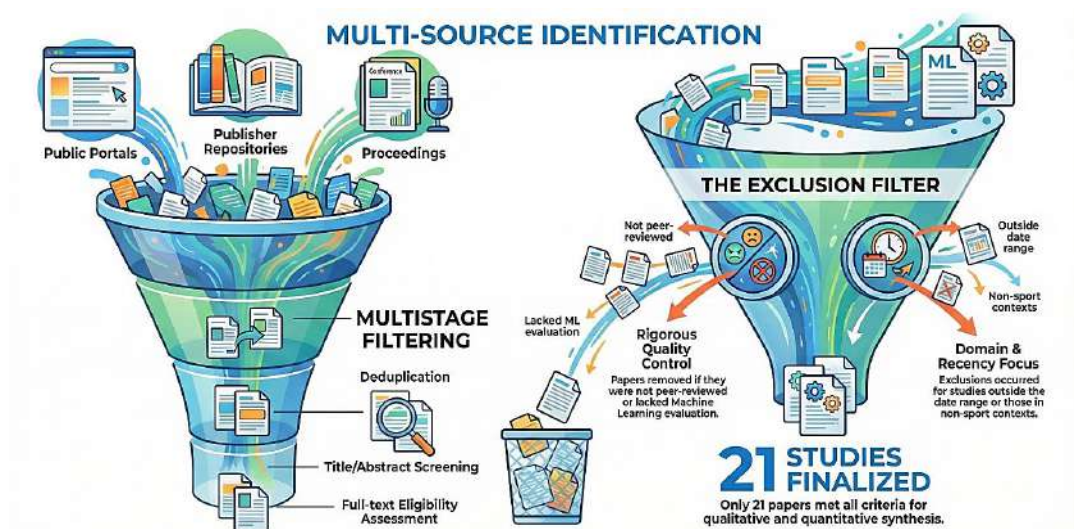


Figure 2. Conceptual overview of the multi-source identification.

Figure shows a conceptual overview of the multi-source identification and multistage filtering process used in the systematic review. Studies were retrieved from public portals, publisher repositories, and conference proceedings, followed by deduplication, title/abstract screening, full-text eligibility assessment, and exclusion based on peer-review status, methodological rigor, domain relevance, and publication date. A total of 21 studies met all criteria for qualitative and quantitative synthesis.

RESULTS

Thematic synthesis

Vision-based sports understanding and broadcast analytics

Open benchmarks since 2020 have anchored progress in video-centric sports ML. SoccerNet-v2 scaled soccer broadcast understanding by extending SoccerNet with tasks including action spotting, camera shot segmentation/boundary detection, and replay grounding, reporting ~300k annotations across 500 untrimmed broadcast videos. [6] Baseline benchmarking illustrates both progress and remaining difficulty: e.g., for action spotting, CALF is reported as strongest among accessible baselines in the SoccerNet-v2 leaderboard excerpted (shown/unshown Average-mAP values reported alongside NetVLAD/AudioVid) (Deliège, 2021).

Tracking and identification have become first-order tasks for tactical and performance analytics. SoccerNet-Tracking introduced a soccer MOT benchmark with 200 sequences of 30 seconds and a fully annotated 45-minute half, including players, referees, and ball (Cioppa, SoccerNet-Tracking, 2022). Reported results show domain difficulty and the value of fine-tuning: FairMOT fine-tuned on the dataset reached HOTA 57.882 (without ground-truth detections), while off-the-shelf models were substantially lower (Cioppa, SoccerNet-tracking: Multiple objects tracking dataset and benchmark in soccer videos, 2022).

Beyond global event understanding, sports-specific micro-prediction tasks are emerging. For pass receiver prediction in soccer, Honda et al. framed a supervised prediction problem using both trajectory and RGB cues: the dataset comprised 15,586 scenes (train/val/test splits reported), and the proposed combined trajectory + RGB approach achieved top-1 accuracy 62.5% (top-3 92.3%, top-5 97.5%)—a large jump over nearest-player and CNN baselines (Honda, 2022).

Trajectory forecasting and sequential decision support

Trajectory forecasting in team sports resembles pedestrian/vehicle forecasting but with specialized constraints (roles, ball interaction, tactics). In NBA movement prediction, Hauri et al. used publicly available movement data from 632 NBA games, extracting 113,760 possessions and evaluating models with ADE/FDE metrics (Hauri, 2021). Their comparison table shows multi-modal trajectory methods improving over simpler baselines across horizons ($H = 10/20/40$), emphasizing the value of modelling multi-modality in player movement (Hauri, 2021).

Reinforcement learning (RL), especially Q-function frameworks, is becoming more common in decision support and valuation because rewards (points/goals) are rare and actions depend on each other in a sequence. Q-Ball suggested a deep reinforcement learning method to model complete basketball games, using 619 NBA games from the 2015–2016 season for training and testing, and combining SportVU trajectories with play-by-play events. It also uses SHAP to explain recommendations (Yanai, 2022). Reported correlations show that derived Q-Ball aggregates are in line with measures of team performance (for example, a coefficient of 0.85 between offensive efficiency and average points scored). However, the paper also points out that these results depend on the data and need to be tested in the future (Yanai, 2022).

Table 1. Representative peer-reviewed studies (2020–2026) on ML in sports.

No	Study information			Data & features			Modelling approach					Key findings/ notes
	Author (s), Year	Sport/ Context	Sample size characteristics	Measurement/ Outcome	Variables/ Features	Feature extraction methods	Measurement instruments	Prediction task/ Target	ML algorithms/ models used	Evaluation Metrics & results	Software/ tools	
1	Sheridan et al., 2025	Simulated team sports physiology	Pilot with 6 participants; data on Zenodo	VO ₂ and energy expenditure estimation	Wrist accelerometry; physiological signals; time-series windows	ML preprocessing per model; comparisons across ML families	Wearable sensors; open Zenodo dataset	Estimate VO ₂ (regression); estimate energy expenditure	LSTM (best VO ₂), CNN, MLP, XGBoost, multiple linear regression	Lowest VO ₂ RMSE reported for LSTM (4.976); energy expenditure lowest for MLP (343.017) as reported	Python notebooks mentioned; other tool details unspecified	Illustrates feasibility and limits of very small-n physiological ML; emphasizes open data availability .
2	Moore, 2025	Baseball pitch location prediction (NCAA ball tracking)	>2 million pitches; 9476 pitchers; 6899 games	Final pitch location error (Euclidean distance; MAE)	Release metrics; projectile-motion predictions as context; spin rate; lateral release position, etc.	Standardization; permutation feature importance; multi-output modelling	Ball tracking system (release metrics); derived physics features	Predict 2D pitch location at plate	Multi-output deep neural network; compared vs linear regression and physics-only predictors	Mean Euclidean error 0.154 m vs 0.215 (linear regression); 95th percentile 0.362 m; MAE for horizontal/vertical 0.105/0.093 m	Python, scikit-learn 1.4.0, PyTorch 2.2.2 [2]	Demonstrates “physics-context features” improve deep learning; identifies modifiable features (release side, spin).
3	Yeung, 2025	Multi-sport athletic 3D pose + kinematic validation (AthletePose3 D)	>1.3 million frames and 165k postures; 12 sports actions	Pose estimation error (MPJPE / P-MPJPE) + waveform validation	High-speed athletic movements; multiple sports actions	Benchmarking SOTA monocular 2D/3D models; fine-tuning analysis	Motion capture ground truth + video; AP3D dataset	Improve monocular pose in athletic movements	Evaluated TCPFormer, MotionAGFormer, MogaNet etc.; fine-tuning on AP3D	MPJPE drops dramatically when trained on AP3D: e.g., TCPFormer MPJPE 65.80 mm (AP3D) vs ~213.64 mm (H3.6M training); combined training yields MPJPE 65.07 and P-MPJPE 7.68	unspecified	Shows strong domain shift from standard pose datasets; includes kinematic validation via waveform comparisons.
4	Bright et al. 2024	Baseball broadcast video analytics (PitcherNet)	MLBPitchDB dataset (details partly unspecified in excerpt)	Pitcher identification; 3D pose/joint error; pitch statistics (velocity, release, etc.)	Kinematic sequences from broadcast poses; pseudo-depth info	TCN for pitcher tracklet identification; 3D human modelling (D2A-HMR 2.0)	Broadcast video; MLBPitchDB; kinematic-driven analytics	Identify pitcher tracklet; estimate pitch statistics	End-to-end deep learning system with TCN + 3D modelling + heuristics	Pitcher tracklet identification 96.82%; reduced joint position error by 1.8 mm; multiple statistics extracted	unspecified	Illustrates full-stack broadcast analytics; targets real-time, low-resolution constraints.
5	Tsilimigkras T., 2024	Professional soccer injury risk from training load	25 professional male players; first-time non-contact muscle injury focus (context)	Muscle injury risk classification	DEV (acute deviation from baseline) + ACWR features; internal & external load (HR zones, distances, sprint metrics)	Feature ranking + RFE-CBR; permutation testing; cross-validation	Training-load monitoring (distances, sprints, HR metrics)	Classify injury vs baseline epochs	SVM-RBF (best); evaluated alternative classifiers (Linear SVM, KNN, LDA, RF)	Accuracy 0.78 ($p < .01$), sensitivity 0.73, specificity 0.85 with 7 features; DEV-only accuracy 0.62; ACWR-only 0.76	unspecified	Shows benefit of combining acute deviations and ACWR; emphasizes explainability and small feature set.
6	Ingwersen, 2023	Multi-sport 3D pose dataset (SportsPose)	>176,000 3D poses; 24 subjects; 5 activities	3D pose estimation benchmark + accuracy validation	3D human joint positions; local movement metric	Multi-camera triangulation; graph-based temporal	7 synchronized cameras at 90 Hz + marker-	Dataset/benchmark for monocular 3D pose estimation	Dataset paper; includes pipeline and comparisons	Mean error vs marker-based system 34.5 mm across evaluation sequences	unspecified	Addresses lack of validated marker less

			(soccer, volleyball, jump, baseball pitch, tennis)			continuity; Butterworth smoothing; pre-trained 2D pose detector	based mocap for validation				sports pose datasets; introduces "local movement" metric.	
7	Robles-Palazón, 2023	Youth soccer injury prediction (screening battery)	260 male youth non-elite players; 45 injuries recorded	Lower-extremity soft tissue injuries over season	Anthropometrics, psychological constructs, ROM, landing kinematics; selected subset of 6 field measures	Screening battery → subset selection; imbalance handling (SMOTE, bagging, etc.)	Field-based tests (drop jump, tuck jump, ROM measures, etc.)	Classify high vs low injury risk	Base classifiers: C4.5, ADTree, SMO, KNN, RF; plus ensembles/resampling/cost-sensitive methods	Best-fit model: AUC 0.700, F-score 0.380; TPR 53.7%, TNR 73.9% using six field measures	unspecified	Emphasizes feasible 5–10 min per player screening; moderate discrimination typical of complex injury outcomes.
8	Chu, 2022	Sports-related concussion in adolescents	293 males (mean 14.0y) + 362 females (mean 13.7y)	Recovery time; protracted recovery (>21 days)	VOMS, King-Devick, C3 Logix Trails + pre/post-injury measures	Tabular modelling; sex stratification	Clinical instruments: VOMS, King-Devick, C3 Logix Trails	Predict days to clearance; classify protracted recovery	Gradient boosting on decision trees (highlight notes CatBoost); 9 ML models compared	AUC for protracted recovery: 0.84 (males), 0.78 (females) vs statistical models 0.74/0.73	unspecified	Shows added value of combining vestibular-ocular data with other tests; demonstrates ML handling of complex clinical measures.
9	Cioppa, 2022	Soccer multi-object tracking (SoccerNet-Tracking)	Dataset: 200 × 30s sequences + 45-min half-time, annotated at 25 fps	Player/referee/ball tracking	Bounding boxes, track IDs; event-context sequences	MOT pipelines (detector + association); fine-tuning	SoccerNet-Tracking dataset (video)	MOT in soccer broadcast	DeepSORT, FairMOT, ByteTrack; FairMOT fine-tuning (FairMOT-ft)	Leaderboard (no-GT detections): DeepSORT HOTA 36.663; ByteTrack HOTA 47.225; FairMOT-ft HOTA 57.882 (MOTA 83.565)	Uses open-source code for ByteTrack; other tool details unspecified	Shows tracking remains challenging under occlusion/fast motion; fine-tuning domain data materially improves.
10	Honda, 2022	Soccer pass-receiver prediction (video + trajectories)	15,586 scenes (train 10,911 / val 1,559 / test 3,116)	Receiver classification accuracy (top-k)	Player trajectories (time series), body movement features from RGB clips	Cropped player clips; cross-entropy; top-k accuracy evaluation	Wide-angle soccer video + extracted trajectories	Predict next pass receiver among candidates	Trajectory-only model + trajectory + RGB; CNN baseline; nearest baseline	Top-1 accuracy: nearest 30.4%; CNN 39.0%; proposed trajectory 49.0%; proposed trajectory + RGB 62.5% (top-3 92.3%; top-5 97.5%)	Adam optimizer reported; other tools unspecified	Demonstrates value of combining visual cues with spatiotemporal trajectories for tactical prediction.
11	Liu, 2022	Badminton monocular video analytics	TrackNetV2: 77k annotated frames from 26 singles matches; plus 40 extra matches	Hit detection; 3D shuttle trajectory reconstruction	Court geometry, shuttle tracking, player pose, physics priors	HRNet pose; GRU-based shot segmentation; HitNet + optimization; reprojection error	TrackNetV2 dataset; monocular badminton video	Identify hits/segment shots; reconstruct 3D shuttle trajectories	HitNet variants; GRU recurrent network; optimization post-processing	Hit detection: HitNet + optimization recall 94.3%, acc 89.7%, prec 94.9%, F1 0.946; shot segmentation ~90% accuracy	Uses impose for HRNet; other tools unspecified	Illustrates hybrid "deep + physics/domain knowledge" pipeline; notes robustness

			labelled for testing (broadcast-view emphasis)									depends strongly on hit detection.
12	Wu, 2022	Tennis (skill level + stroke classification)	36 right-handed male players (elite/sub-elite/amateur; 12 each)	ITN level discrimination; stroke classification	Wrist IMU (6-axis, 50 Hz); engineered features; PCA	Preprocessing, segmentation, feature extraction, PCA, classification	Single wrist IMU; BLE to smartphone; cloud to computer	Predict stroke type; evaluate skill-level differences	SVM (various scalars), KNN, Naive Bayes; SVM+PCA highlighted	F1 > 0.90 for serve/forehand/backhand and at multiple skill levels; volley lower; ANOVA $p < .001$	SPSS 26 for ANOVA; smartphone + BLE + cloud pipeline reported	Demonstrates feasibility of single-sensor tennis analytics with classical ML and reduced sampling frequency.
13	Yanai, 2022	Basketball decision evaluation (Q-Ball)	619 NBA games (2015–2016 season)	Team/player action value; correlation with team performance; decision alternatives	SportVU trajectories + play-by-play; player attributes; clocks; discrete & continuous actions	Data merging by clock alignment; SHAP for explanation	SportVU tracking + play-by-play	Learn Q-values for actions; recommend alternatives	DRL framework (extension of DDPG handling discrete + continuous); SHAP interpretability [	Correlation: Q-Ball vs points-per-game coefficient 0.622; offensive efficiency vs average points coefficient 0.85 (reported)	unspecified	Connects RL value estimation to coaching “what-if” analysis; notes cold-start and need for prospective evaluation.
14	Costa, 2021	Swimming training analytics (IoT + wearables)	10 athletes (15–17y); ~8000 samples in training setup	Stroke classification; real-time coach feedback	AHRS inertial signals; heart rate; SpO2; turns; derived performance (avg speed, stroke count)	Feature representation over recent positions; ensemble strategy discussion	Wearable AHRS + biosensors (heart rate band; LED SpO2), RF links; pool setup	Classify swim style (6 classes incl. turn)	Random Forest (best), plus mention of NB/KNN/DT/SVM in ensemble framing	Best macro-F1 95.02% (Random Forest); real-time feedback goal	Implemented in Python 3.8.0 (Visual Studio Code)	Emphasizes real-time constraints and trust for coaches; demonstrates high F1 with limited athlete sample.
15	Deliège, 2021	Broadcast soccer understanding (SoccerNet-v2)	500 untrimmed videos; ~300k annotations	Action spotting, camera shot segmentation/boundary detection, replay grounding	ResNet features; temporal context; audio/video cues (AudioVid baseline)	Feature pooling (MaxPool, NetVLAD); context-aware loss (CALF)	SoccerNet videos; broadcast video pipeline	Multi-task benchmark + baselines	NetVLAD/MaxPool, AudioVid, CALF (adaptations)	Action spotting shown/unshown Average-mAP: e.g., NetVLAD (31.4/34.3), AudioVid (39.9/43.0), CALF (40.7/42.1) in excerpted table; Shot segmentation mIoU: basic 35.8 vs CALF 47.3; boundary detection mAP: up to 78.5 (Histogram baseline)	unspecified	Demonstrates multi-task sports broadcast understanding; highlights effect of temporal context and multimodal cues.
16	Gomaz, 2021	Baseball pitching biomechanics (youth)	25 youth pitchers; 10 maximal pitches each	Ball velocity prediction	Peak angular velocity pelvis/trunk; pitcher height	Signal processing to peak angular velocity; multilevel modelling	IMUs on pelvis & sternum (500 Hz); radar gun velocity labels	Predict ball velocity (continuous)	Bayesian regression multilevel models (Full/Personal/Observations)	Full model R ² 0.975, RMSE 0.014; height adds value; reported led comparisons	unspecified	Highlights individualization (height) improves performance; openly references underlying dataset availability.

17	Hauri, 2021	NBA player trajectory prediction	632 NBA games; 113,760 possessions; 1.1M seconds gameplay (0.04s sampling; down sampled)	Future location prediction errors (ADE/FDE)	Player/ball positions and velocities; shot clock; ordered by proximity	Sequence modelling; multi-modal loss; evaluation choosing best mode	NBA tracking dataset (public movement data)	Multi-modal trajectory forecasting for offensive players	Multi-modal LSTM-based models (MBT variants); baselines incl CNN, location-LSTM, SocialGAN	Table reports ADE/FDE (feet) across horizons; e.g., MBT1 for H = 10 ADE 1.43 / FDE 2.98 vs baselines (exact values in table excerpt)	Training on Nvidia GTX 1080; other software unspecified	Demonstrates multi-modality and uncertainty-aware training benefits; highlights horizons and normalization issues.
18	Sen, 2021	Cricket batting shot recognition (video)	Novel dataset CricShot10; also references prior 800-shot dataset; further dataset size details unspecified in excerpt	Multi-class shot classification accuracy	Video frames; temporal dependencies in shot sequences	CNN feature extraction + GRU; transfer learning and fine-tuning (VGG16 variants)	CricShot10 dataset (YouTube-based cricket videos)	Classify 10 batting shot types	VGG16-GRU; transfer learning (VGG16, InceptionV3, Xception, DenseNet169)	VGG16-GRU 86% accuracy; fine-tuned VGG16 variants reach 93% accuracy on CricShot10	unspecified	Demonstrates hybrid CNN-RNN for sports action recognition and the role of transfer learning in small datasets.
19	Luo, 2020	Team-sport valuation (ice hockey)	4.5M NHL play-by-play events (evaluation stated)	Player/action valuation; correlation with success measures; policy-likelihood metrics	NHL play-by-play state/action sequences; sparse goal rewards + learned dense rewards	IRL to infer reward; transfer learning regularization; compute Q-values	NHL play-by-play dataset	Learn dense rewards and rank players/actions	IRL-DK (IRL + domain knowledge), Q-function learning; alternating learning for multi-agent setting	Policy evaluation: NLL/HMD improved (e.g., IRL-DK NLL 49.5; HMD 7.77 vs rule reward NLL 185.0; HMD 13.37); correlations with many success measures reported in tables [19]	unspecified	Motivates IRL for sparse-reward sports; shows denser rewards improve downstream ranking stability.
20	Luu, 2020	NHL injury prediction	2322 players (2007–2017); 2109 skaters + 213 goalies	Next-season injury risk (binary)	Age, 85 performance metrics, injury history (publicly reported)	Feature compilation; model comparison; ensemble	Public injury/performance databases (no official NHL database)	Predict whether injury occurs next season	Random Forest, KNN, Naive Bayes, XGBoost, Top-3 Ensemble; logistic regression baseline	AUC: XGBoost 0.948 (skaters) vs LR 0.937; XGBoost 0.956 (goalies) vs LR 0.947	unspecified	Demonstrates strong discriminative performance but relies on public reporting; highlights ML vs LR comparison.
21	Shao, 2020	Gymnastics video understanding (FineGym)	303 competition records (~708 hours); 530 element categories; 4,883 event instances; 32,697 sub-action instances (v1.0)	Fine-grained action recognition/localization benchmark	Multi-level labels (event/set/element); temporal structure (action/sub-action)	Video annotation hierarchy; baselines include CNN/3D CNN & temporal modelling	FineGym dataset (high-res competition video)	Benchmarking fine-grained recognition & temporal decomposition	Baseline action-recognition pipelines (2D CNN + temporal module; 3D CNN; etc.) described	Paper reports performance still "far from satisfactory" and highlights importance of motion and temporal dynamics	unspecified	Establishes dataset and modelling challenges; open benchmark for fine-grained sports actions.

IRL methods address sparse rewards by inferring dense reward surrogates from demonstrations. Luo et al. (IJCAI 2020) combined Q-function learning with inverse reinforcement learning and domain knowledge (IRL-DK), reporting empirical evaluation based on 4.5M NHL play-by-play events and demonstrating improved policy-likelihood metrics (NLL/HMD) and correlations with multiple success measures (tables provided for offensive and defensive players) (Luo, 2020).

Wearables, IoT, and physiological/biomechanical modelling

Wearables-driven sports ML often confronts smaller n but higher-frequency sensing, requiring careful feature representation and latency-aware design. A swimming analytics framework combined wearable inertial sensing (AHRS) with biosensors (heart rate, pulse oximetry) in a real training setup of 10 athletes (15–17 years) generating ~8000 samples, achieving best macro-F1 95.02% with a Random Forest classifier and implementing the coach-facing tool in Python 3.8 (Costa, 2021).

Tennis stroke classification and skill-level evaluation demonstrate a parallel pipeline: a single wrist-worn IMU (tri-ax accelerometer $\pm 16g$; gyroscope $\pm 2000^\circ/s$) sampled at 50 Hz and evaluated on 36 right-handed male players, using preprocessing, segmentation, feature extraction, dimensionality reduction (PCA), and classical classifiers (SVM, KNN, Naive Bayes). Reported results highlight SVM configurations achieving F1-scores above 0.90 for several strokes (serve/forehand/backhand) and statistically significant discrimination across skill groups in ITN testing (Wu, et al., 2022).

In sports engineering and biomechanics, ML increasingly integrates physics priors and interpretable feature attribution. A Sports Engineering study trained a multi-output deep neural network to predict final baseball pitch location from ball tracking release metrics and physics-derived context features, using >2 million NCAA Division I pitches; mean Euclidean error on validation was 0.154 m, outperforming linear regression and showing that excluding projectile-motion features degraded performance. Tooling was explicitly reported as Python with scikit-learn 1.4.0 and PyTorch 2.2.2 (Honda, 2022).

For IMU-based prediction of baseball pitch outcomes, Gomaz et al. modelled ball velocity with hierarchical/Bayesian regression using IMUs on pelvis and sternum and radar-gun labels; 25 youth pitchers performed 10 maximal pitches each, and the full model achieved R^2 0.975 with RMSE 0.014 (as reported in their comparison table) (Gomaz, 2021).

Sports medicine and injury risk prediction

Injury risk prediction exemplifies the tension between strong performance claims and practical deployment constraints (imbalance, label noise, causal confounding, and generalization across leagues and seasons). A large NHL study used publicly reported data to predict next-season injury risk, training and comparing multiple ML algorithms (random forest, KNN, Naive Bayes, XGBoost, ensemble) vs logistic regression; XGBoost achieved AUC 0.948 (position players) and 0.956 (goalies) with statistically significant differences vs logistic regression in the reported sample (2007–2017) (Costa, 2021).

Clinical prognosis tasks share similar structure. In adolescent sports-related concussion recovery prediction, sex-stratified ML models were trained using multi-part clinical measures (including VOMS, King-Devick, and C3 Logix Trails); gradient-boosted decision-tree algorithms achieved AUC 0.84 (males) and 0.78 (females) for predicting protracted recovery, improving over statistical baselines (Chu, 2022).

At the team level, soccer injury modelling from training-load deviations combined acute deviations from baseline with ACWR features to classify injury vs baseline epochs, yielding accuracy 0.78, sensitivity 0.73,

specificity 0.85 and reporting that SVM-RBF outperformed alternative classifiers for the selected feature subset (Tsilimigkras T. , 2024). A prospective youth soccer screening-battery study (non-elite players) used multiple base classifiers (C4.5, ADTree, SMO, KNN, Random Forest) and imbalance-handling ensembles/resampling, reporting a “best fit” model with AUC 0.700 and F-score 0.380 using six field-based measures and emphasizing practical feasibility for screening (Robles-Palazón, 2023). Tableau 1: Representative peer-reviewed studies (2020–2026) on ML in sports.

Quantitative synthesis

Representative study table

Table entries are restricted to publications ≥ 2020 . If an item’s peer-reviewed status, software stack, or other detail could not be confirmed from accessible full text/extended abstract, it is explicitly marked unspecified.

Algorithm frequency in the representative table

The following counts are computed from Table 1 by assigning each study a *primary* model family (dataset papers with embedded deep pose components are counted under deep learning/CV). This is a descriptive statistic, not a meta-analytic weight.

Table 1. Descriptive statistic of models.

Algorithm family (Primary)	Count	% (n = 21)
Deep learning	12	57.1%
Tree/boosting ensembles	5	23.8%
Reinforcement learning / IRL	2	9.5%
Classical ML	1	4.8%
Bayesian regression	1	4.8%
Total	21	100%

Tree-based models remain prominent in injury and clinical prognosis (e.g., NHL injury XGBoost; concussion recovery boosting; swimming RF; youth soccer battery decision-tree ensembles), [3] while deep learning dominates video, pose, and large-scale tracking tasks (SoccerNet-v2/-Tracking, AthletePose3D, PitcherNet) (Deliège, 2021).

Sport/context frequency in the representative table

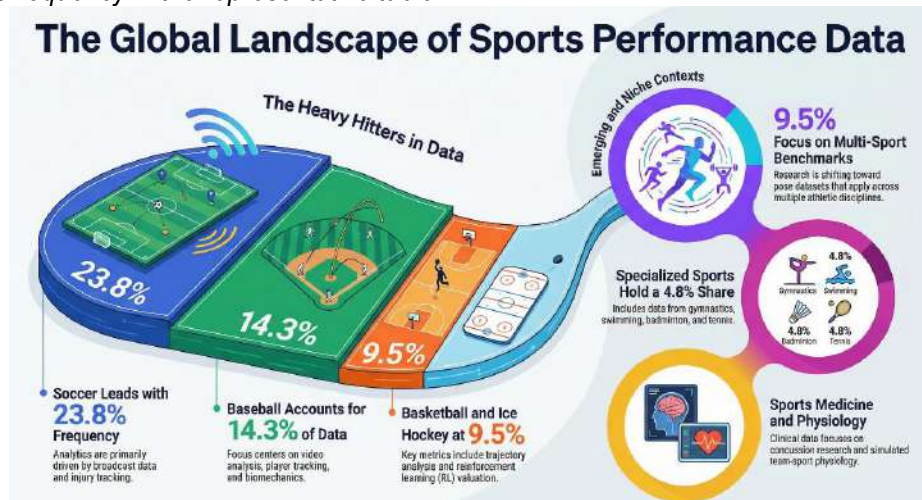


Figure 3. Distribution of machine learning applications across sports domains (2020–2026).

Figure shows a distribution of machine learning applications across sports domains (2020–2026). Soccer represents the largest proportion of published studies (23.8%), driven both by broadcast benchmarks (SoccerNet) and injury-risk modelling studies (Deliège, 2021), followed by baseball (14.3%), baseball representation is amplified by ball tracking and pitch analytics contributions in sports engineering and CV workshops. [11], and basketball and ice hockey (9.5% each). Emerging multi-sport benchmarks account for 9.5%, while specialized sports (e.g., gymnastics, swimming, badminton, tennis) individually represent approximately 4.8%. Sports medicine and physiological applications constitute a distinct and growing research area.

Thematic relationships and timeline

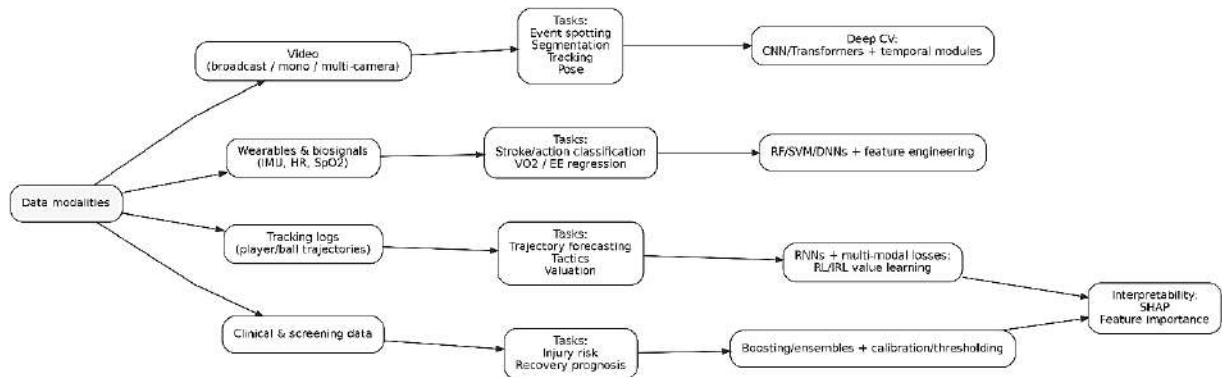


Figure 4. Timeline of representative peer-reviewed ML-in-sports contributions (2020–2025).

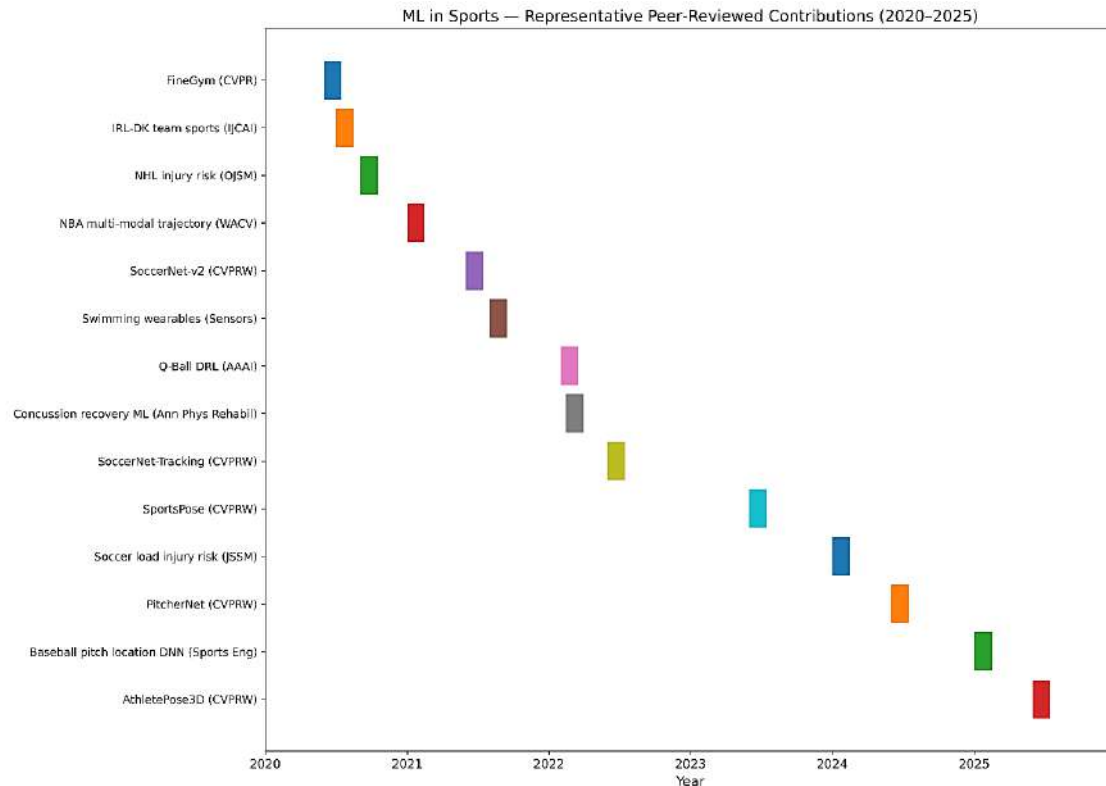


Figure 5. Timeline of representative peer-reviewed machine learning contributions in sports research (2020–2025).

Figure shows a conceptual framework linking data modalities, task families, and dominant machine learning approaches in sports research (2020–2025). Video data primarily supports event spotting, segmentation, tracking, and pose estimation using deep convolutional and transformer-based architectures. Wearable and bio signal data are commonly analysed using classical and ensemble methods for classification and regression tasks. Tracking logs enable trajectory forecasting and reinforcement learning–based valuation, while clinical and screening data are frequently modelled using boosting and calibrated ensemble approaches. Interpretability techniques (e.g., SHAP, feature importance) increasingly support decision translation.

Figure illustrates key benchmark datasets, methodological advances, and applied studies across computer vision, reinforcement learning, wearable analytics, and sports medicine, highlighting the progressive diversification of machine learning applications in sport.

DISCUSSION

The co-evolution of open benchmarks and methodological specialization is a key trend that began in 2020. A common benchmark promotes comparability, identifies failure modes (occlusion, fast motion), and makes domain fine-tuning quantifiable, as demonstrated by SoccerNet-v2 and SoccerNet-Tracking (Cioppa, SoccerNet-tracking: Multiple objects tracking dataset and benchmark in soccer videos, 2022). Similarly, "*fine-grained*" sports actions are formalized by FineGym's hierarchical label space, which also reveals that coarse-grained action recognition heuristics do not translate well to subtle, elite motor patterns (Shao, 2020).

The rise of hybrid modelling is a second trend: learning with constraints or priors is often beneficial for sports problems. The monocular badminton pipeline from MonoTrack serves as an example. It combines physics-informed optimization, court geometry, and deep pose and hit detection. The results indicate that upstream error propagation (hit detection) can dominate end-to-end performance (Liu, 2022). Similar to this, the baseball pitch-location study employs projectile predictions derived from physics as contextual features, empirically enhancing deep model performance and confirming that "*learning the physics*" is made simpler when the feature space contains pertinent structure (Honda, 2022).

Third, models that target decisions with downstream consequences make interpretability mandatory. In order to interpret alternative tactical scenarios and feature contributions to Q-values, Q-Ball specifically uses SHAP (Yanai, 2022). To bridge the gap between coach-relevant insight and black-box prediction, permutation-based feature importance is utilized in sports engineering to identify which release metrics influence predicted pitch location (Moore, 2025). The trend toward parsimonious feature subsets in injury-risk contexts—such as six field-based measures in youth screening or seven load-derived features that yield an accuracy of 0.78 in soccer—reflects a desire for deployable screening rules rather than maximal model complexity (Tsilimigkras T., 2024).

Lastly, there is still a clear gap between domains where data are naturally small-n and noisy (physiology, injury events) and domains with massive, labelled data (broadcast video benchmarks, ball tracking). Due to its explicit small sample size ($n = 6$), the PLOS pilot study on VO_2 and energy expenditure is better understood as benchmarking and feasibility in the face of data scarcity rather than as deployable evidence (de Beukelaar, 2025). On the other hand, fields such as NCAA pitch tracking offer millions of examples and can support contemporary deep learning regimes with strong holdout evaluation (Honda, 2022).

CONCLUSIONS

This systematic review consolidates peer-reviewed journal papers and significant conference proceedings published from January 1, 2020, to February 11, 2026, that utilize machine learning (ML) in the domains of sports performance, tactics, officiating/production, athlete monitoring, biomechanics, and sports medicine. The dominant methodological shift since 2020 is the consolidation of deep learning pipelines for vision-based sports understanding (event spotting, tracking, pose estimation), enabled by open benchmarks such as SoccerNet-v2 (broadcast soccer with ~300k annotations across 500 videos) and its extensions for tracking, and fine-grained action benchmarks like FineGym in gymnastics (Deliège, 2021). Deep learning also expanded into trajectory forecasting (e.g., NBA player movement prediction across 632 games and 113,760 possessions) and decision support/reinforcement learning (e.g., Q-value-based basketball evaluation on 619 NBA games) (Hauri, 2021).

Across sports science and medicine, the post-2020 period shows a pragmatic trend toward tree-based ensembles and support vector machines for structured tabular data (training load, screening batteries, injury risk, and clinical/physiological outcomes). Examples include (i) next-season NHL injury prediction with XGBoost achieving AUC ~0.948 for position players and 0.956 for goalies in a dataset of 2322 players (2007–2017) and (ii) adolescent sports-related concussion recovery prognosis where gradient-boosted decision trees achieved AUC 0.84 (males) and 0.78 (females) (Luu, 2020). In soccer injury-risk modelling from training-load deviations, a study combining acute deviations and “chronic” (ACWR) features reported accuracy 0.78, sensitivity 0.73, specificity 0.85, with SVM-RBF outperforming alternative classifiers on the selected feature set (Tsilimigkras T. , 2024).

Methodologically, the field increasingly pairs predictive performance with interpretability and actionable insights. This is visible in tactical RL work explicitly using SHAP to interpret recommendations, and in sports engineering work using permutation feature importance to interpret a deep neural network predicting pitch location from >2 million NCAA pitches with mean Euclidean error ~0.154 m and explicit reporting of implementation in Python (scikit-learn, PyTorch) (Yanai, 2022).

From 2020 through early 2026, ML in sports has matured from isolated modelling efforts into an ecosystem structured around open benchmarks (especially for video and pose), richer sequential modelling of multi-agent dynamics, and practical predictive modelling for sports medicine and performance monitoring. Deep learning dominates vision-centric tasks and large tracking datasets, while tree/boosting ensembles and SVM remain central for structured clinical and wearable analytics. Across domains, interpretability methods (SHAP, permutation importance) and hybrid “learning + priors” approaches are increasingly used to translate model outputs into coach- and clinician-actionable insights.

The field’s next methodological frontier is less about marginal gains on closed benchmarks and more about generalization and deployment: cross-competition domain shift, label quality and missingness, causal confounding in injury and performance studies, and transparent model reporting that supports reproducibility and safe decision-making.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Karim Midoul: conceptualization, methodology, software, data curation, visualization, validation, resources, supervision, writing - review & editing. Badr Eddine EL Mohajir: supervision, validation, writing – review & editing. Outman El Hichami: supervision, validation, writing – review & editing. Adnan Souiri: supervision, supervision, validation, writing – review & editing. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Sports cardiology field as a key player in optimizing cardiovascular health during sports

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ABSTRACT

Background: Sudden cardiac death (SCD) in athletes, though rare, continues to make headlines, raising questions about its underlying causes. Athletes are generally healthy, yet life-threatening cardiac events can occur unexpectedly in those without prior symptoms. Early detection of high-risk cardiac conditions is critical for prevention. **Main text:** Sports cardiology is an emerging specialty focused on the cardiovascular health of competitive athletes and highly active individuals, including those with known or undiagnosed heart disease. It encompasses structural, functional, and electrical cardiac assessment, exercise physiology, and preventive strategies. Screening and preparticipation evaluation are vital to identify hidden cardiovascular risks and differentiate physiological adaptations from pathology. This review highlights the importance of sports cardiology in optimizing cardiovascular performance, preventing SCD, and managing cardiovascular conditions such as arrhythmias, cardiomyopathies, coronary artery disease, and hypertension in physically active populations. **Conclusions:** Sports cardiology is rapidly evolving and plays a crucial role in safeguarding the health of athletes and active individuals. Optimal care requires an integrated approach, specialized knowledge, and targeted research initiatives to ensure safe participation in competitive and recreational exercise while minimizing cardiovascular risks.

Keywords: Sport medicine, Athletic injuries, Cardiovascular diseases, Sudden cardiac death, Exercise.

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INTRODUCTION

An increasing body of evidence substantiates the notion that consistent physical activity (PA) and exercise are detrimental to health. Premature mortality and morbidity associated with metabolic syndrome, stroke, coronary artery disease, osteoporosis, and various cancers (including colon, breast, bladder, kidney, rectal, head and neck, endometrial, gastric cardia, lung, and oesophageal adenocarcinoma), depression, falls, functional decline, and constipation have been shown to have a strong dose–response relationship with PA and exercise (Moore et al., 2016). This relationship has been confirmed in both men and women across different ethnic groups (Pelliccia et al., 2019). Several studies have demonstrated that aerobic activity significantly reduces the risk of premature all-cause mortality and cardiovascular disease (CVD) mortality. Higher cardiorespiratory fitness can be achieved with increased intensity of regular PA, leading to multiple health benefits, and exercise is widely recognized as a key lifestyle modification for improving health (Paquette et al., 2020; Baggish et al., 2017).

There is no doubt that regular PA significantly reduces CVD risk; however, complete protection is not achieved (Pelliccia et al., 2021). Athletes and highly active individuals remain vulnerable to musculoskeletal injury and cardiovascular (CV) events. Musculoskeletal injuries are related to exercise type and intensity, underlying musculoskeletal abnormalities, and preexisting conditions (Teyhen et al., 2020). The most serious CV events associated with high-intensity PA include acute myocardial infarction and sudden cardiac arrest (SCA), which may result in mortality and morbidity (Han et al., 2023).

Sudden cardiac death (SCD) can occur in symptomatic athletes or physically active individuals engaging in strenuous or competitive exercise. The reported incidence of SCD among athletes is variable, ranging from 1 in 40,000 to 1 in 300,000 (Weizman et al., 2023). Physical activity may paradoxically increase the incidence of acute CV events, even in well-trained individuals. In rare cases, exercise may unexpectedly precipitate SCA in individuals with underlying cardiovascular disease, particularly in previously sedentary individuals or those with advanced disease (Pelliccia et al., 2019).

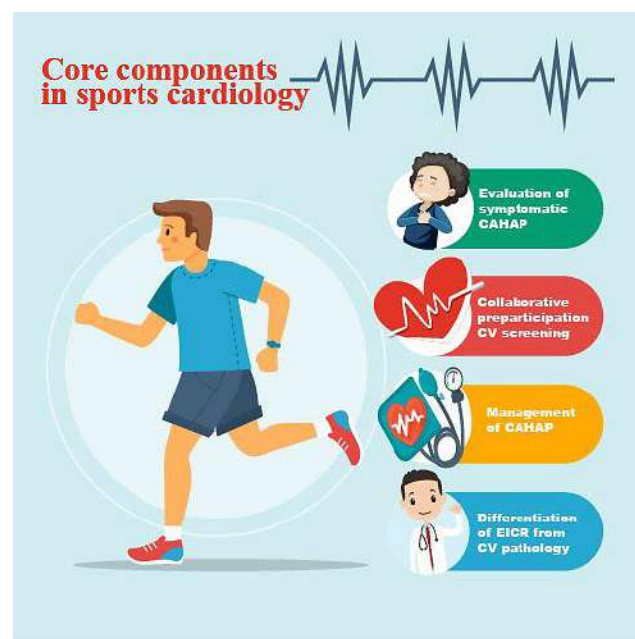


Figure 1. Core curriculum of sports cardiology.

The principal aim of sports cardiology is to ensure safe and optimal cardiovascular system performance during exercise (Baggish et al., 2017). The core curriculum of sports cardiology includes four fundamental domains of knowledge essential for the care of competitive athletes and highly active individuals (CAHAP) (Baggish et al., 2017). Sports cardiology is a novel and emerging subspecialty focused on the cardiovascular care of athletes and active individuals with known or undiagnosed cardiac conditions. It integrates cardiovascular imaging, exercise physiology, cardiac electrophysiology, and structural heart disease, reflecting the increasing population of CAHAP (Figure 1) (Karam et al., 2022).

PHYSIOLOGICAL ADAPTATION TO EXERCISE

Sustained moderate- to high-intensity exercise is associated with adaptive structural and functional changes in the cardiovascular system (Dawes et al., 2016; Baggish & Wood, 2011). These changes include enlargement of cardiac chambers and increased ability to augment cardiac output, a phenomenon known as exercise-induced cardiac remodelling (Scharhag et al., 2002; Gleason & Kim, 2017). Adaptation may involve enlargement of both ventricles and atria, along with enhanced early diastolic filling (Finch & Baggish, 2016). The extent of this remodelling varies among individuals depending on sex, ethnicity, genetic predisposition, type of sport, and duration and intensity of training (Baggish & Wood, 2011).

Isometric (strength) exercises, such as weightlifting, are characterized by transient increases in peripheral vascular resistance and systolic blood pressure, leading to left ventricular pressure overload. In contrast, isotonic (endurance) exercise, such as swimming or running, results in sustained increases in cardiac output with volume overload affecting all cardiac chambers (Ito, 2022; Barker & Eickmeyer, 2020).

A “grey zone” exists between physiological adaptation and early pathological cardiac remodelling (Gleason & Kim, 2017). This includes increased left ventricular wall thickness, left ventricular dilatation, and right ventricular dilatation. Differentiation between physiological and pathological changes requires integration of clinical history, including sport type, intensity, duration, sex, and ethnicity, along with imaging findings (Pelliccia et al., 2019). Physiological remodelling typically involves balanced enlargement of all chambers with preserved or enhanced systolic function during exercise, whereas isolated chamber enlargement or functional impairment suggests pathology. Left ventricular wall thickness exceeding 15 mm should prompt evaluation for cardiomyopathy (Gleason & Kim, 2017).

Exercise detraining may be used in ambiguous cases where differentiation between physiological adaptation and cardiomyopathy is uncertain (Corrado et al., 2010). The concept is based on the reversibility of physiological remodelling following cessation of exercise; however, data remain limited regarding the duration and extent of reversibility (McDiarmid et al., 2016). Moreover, the effects of detraining in patients with established cardiomyopathies remain unclear, warranting cautious application (Teyhen et al., 2020).

In addition to structural and functional changes, athletes exhibit electrical remodelling manifested as distinct electrocardiographic (ECG) patterns. Sports cardiologists must differentiate benign exercise-induced ECG changes from pathological findings. Athletes commonly exhibit benign bradyarrhythmias due to increased vagal tone (Sharma et al., 2018; U.S. Department of Health and Human Services, 2008).

PREVENTION AND SCREENING FOR SUDDEN CARDIAC DEATH

Comprehensive recommendations regarding athletics participation are revised periodically. However, evidence is scarce about the normal course of disease progression or the risk of mortality during vigorous exercise and competitive sports among patients with CVD (Petek & Baggish, 2020).

As there is still debate about the true incidence and causes of SCD in athletes, the optimal modalities of preparticipation cardiovascular screening (PPCS) are still controversial. It is important to highlight that there is a paucity of data supporting the effectiveness of PPCS as a strategy for lowering the occurrence of sport-related cardiac arrest and SCD. However, PPCS is compulsory for competitive athletes. Controversies exist on the value of several screening modalities such as ECG and cardiac imaging.

Preparticipation physical evaluation (PPE) is recommended to detect concealed CVD, especially those linked to the risk of SCD and to provide a chance to mitigate negative outcomes by implementing targeted treatments or imposing limitations on PA. Existing evidence supports the value of standardized comprehensive medical history and thorough physical examination protocols such as PPCS. PPCS encompasses several aspects such as education, screening for substance addiction, identification of other medical conditions, and facilitation of access to healthcare providers for young athletes involved in competitive sports (MacLachlan & Drezner, 2020; Maron et al., 1996).

Clinical evaluation is of limited sensitivity and specificity for CVD. However, it is a cost-effective tool in limited resource settings for utilization of the limited care provider skills and implementation with minimal resource commitment. Hence, incorporating additional diagnostic testing such as ECG can enhance the overall precision of PPCS diagnosis. Meanwhile, standardization of preparticipation protocols such as PPE-monograph entailing high-quality primary care preventive services. Additionally, cardiac imaging may help identify congenital, structural, and functional cardiac abnormalities. However, this is opposed by high cost and the required high-skill and financial infrastructure. ECG interpretation has a special approach for athletes which could decrease the false positive diagnosis and is usually best achieved by sports cardiologists (MacLachlan & Drezner, 2020; American Heart Association, 2021; Pescatello et al., 2015).

EVALUATION OF SYMPTOMS IN ATHLETES

Concerns regarding SCD in athletes are the top hot topics during sports seasons. Evaluating different cardiac symptoms in an athlete or highly active individual is a challenging process that requires an integrated approach with the implementation of the basics of cardiology, exercise physiology, and specific issues related to this subgroup of population. Also, careful evaluation of symptoms requires awareness of the atypical presentation. Solving this puzzle is one of the important skills of sports cardiologists. The main symptoms among CAHAP include chest pain, palpitations, syncope, and impaired exercise tolerance (Weizman et al., 2023).

Chest pain

The approach for the diagnosis and management of chest pain in athletes is different from that in the general population. It is crucial to keep in mind the different incidence and presentation as well as the differences that exist according to the type and level of exercise and preexisting cardiac condition.

Non-cardiac causes of chest pain such as gastrointestinal, chest, and musculoskeletal problems are common among athletes of all age groups (Baggish et al., 2017). Cardiac causes of chest pain are age specific. The incidence of chest pain due to CVD in young athletes ≤ 35 years old is much lower than that in athletes > 35 years and is usually due to life-threatening conditions such as hypertrophic cardiomyopathy, coronary artery anomalies, and congenital valvular heart diseases (Maron et al., 1996).

Diagnosis of chest pain due to coronary anomalies in young athletes requires a high index of clinical suspicion due to atypical presentation in most cases. The most common presenting symptom of coronary anomalies is

exertional dyspnoea with no chest pain which is usually misdiagnosed. Sometimes it is described as chest discomfort at violent and intense exercise (Williams et al., 2014). The main cause of exertional chest pain in senior athletes > 35 years old is atherosclerotic CVD which usually presents as a warm-up angina (Williams et al., 2014).

Generally, exertional chest discomfort that is associated with newly developed decreased exercise tolerance, dizziness, or syncope in all athletes is an alarming sign of possible and high suspicion of CVD (Weizman et al., 2023).

Exercise-induced asthma can be one of the causes of exercise-induced chest discomfort and can be diagnosed by including spirometry in the work-up before and after the cardiac stress test (Ora et al., 2024). Pleuritic and musculoskeletal chest pain can be associated with strenuous exercise and usually occur in less-trained individuals (Maron et al., 1996).

Thorough and careful assessment of chest pain should be done including history taking with a special focus on the family history of any cardiovascular risk factors, sudden cardiac arrest, familial cardiomyopathies, premature coronary artery diseases (CAD), medications, and illicit or energetic drug use besides a comprehensive clinical examination. The sports cardiologist should postulate the possible aetiology and subsequently request supporting investigations including 12 leads resting ECG, echocardiography, exercise testing, and any further investigations required to discover cardiac aetiology (Gulati et al., 2021).

Echocardiography is the initial investigation of choice to diagnose suspected coronary anomalies being specific and non-invasive, if echocardiography is inconclusive then cardiac magnetic resonance or computed tomography is indicated (Barker & Eickmeyer, 2020).

Syncope

Sudden loss of consciousness and collapse during or shortly after exercise is considered an emergency that needs immediate evaluation (Colivicchi et al., 2004).

More than 6% of athletes experience syncope during their athletic life, preparticipation syncope is usually of neurally mediated type and is of benign outcome (Troiano, 2023). Causes of collapse in athletes, as in the general population, include cardiac and neurally mediated syncope, and other non-cardiac causes like seizures, hyponatremia, and heat stroke. In the case of non-cardiac causes, the collapsed person remains conscious to some extent during the event while in cardiac and neurally mediated syncope the collapsed person develops typical complete loss of consciousness. Cardiac and neurally mediated syncope may mimic the seizures due to acute brain anoxia. The clinical clues of differentiation are that in neurological causes, seizures occur at any time including exercise and the convulsions usually happen before the loss of consciousness. Syncope may be caused by potentially life-threatening circumstances like LV outflow tract obstruction, tachyarrhythmias, bradyarrhythmia (Hosenpud et al., 1987). It may be also related to post-exercise hypotension (Halliwill et al., 2013).

Neurally mediated syncope happens shortly after exercise as well as in special circumstances that are not related to exercise. It is usually preceded by alarming symptoms like flushing and warmth forcing the affected person to lie down or fall slowly. Syncope due to arrhythmia is typically associated with the abrupt loss of consciousness with dramatic fall and possible harm (Colivicchi et al., 2004).

The clues for the diagnosis of syncope include careful history taking, review of circumstances preceding, or if available video capture of the event, time and duration of the event, and potential risks for recurrence (Barker & Eickmeyer, 2020). Adjunct tests like 12 leads ECG and cardiac imaging can be done to exclude underlying structural, electrical, or myocardial disease in case of inconclusive history. Exercise testing may be required to uncover hidden ECG features of electrical disorders like arrhythmia and congenital long QT syndrome (LQTS). Ambulatory rhythm monitoring may be required to diagnose arrhythmias. Prolonged rhythm monitoring, like implantable loop recorders, should be done in some cases of arrhythmia when ordinary tests are non-diagnostic. It should be noted that relative orthostatic intolerance is common in CAHAP as one mechanism of cardiovascular adaptation, positive tilt-table testing is not specific and should not be used to confirm the diagnosis of neurally mediated syncope (García-Sánchez et al., 2020).

Palpitations

There is no doubt that palpitation is common in the athletic population due to the presence of times of excitement, fear, psychological stress, and increased awareness. Benign conditions are the most common causes of palpitation in athletes with subsequent reassurance, and only in rare cases medications to suppress the arrhythmia are required. Palpitations not associated with triggers, those of sudden onset and offset pattern (Abdelfattah & Froelicher, 2015), and palpitations associated with syncope are mostly due to pathological arrhythmia (Abdelfattah & Froelicher, 2015). Alcohol consumption and high caffeine intake including soda and energy drinks are non-cardiac causes of palpitations (Reissig et al., 2009). A family history of SCD, syncope, and palpitations may be an alarm to high risk of Wolf Parkinson White (WPW) syndrome and LQTS (Moore et al., 2016). Clues for detection of life-threatening causes include but are not limited to resting ECG for detection of preexcitation, structural heart disease, and evidence of repolarization abnormalities like the case in LQTS and Brugada syndrome. When the initial diagnostic approach fails to diagnose the nature of the palpitations, ambulatory rhythm monitoring should be done to detect abnormal rhythm correlated to the symptoms. Cardiac stress testing and cardiac imaging may be required to uncover underlying structural or electrical pathology (Abdelfattah & Froelicher, 2015; Reissig et al., 2009).

Shortness of breath and impaired ability to exercise

CAHAP with limited exercise capacity offer subjective accounts of their exercise tolerance by comparing it to that of their more proficient counterparts. Exercise intolerance can manifest either independently or in combination with many symptoms, including chest pain, shortness of breath, dizziness, fainting, palpitations resembling fainting, and overall weariness (Baggish et al., 2017).

Dyspnoea is a major concern in CAHAP. Exertional dyspnoea may be due to respiratory causes such as exercise-induced asthma (EIA) or exercise-induced bronchospasm (EIB), decreased oxygen transport, or may be due to cardiac or musculoskeletal abnormalities. Sometimes it is subjective and does not indicate a true pathology (Carlsen, 2012).

An integrated strategy combining several medical professionals is necessary for a full evaluation of exercise intolerance in CAHAP, depending on the clinical context (Stöhr & Pugh, 2021). The evaluation involves a comprehensive medical history, with a specific focus on exercise training techniques, prospective modifications to lifestyle, previous performance records, and data obtained from wearable monitors. Physical examination involves evaluation of CVD alongside the identification of potential indicators of alternative pathologies such as overtraining, autoimmune diseases, iron deficiencies, viral illnesses, asthma, laryngeal dysfunction, and endocrine problems. Further diagnostic testing should be focused on ruling out CVD, including conditions such as chronotropic incompetence, reduced LV function, coronary artery disease, atrial fibrillation (AF), aortic stenosis, and hypertrophic cardiomyopathy. This should be followed by a more

comprehensive evaluation aimed at excluding dysfunction in other organ systems, systemic diseases, and psychiatric disorders, such as depression and anxiety. According to Rajendran et al. (2023), it is recommended that athletes who experience exercise intolerance should regularly check their peak oxygen consumption alongside a relevant measure of external effort, such as treadmill speed/incline or cycle ergometer power. This approach allows for an objective evaluation of their exercise capacity. The differential diagnosis of athletes aged ≥ 35 years should include an assessment of normal aging. It is important to acknowledge, however, that the process of aging does not lead to sudden and significant decreases in exercise capacity (Maron et al., 2009).

MANAGEMENT OF CARDIOVASCULAR DISEASES IN ATHLETES

One of the most essential duties of a sports cardiologist is to provide athletes with confirmed CVD with continuous and optimal care. Health and safety should always take precedence over athletic objectives, and in most cases, simultaneous attention to both outcomes based on risk-benefit facilitates optimal care (Borjesson et al., 2019).

Myocardial diseases

Hypertrophic cardiomyopathy was the initial genetic cardiac disorder to be associated with sudden death occurring during physical exertion (Zelenović et al., 2021). The diagnostic criteria and clinical management procedures for CAHAP with cardiomyopathy should be consistent with those utilized for less physically active individuals within the broader community. PA and exercise may provoke cardiac dysrhythmias. CAHAP with coexisting cardiomyopathy face a heightened susceptibility to the development of malignant tachyarrhythmias, as well as a greater likelihood of experiencing the advancement of the underlying cardiac condition (Dickie & Terblanche, 2020). Recent results indicate that regular intense PA may potentially elevate the likelihood of developing congestive heart failure and subsequent arrhythmias in individuals diagnosed with arrhythmogenic RV cardiomyopathy (Ahmadi et al., 2022). It is recommended that those diagnosed with or potentially having arrhythmogenic RV cardiomyopathy are discouraged from engaging in strenuous PA. The absolute risk of arrhythmia and disease development in CAHAP with other cardiomyopathies is currently not well understood and is challenging to measure. As a result, there is a lack of consensus advice on involvement in sports, leading to a conservative approach. Conversely, imposing limitations on PA within this demographic could potentially result in noteworthy negative consequences, such as increased body weight and diminished psychological welfare (Corrado et al., 2010). Sports cardiologists have a significant role in the management of CAHAP with cardiomyopathy. They are responsible for developing and improving treatment strategies, which include providing exercise recommendations that aim to minimize risk and maximize the health benefits of regular low- to moderate-intensity exercise according to the study conducted by Ahmadi and colleagues (Ahmadi et al., 2022).

Exercise and even PA can trigger and/or exaggerate myocardial damage in CAHAP. Myocarditis may be due to infectious and non-infectious causes (Dickie & Terblanche, 2020). It is of note that moderate-level PA has a positive effect on the immune system while extreme exertion may impair immune response (Pyne, 1994). The clinical presentation is variable and usually presented as flu-like symptoms for a few days followed by chest pain which may be atypical, a prominent effort intolerance and fatigue. CAHAP are more sensitive to the changes in physical effort. Magnetic resonance imaging of the heart is the most sensitive diagnostic method in athletes. It is important to avoid any form of exertion during the early phase of myocarditis and perform a comprehensive assessment of cardiac function before returning to physical activity and/or competitive exercise (Hurwitz & Issa, 2020).

There is a correlation between myocarditis and a heightened likelihood of experiencing arrhythmia while engaging in athletic activities. Additionally, existing animal studies indicate that exercising during the acute stages of myocarditis may worsen cardiac dysfunction. Therefore, it is advisable to impose limitations on athletic involvement when there is suspicion or confirmation of myocarditis in the individual. Typically, myocarditis is a temporary and restricted condition. After confirming the remission of the disease using a combination of biochemical tests, exercise testing, non-invasive imaging, and ambulatory rhythm monitoring, it is generally suitable to resume exercise fully. The thorough characterization of the time course for the resolution of myocarditis and the prognostic implication of persistent myocardial scarring is still lacking. Most CAHAP will experience full resolution within a period of 3 to 6 months. However, it is worth noting that there are cases when symptoms persist or return, and there may be evidence of persistent inflammation through laboratory tests or imaging. In such instances, it may take longer for individuals to safely resume their training and participation in competitive activities. In addition, it is important to note that exercise alone does not solely account for morbidity and mortality rates. Various other risk variables, like stress and competitive environments, as previously indicated, also play a significant role in contributing to these outcomes (Dickie & Terblanche, 2020; Bonhorst, 2018).

Arrhythmias

In recent decades there has been an ongoing discussion about the relationship between physical activity and arrhythmias. Several factors interact with the effect of PA on cardiac rhythm including demographic criteria and level and type of exercise (Newman et al., 2021).

AF is well recognized as the predominant arrhythmia within the general population as well as in athletes. There is a substantial body of published evidence indicating that younger athletes and those who participate in endurance and mixed-type sports have a higher susceptibility to AF (Wilhelm, 2014). The mechanisms and risk factors responsible for the development of atrial arrhythmia in CAHAP are mixed, complex, and not fully comprehended. Causal factors encompass exercise-related atrial remodelling and/or elevated atrial pressure, imbalance in autonomic control including exaggerated vagal tone, inflammation, and genetic predisposition (Hindricks et al., 2021). Diagnosis involves a thorough history targeting to identify the factors that precipitate arrhythmia, physical examination, resting ECG, ergometry, and possibly signal-average analysis of P-wave (Rao & Shipon, 2019).

Due to limited data, the management of atrial arrhythmia in CAHAP is like non-athletes. It includes the elimination of risk factors, rate control or rhythm control strategies, and thromboembolic prophylaxis. Catheter radiofrequency ablation is also successful management. Class IC antiarrhythmic drugs are preferred due to the low risk of adverse effects. Controversies exist about whether it is better rate control or rhythm control, and shared decision-making is advisable. Administration of the first dose of anti-arrhythmogenic therapy should be done under medical observation to guard against unexpected responses (Siegel, 2023).

Several patients with chronic AF or those with modest thromboembolic risk profiles may not require anticoagulant therapy. The selection of either warfarin or a novel oral anticoagulant should be determined by employing algorithms that have been suggested for utilization in the broader community. It is advisable to provide athletes who are using these substances with appropriate counselling regarding the potential hazards of experiencing bleeding incidents during contact sports or sports activities that include a significant risk of physical harm, such as cycling or martial arts. After undergoing catheter ablation, it is recommended to maintain anticoagulation for a certain duration, despite the absence of sufficient data to establish the ideal length of treatment (Figure 2) (Tanasescu, 2002).

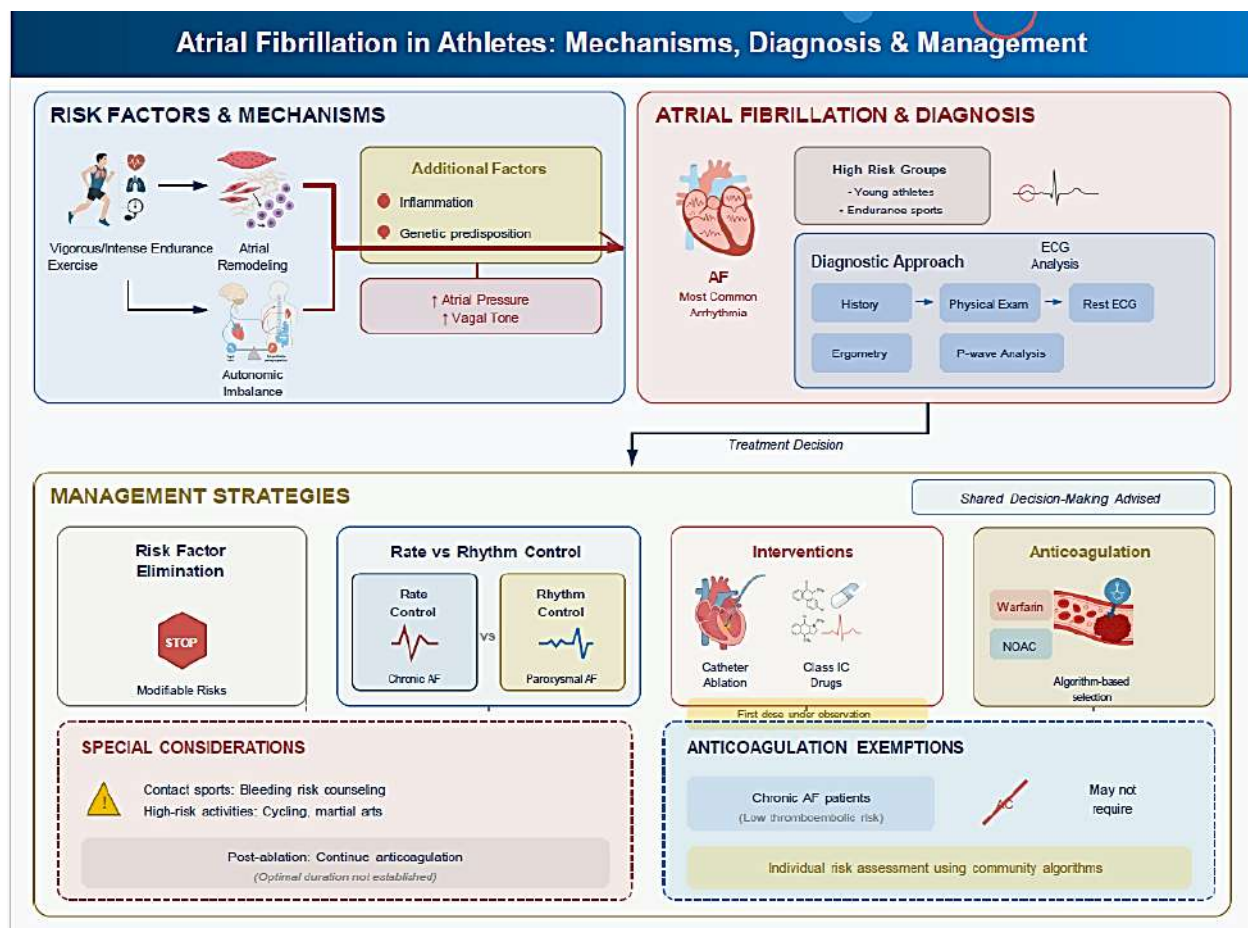


Figure 2. Atrial fibrillation in athletes: mechanisms, diagnosis and management.

Channelopathies

The presence of ion channel abnormalities can potentially elevate susceptibility to malignant arrhythmias, which may lead to catastrophic outcomes, particularly in the context of engaging in athletic activities. Patients with suspected or confirmed channelopathy should undergo evaluation at a specialist centre that demonstrates proficiency in the fields of cardiac electrophysiology and sports cardiology. The utilization of a multidisciplinary approach enables precise assessment of the risk faced by each patient, the tailoring of treatment plans that align with current guidelines, and the provision of informative guidance on long-term strategies for engaging in competitive sports and recreational physical activities.

Preventive measures for CAHAP with channelopathy encompass the avoidance of specific prescription and over-the-counter drugs, as well as the prevention of dehydration, fever, and heat stroke. It is crucial to construct an emergency action plan that prioritizes accessibility to external defibrillators. The engagement in physical activity by individuals diagnosed with LQTS, namely those with type-1, has been linked to a heightened susceptibility to experiencing abnormal heart rhythms (MacLachlan & Drezner, 2020). Nevertheless, the most recent observational data indicates that there have been no reported fatalities among athletes with LQTS who choose to continue participating in sports while receiving adequate treatment for their condition (Lampert et al., 2023).

A comprehensive collaborative decision-making process is required to engage the sports cardiologist in the decision-making to permit unrestricted sports participation among athletes diagnosed with LQTS or other comparable conditions carrying equivalent risks. CAHAP often exhibits WPW syndrome, as well as benign ventricular and supraventricular arrhythmias. The definitive diagnosis, risk classification, and therapy are the joint responsibilities of the sports cardiologist and the cardiovascular electrophysiologist. The assessment may encompass exercise testing that is restricted by maximal exertion and an invasive electrophysiological study, which can be employed to ascertain the most effective approaches for managing the condition. These approaches may involve observation, medication therapy, or catheter ablation. Catheter-based ablation provides a long-lasting remedy. Usually, the implementation of an efficacious treatment regimen will adequately diminish or eradicate potential risks, enabling individuals to engage in competitive athletic activities without any limitations (Mora et al., 2007).

Coronary artery disease

Regular PA has been shown to have positive impacts on conventional risk factors associated with CVD (Borjesson et al., 2019). Despite this fact, atherosclerotic coronary artery disease is a common cause of sudden death in veteran athletes. Usually CAD is due to rupture of/ or haemorrhage inside superficial plaques. Exercise-related vascular effects are blunted with increased exercise intensity. High-intensity exercise is associated with increased inflammatory mediators and oxygen-free radicals. Mismatched myocardial needs and supply is the main mechanism for CAD. Other factors contributing to CAD in athletes are age, genetic factors, infections, and structural, functional, and physiologic changes associated with exercise. Endurance-type is also associated with increased calcification of coronary arteries. The relationship between exercise and CAD has several grey areas and unclear mechanisms that are still under discussion (Dores et al., 2018; Katsi et al., 2021; Borjesson et al., 2019).

The presentation of CAD in athletes may be silent or with symptoms of angina. The management is based on the recent guidelines. Exercise tests and stress imaging are important to select those with suspected CAD for further coronary artery evaluation. Those with established CAD are to be treated according to guidelines and restriction of high-intensity PA or complete prevention of competitive sports is recommended based on the risk of cardiac events category (Borjesson et al., 2019).

Statins or cholesterol-lowering agents and antiplatelet drugs are prescribed according to the results of imaging of coronary arteries and risk for cardiac events (Aengevaeren & Eijssvogels, 2020). It is worth mentioning that musculoskeletal adverse events resulting from statins can be exaggerated by PA. Nevertheless, it is imperative to emphasize statin therapy after an acute coronary syndrome, even if it necessitates reducing exercise training and competitiveness (Deichmann et al., n.d.).

However, the potential utilization of these agents could be contemplated. It is strongly recommended that individuals with coronary artery disease who are experiencing acute coronary syndrome should actively engage in a structured cardiac rehabilitation program under the supervision of a sports cardiologist. This professional can customize an exercise plan that may involve higher intensity levels than those typically prescribed for individuals with a more sedentary lifestyle (van Hattum et al., 2022).

Hypertension

There is an inverse relationship between PA and blood pressure (Bp). However, athletes are not fully protected. Hypertension is reported to be prevalent among CAHAP, though underdiagnosed and undertreated. Preparticipation measurement of Bp as well as evaluation of those at risk of hypertension. Evaluation of Bp response to exercise can be evaluated during stress tests (Schweiger et al., 2021).

Office BP measurements are recommended, and ambulatory measurement is to be carried out for those with suspected white-coat or masked hypertension. Besides, evaluation of organ dysfunction and associated comorbidities. It is recommended to evaluate the blood pressure in both brachial arteries during each clinical contact in CAHAP. Additionally, it is advisable to monitor blood pressure at least once in the leg (Mancia et al., 2023).

Individuals without pre-existing cardiovascular disease or resting hypertension are expected to experience transient maximal systolic blood pressures of 250 mm Hg or greater, which is both normal and expected (Refoyo et al., 2023).

Management of hypertension in CAHAP is the same as in the general population. Non-pharmacologic therapy such as lifestyle Modulation and endurance exercise if not already performed may be beneficial. In the case of grade 3 hypertension and those with associated comorbidities, pharmacotherapy should not be delayed. Diuretics and beta blockers are banned. Vasodilators have a low impact on exercise physiology such as angiotensin-converting enzyme inhibitors, angiotensin-II receptor antagonists, calcium channel blockers or alpha-blockers are the recommended drugs. Exercise intensification or restriction is tailored based on the patient's clinical condition and other CVD risk factors as well as the results of exercise blood pressure measurement (Mancia et al., 2023).

Coronavirus Disease-2019 (COVID-19) and the athletic heart

It is well-established that COVID-19 has cardiovascular effects (Sobh et al., 2021). These effects are variable in CAHAP. Some studies reported more profound and persistent effects especially myocarditis. However, the exact frequency and significance of cardiac abnormalities associated with COVID-19 in athletes is still unknown. The development of a safe return-to-play algorithm specifically designed for adult athletes engaged in competitive sports is crucial for risk prevention (Gluckman et al., 2022). Finally, shared decision making is important for athletes, especially in areas of controversies or debates.

CONCLUSIONS

Sports cardiology is an emerging field in cardiology with rapid evolution. Optimal care of physically active people requires an integrated approach with enough relevant knowledge and skills. Subsequently, it is of vital importance that high-quality standards of care and target-based research initiatives continue to develop to achieve the main goal of sports cardiology ensuring maximum safety for this group of the population. To advance cardiovascular knowledge and skills among trainees and practitioners, it is imperative to implement educational initiatives in the future. These initiatives should be specifically tailored to meet the needs of both aspiring cardiovascular professionals and those who are already established in the field. Furthermore, the scientific community must assume the responsibility of overseeing outcomes-based research to effectively address the numerous unresolved controversies.

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: Mohammed Mohyeldin, Muhammad Reihan. Methodology: Mohammed Mohyeldin, Mohamed Roshdi. Formal analysis: Eman Sobh. Investigation: Husna Irfan Thalib, Ayesha Jamal. Data curation: Fatma Ahmed, Muhammad Reihan. Writing – original draft: Husna Irfan Thalib, Ayesha Jamal.

Writing – review & editing: Mohammed Mohyeldin, Mohamed Roshdi, Eman Sobh. Supervision: Mohammed Mohyeldin, Eman Sobh All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Nutritional strategies for elite breakdancers: From street culture to Olympic performance



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ABSTRACT

Breaking (breakdancing) has recently been added to the Olympic program, yet sport-specific evidence to guide nutrition support remains scarce. This narrative review synthesizes literature on the physiological demands of breaking and translates evidence from dance medicine and sport nutrition into a practice-oriented framework for elite and semi-elite breaking athletes. Searches of PubMed, Web of Science, and Google Scholar were conducted from inception to December 2025 using terms related to breaking, dance, energy expenditure, energy availability, hydration, macronutrients, micronutrients, relative energy deficiency in sport (RED-S), and supplementation. Evidence was synthesized qualitatively and integrated with established sport nutrition guidance when breaking-specific data were unavailable. Available reports indicate substantial training volumes and intermittent high-intensity efforts during battles, supporting individualized strategies to optimize energy intake, carbohydrate availability, protein distribution, hydration planning, and monitoring of low energy availability/RED-S risk indicators. Recommendations are presented as practical starting points for coaches, athletes, and medical teams, explicitly distinguishing direct evidence from extrapolation. Future research should quantify breaking-specific energy expenditure, sweat rates, and competition-day constraints to refine guidance and improve performance and health outcomes.

Keywords: Breaking, Applied sport nutrition, Energy availability, Intermittent high-intensity exercise, Competition fuelling, Athlete hydration.

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INTRODUCTION

Breaking (breakdancing) attracted substantial attention during the Paris 2024 Olympic Games, marking a transition from its street origins to the global elite sport stage (Li & Vexler, 2019). Beyond performance, breaking is embedded in cultural practices that support identity, self-expression, and community formation in urban environments (Bakker & Nuijten, 2018; Fasting, Kari & Fjogstad-Langne, Tonje, 2014). From a sport-science perspective, breaking performance relies on repeated high-intensity efforts that integrate strength, power, agility, and endurance, all of which are sensitive to training load, recovery, and nutrition strategies.

Despite the growth of competitive circuits and Olympic inclusion, evidence to guide high-performance support in breaking remains limited. Recent pre-Olympic work suggests that competitive breakers may present anthropometric and somatotype characteristics distinct from other dance modalities (Arundale et al., 2023; Montalbán-Méndez et al., 2023), and one cohort study reported low stature and body mass, low body fat percentage, and a predominantly mesomorphic profile in Italian breakers (Ruscello et al., 2024). While injuries in breaking have been more frequently studied (Arundale et al., 2023; Montalbán-Méndez et al., 2023), comparatively less attention has been paid to nutrition-relevant determinants of performance, including energy expenditure, hydration demands, macronutrient periodization, and risk indicators consistent with low energy availability/RED-S (Ruscello et al., 2024).

Therefore, the aim of this narrative review is to synthesize available evidence on the energetic and nutritional demands of breaking and to provide an evidence-informed, practice-oriented framework to support coaches, athletes, and practitioners. Recommendations are presented as practical starting points and explicitly distinguished between evidence specific to breaking and extrapolations from dance medicine and established sport nutrition guidelines.

METHODS

This study was conducted as a narrative review with a practice-oriented synthesis. A literature search was performed in PubMed, Web of Science, and Google Scholar from inception to December 2025. Search terms combined (i) the sport and athlete descriptors (“*breaking*”, “*breakdance*”, “*breakdancing*”, “*B-boy*”, “*B-girl*”, “*breaker*”, “*battle*”) with (ii) nutrition and physiology concepts (“*energy expenditure*”, “*energy availability*”, “*carbohydrate*”, “*protein*”, “*hydration*”, “*sweat rate*”, “*micronutrients*”, “*iron*”, “*vitamin D*”, “*RED-S*”, “*relative energy deficiency in sport*”, “*supplements*”, “*ergogenic aids*”). Searches were adapted to each database using Boolean operators and, when available, truncation.

Eligibility criteria were intentionally broad to capture the limited sport-specific evidence. We included peer-reviewed original studies, reviews, and consensus/guideline documents that reported outcomes relevant to nutritional support in breaking, including energy expenditure or training/competition demands, dietary intake patterns, hydration-related measures, macronutrient strategies, micronutrient status, RED-S/low energy availability indicators, or supplement use. Studies were eligible when they involved elite or semi-elite breaking athletes; when breaking-specific evidence was unavailable, we also considered studies in closely related proxy populations (e.g., hip-hop/street dance or other dance forms) and established sport nutrition guidelines to inform practical recommendations.

Records were screened by title/abstract, then by full text for relevance. Duplicates were removed. The final set comprised 35 sources, which were synthesized qualitatively and organized by thematic domains (physical demands; energy and energy availability; macronutrients; micronutrients/RED-S; hydration; competition-day

strategies; supplements). Recommendations were explicitly labelled as based on breaking-specific evidence versus extrapolated guidance from related literature and established sport nutrition frameworks.

PHYSICAL DEMANDS OF BREAKING ATHLETES

Breaking (breakdancing) is a high-demand dance-sport discipline that integrates acrobatic skills, repeated high-intensity whole-body efforts, and rhythmic motor control. Although the movement vocabulary is diverse, commonly described elements include top rock (upright steps), transitions to the floor (go-downs), footwork/down rock (ground-based locomotor patterns), power moves (rotational skills requiring momentum and technique), and freezes (brief isometric holds in mechanically challenging positions) (Fogarty, 2018). From a sport-science perspective, this profile suggests intermittent bouts of high neuromuscular and metabolic stress, with substantial mechanical loading—features directly relevant to fuelling, hydration, and recovery planning.

Breaking is often practiced within peer-based learning environments (e.g., “*each one teaches one*”), and many athletes train without continuous coaching support, which may contribute to a higher injury burden and inconsistent training periodization (Arundale et al., 2023; Kauther et al., 2009; Tsiouti & Wyon, 2021). Consequently, training organization and load management can vary markedly across athletes and settings.

Empirical descriptions of elite training load remain limited. In a sample of national-squad professional breakers ($n = 12$), Lindner et al. (2024) reported an average total training volume of 24 ± 10.2 h·week⁻¹, including 9.5 ± 6.9 h·week⁻¹ of breaking-specific practice and 9.5 ± 6.5 h·week⁻¹ of non-breaking modalities. Non-breaking training was primarily devoted to strength training and full-body workouts, followed by conditioning/flexibility-oriented work (e.g., functional fitness, Pilates, yoga), aerobic/fitness training (e.g., running, cycling, swimming, plyometrics), and recovery-oriented practices (e.g., stretching, foam rolling, massage, sauna) (Lindner et al., 2024). This distribution supports the notion that breaking preparation resembles that of other high-performance sports, combining technical practice with structured strength/conditioning and recovery work.

Training sessions commonly include repeated “*full-out*” rounds performed individually or in small groups, sometimes using timed formats to simulate competitive exchanges (Arundale et al., 2023). Heart-rate monitoring data indicate an intermittent high-intensity profile: in 14 elite breakers, approximately 45% of training time was spent in moderate-to-vigorous intensity zones (Zones 2–3, as defined by the authors), and peak heart rates during intense rounds could exceed values observed during a cycle ergometer test (Arundale et al., 2023). These findings are consistent with substantial acute cardiovascular strain and suggest that carbohydrate availability and between-round recovery strategies may be relevant during high-density training and competition simulations.

Competition is typically organized as head-to-head “*battles*”, in which athletes exchange short performance bouts across multiple rounds. Bouts are often ~30–45 s, although longer efforts have been reported depending on event rules and format (Fogarty, 2018; Lindner et al., 2024). Judging integrates technical execution, athleticism, musicality/artistry, and transition fluency, requiring both physical capacity and rapid decision-making under fatigue (Fogarty, 2018). Competitive calendars may include multiple local to international events across the year, implying prolonged seasons with repeated travel, variable schedules, and irregular meal timing—factors that can compromise energy intake and recovery if not proactively managed.

Physiological profiling in related hip-hop disciplines further supports high cardiorespiratory demands. Wyon et al. (2018) compared nine male breakers and nine female “*new style*” dancers and reported that breakers’ VO_2peak was higher than values published for several dance forms, and mean heart rate during performance exceeded reports from ballet, contemporary dance, and dance sport. Collectively, available evidence supports classifying breaking as an intermittent high-intensity discipline with meaningful strength/power requirements and non-trivial aerobic demands, reinforcing the need for individualized nutrition strategies across training phases and competition periods.

BUILDING A PRACTICE-ORIENTED NUTRITION FRAMEWORK FOR ELITE BREAKING ATHLETES

As in other high-performance sports, nutrition supports physical and cognitive demands relevant to training quality, competition readiness, recovery, and injury risk management (Challis, 2023; Clarkson & Skrinar, 1988; Sandri, 1993). Breaking athletes often face intermittent high-intensity workloads, dense training volumes, and irregular schedules (including evening events and travel), which can constrain meal timing and recovery opportunities. Collectively, these constraints make nutrition planning a plausible contributor to reducing fatigue, supporting adaptation, and mitigating injury risk, even though breaking-specific evidence remains limited.

Given the current scarcity of studies quantifying dietary intake, energy expenditure, and sweat losses in breaking, the recommendations below are presented as practical starting points. Where breaking-specific data are unavailable, guidance is extrapolated from dance medicine and established sport nutrition consensus documents and should be individualized.

Energy and energy availability

At present, there are no direct measurements establishing energy requirements in breaking athletes. Therefore, a useful organizing construct is energy availability (EA), defined as: $\text{EA} = (\text{Energy intake} - \text{Exercise energy expenditure}) / \text{fat-free mass (FFM)}$, typically expressed in $\text{kcal} \cdot \text{kg FFM}^{-1} \cdot \text{day}^{-1}$ (Burke et al., 2021).

In healthy athletes, an EA around $\sim 45 \text{ kcal} \cdot \text{kg FFM}^{-1} \cdot \text{day}^{-1}$ is often cited as a reference point for supporting physiological function, although individual needs vary by sex, training load, and body composition (L. Burke et al., 2021). In dance populations, applied guidance has similarly emphasized maintaining adequate EA during intensive training periods (Challis & Stevens, 2019). Because breaking-specific energy expenditure data are not yet available, practitioners may initially estimate exercise energy expenditure using two components: (i) breaking-specific practice, approximated using MET values from activities with intermittent high-intensity characteristics; and (ii) non-breaking conditioning (e.g., resistance training, aerobic work, flexibility), using MET values specific to those modalities. These estimates, combined with body composition assessment (to obtain FFM) and dietary intake monitoring, can be used to approximate EA and guide iterative adjustments to energy intake across training phases.

Macronutrients

General sport nutrition guidelines recommend daily carbohydrate and protein intakes scaled to training demands and body mass, with fat contributing an appropriate proportion of total energy (L. Burke et al., 2021). In dance medicine guidance, carbohydrate is often emphasized during intensive training and rehearsal periods, with practical ranges commonly $4\text{--}8 \text{ g} \cdot \text{kg}^{-1} \cdot \text{day}^{-1}$, depending on workload (Challis & Stevens, 2019). For breaking—given its intermittent high-intensity profile and repeated “*round*” efforts—carbohydrate intake

may reasonably trend toward the upper end of these practical ranges during high-density training blocks and competition periods, provided gastrointestinal tolerance and total energy intake are adequate.

Protein intake should support repair and adaptation, with emphasis on distributing protein across the day and including a post-exercise feeding, while total fat intake should ensure sufficient energy density and support hormonal and micronutrient absorption (L. Burke et al., 2021). Because studies on macronutrient requirements specific to breaking are lacking, these targets should be individualized based on training load, performance goals, and recovery markers.

Micronutrients and red-s risk

Weight-sensitive aesthetic and performance cultures in dance have been associated with elevated risk of low energy availability and Relative Energy Deficiency in Sport (RED-S), which can compromise bone health, immunity, and performance. In a large dance cohort, Keay et al. (2020) reported substantial proportions of dancers who screened at risk for RED-S. Although breaking differs from other dance forms, prolonged seasons, irregular schedules, and pressures on body composition may similarly increase risk in some athletes. Practical monitoring should prioritize micronutrients commonly implicated under low energy availability, including iron, calcium, and vitamin D, alongside clinical indicators (e.g., fatigue, recurrent injuries, menstrual dysfunction in females). Where feasible, periodic assessment of iron status and vitamin D, together with nutrition counselling, may support both health and performance (L. Burke et al., 2021).

Hydration

Hydration is a modifiable factor that can influence perceived exertion, cognitive function, and performance, and inadequate hydration may contribute to fatigue and elevated injury risk (Challis & Stevens, 2019). Dance guidance notes that fluid losses during intense sessions may be substantial, with reported sweat losses potentially approaching $\sim 2 \text{ L} \cdot \text{h}^{-1}$ in some high-intensity dance contexts (Challis & Stevens, 2019; Mastin, 2009). However, sweat rates and hydration behaviours have not been quantified in breaking. Therefore, athletes should adopt an individualized plan based on simple field monitoring (e.g., pre/post-session body mass change, urine colour/volume) and adjust fluid and electrolyte intake across environmental conditions and session density. Further research is needed to quantify breaking-specific sweat rates and competition-day hydration constraints to refine recommendations.

COMPETITION- AND TRAINING-DAY NUTRITION STRATEGIES FOR BATTLES (B-BOYS AND B-GIRLS)

Unlike sports with clearly delimited peak and off-season periods, breaking athletes may experience prolonged seasons in which training and competition demands overlap (Montalbán-Méndez et al., 2023). Therefore, nutrition strategies should be feasible year-round and account for constraints such as irregular schedules, late-night events, and travel. Given the limited evidence specific to breaking, the recommendations below are adapted from established athlete and dance-sport guidance and should be individualized, particularly for athletes managing body composition and weight-control goals (ADA & DC, 2016; Sandri, 1993).

Before training or battles

Before exercise, breaking athletes should consume a meal or snack that supports hydration and carbohydrate availability while minimizing gastrointestinal discomfort. Practically, pre-exercise foods are typically low-to-moderate in fat and fibre to facilitate gastric emptying and reduce gastrointestinal symptoms (ADA & DC, 2016; Sousa et al., 2013). A common pre-exercise carbohydrate target is $\sim 1\text{--}4 \text{ g} \cdot \text{kg}^{-1}$ in the 1–

4 h window before prolonged or repeated high-intensity exercise, adjusted to individual tolerance and the planned duration/intensity of the session (L. M. Burke et al., 2006).

Hydration strategies should aim to limit body mass losses (e.g., keeping losses $< \sim 2\%$ when possible). Sodium-containing fluids may be useful when sweat losses are high, especially during prolonged sessions or hot environments (L. Burke et al., 2021). As a practical starting point, general guidance recommends consuming approximately $5\text{--}7 \text{ mL}\cdot\text{kg}^{-1}$ of fluid about 4 h before exercise, with additional intake guided by urine output and comfort (L. M. Burke et al., 2006).

During training (long sessions or high-density rounds)

When sessions last $\sim 1.5\text{--}3$ h, as reported for some professional breakers (Lindner et al., 2024), within-session strategies may focus on replacing fluid losses and, when appropriate, providing carbohydrates to maintain blood glucose and perceived capacity (ADA & DC, 2016). Carbohydrate intakes around $\sim 30\text{--}60 \text{ g}\cdot\text{h}^{-1}$ are commonly suggested for prolonged exercise, with the exact amount depending on session density and gastrointestinal tolerance (ADA & DC, 2016). Fluid intake should be individualized (e.g., guided by pre- and post-session body mass changes). When dehydration is substantial, or sweat losses are high, electrolytes—particularly sodium—may be indicated (L. Burke et al., 2021; L. M. Burke et al., 2006).

After training or battles (recovery)

Post-exercise recovery should prioritize rehydration and the restoration of carbohydrate and protein availability, especially when training or competition continues within the next 24 h. General guidance recommends initiating recovery nutrition soon after exercise and continuing intake at regular intervals when rapid recovery is required. Practical targets in the early recovery period often include carbohydrate provision scaled to body mass and session demands, combined with protein at frequent intervals to support muscle repair and adaptation (ADA & DC, 2016). Rehydration should replace both water and electrolytes lost in sweat. When meaningful dehydration has occurred, ingesting approximately $\sim 150\%$ of the estimated fluid deficit over the subsequent hours has been suggested to fully restore fluid balance (L. M. Burke et al., 2006).

NUTRITION DURING AND AFTER BREAKING BATTLES (EVENT-DAY PRACTICALITIES)

On event days, meal timing should be planned around the expected start time of battles. As a practical approach, a larger meal is typically consumed about ~ 4 h before performance, whereas a smaller snack may be consumed $\sim 1\text{--}2$ h prior, depending on individual tolerance. Because battles often occur in informal settings and may finish late at night, athletes should be encouraged to bring portable foods and fluids to avoid prolonged fasting and reduce the risk of gastrointestinal issues from unfamiliar options.

During battles, fluid intake should be prioritized to support cognition, motivation, and motor skill performance. When events are prolonged or include multiple rounds with short recovery windows, carbohydrate provision (e.g., sports drinks or easily digested snacks) may help maintain circulating glucose and perceived capacity (Challis, 2023; Challis & Stevens, 2019; Mastin, 2009).

After battles, recovery nutrition should emphasize carbohydrates to replenish muscle glycogen and protein to support repair, particularly when the next training session occurs the following day (Challis & Stevens, 2019). Because events often end late, carrying ready-to-eat recovery snacks can help athletes meet recovery targets despite limited food availability after competition.

DIETARY SUPPLEMENTS AND ERGOGENIC AIDS

Evidence on dietary supplement use and ergogenic aids in breaking athletes is limited, and no breaking-specific intervention studies were identified. Available survey data from related dance populations suggest that supplement knowledge and use may be variable and, in some contexts, lower than in other sport disciplines (Prus et al., 2019). Among a sample of hip-hop dancers, the most reported products were caffeine and multivitamin/vitamin supplements, whereas fewer participants reported using protein supplements or creatine. In another small sample, most breakdancers reported rarely or never consuming several sports nutrition products (e.g., isotonic drinks, carbohydrate or recovery drinks), although these findings should be interpreted cautiously due to limited sample size and self-report bias (Prus et al., 2019).

From an applied perspective, supplements may be considered only when they address a clearly defined need (e.g., documented micronutrient deficiency, inability to meet macronutrient targets with food, or evidence-based acute performance strategies) and when implemented under professional supervision (Challis & Stevens, 2019). Because restrictive or unbalanced dietary patterns have been reported in some dance settings, a multivitamin/mineral supplement may be considered in selected cases; however, it should not replace food-based strategies, and decisions should ideally be guided by dietary assessment and clinical markers (Challis & Stevens, 2019).

Table 1. Practical nutrition framework for breaking athletes around training and battles.

Timing	Core recommendation (starting point)	Practical food/fluid examples	Evidence base*
Before training/battles	Carbohydrate: ~1–4 g·kg ⁻¹ in the 1–4 h pre-exercise window (adjust to tolerance and session demands). Hydration: ~5–7 mL·kg ⁻¹ ~4 h pre-exercise; consider additional small volumes if urine remains dark/low.	Sports drink (~6% CHO) as tolerated; cereal bar; banana/fruit; dried fruit; bread with jam/honey; water and/or sodium-containing fluids if sweat losses are high.	Guideline-based
During (prolonged sessions / high-density rounds)	Carbohydrate: ~30–60 g·h ⁻¹ when sessions are prolonged or when repeated high-intensity bouts occur with limited recovery. Fluids: individualize to sweat losses; aim to limit body mass loss to <~2% when possible; include sodium when sweat losses are high or conditions are hot.	Sports drink; gels/chews (if tolerated); small CHO snacks. Use pre/post body mass change to calibrate fluid needs over time.	Guideline-based / Indirect
After (recovery)	Carbohydrate + protein: begin recovery nutrition soon after exercise when rapid recovery is required; continue at regular intervals. Rehydration: if meaningful dehydration occurred, ingest ~150% of estimated fluid deficit over subsequent hours to restore fluid balance.	Recovery snack pack: milk or yogurt + fruit; sandwich + milk; cereal + milk; smoothie; water + salty foods or electrolyte drink if sweat losses were high.	Guideline-based

Notes. (1) Values are practical starting points and should be individualized based on training load, gastrointestinal tolerance, body composition goals, and environmental conditions; (2) Recommendations are not breaking-specific requirements; they are extrapolated from consensus guidance for athletes and from dance medicine resources due to limited breaking-specific evidence; (3) Carbohydrate and hydration ranges reflect the joint position statement on Nutrition and Athletic Performance (ADA & DC, 2016) and sport nutrition guidance (L. Burke et al., 2021); (4) The ~150% fluid deficit guideline is included to support post-exercise rehydration when rapid restoration is needed; (5) Dance-specific carbohydrate guidance (commonly ~4–8 g·kg⁻¹·day⁻¹ depending on workload) can be used to contextualize daily planning outside the “around-exercise” windows. *Evidence base: Guideline-based = derived from consensus/position statements for athletes; Indirect = inferred from dance medicine / related populations rather than breaking-specific trials.

Given the anti-doping context of elite sport, any supplement use should follow a risk-minimization approach, prioritizing third-party tested products and conservative dosing strategies. Overall, the current evidence base does not support sport-specific supplement “*protocols*” for breaking, and future studies should quantify habitual intake patterns, micronutrient status, and the acute effects of commonly used ergogenic aids (e.g., caffeine) under ecologically valid battle formats.

Table 1 summarizes a practice-oriented nutrition framework for training and battle contexts; supplement use should be considered adjunctive and only when supported by assessment and evidence.

CONCLUSIONS AND FUTURE DIRECTIONS

Breaking’s recent Olympic debut has accelerated interest in evidence-informed performance support, yet evidence on nutrition specific to breaking remains scarce. The available literature suggests that elite breaking preparation can involve substantial weekly training volumes and intermittent high-intensity demands, supporting the relevance of individualized strategies for energy availability, carbohydrate planning, hydration, and recovery. However, most current recommendations must be extrapolated from dance medicine and general sport nutrition guidance, as there are limited direct measurements in breaking.

A practical implication is the need to strengthen access to qualified sport nutrition support within breaking environments, particularly given indications from dance populations that many athletes obtain nutrition information primarily through informal channels rather than structured professional guidance. Accordingly, practitioners should prioritize food-first strategies, systematic monitoring for low energy availability/RED-S risk indicators, and individualized plans that accommodate late-night events, travel, and variable training density.

Future research should quantify breaking-specific demands and test feasible interventions under ecologically valid “*battle*” formats. Priority directions include: (i) direct assessment of energy expenditure and energy availability across training phases; (ii) measurement of sweat rates and electrolyte losses in typical venues and climates; (iii) characterization of habitual dietary intake patterns and micronutrient status in elite breakers; (iv) prospective surveillance linking nutrition-related markers (e.g., low energy availability indicators) with injury and illness outcomes; and (v) controlled evaluations of commonly used ergogenic aids (e.g., caffeine) using anti-doping-compliant protocols and performance-relevant endpoints.

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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.

DATA AVAILABILITY

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Technological devices for the assessment and rehabilitation of hand and finger function in multiple sclerosis: A systematic review

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ABSTRACT

Multiple sclerosis (MS) is a chronic neurological disease that often leads to impairments in hand function, these limitations affect their quality of life. The use of technological devices in the parameterization and rehabilitation of manual dexterity in people with multiple sclerosis (pwMS) has gained significant attention due to their potential to improve the assessment and rehabilitation for the upper limb. This systematic review aims to provide an overview of the technological devices used for assessing and rehabilitating hand function in pwMS. It focuses on sample size, participant characteristics, tools and methodologies, intervention types, frequency and duration, and the anatomical regions and variables analysed. A systematic search was conducted in PubMed, Web of Science and Scopus, identified studies using technological devices for hand function assessment and rehabilitation in PwMS. Data were extracted on sample size, participant demographics (age, sex, MS type, and disease duration), tools used, intervention protocols and primary variables analysed. The review included 15 studies with a total of 865 pwMS, 28 healthy persons and 2123 healthcare professionals. The studies employed a variety of tool, tests, activities and protocols, going from traditional appliance to sensor-equipped devices. Rehabilitation protocols varied in frequency, duration and in format, with sessions lasting between 40 and 60 minutes, conducted 2–6 times per week over 4–8 weeks and conducted in person or telematic. Technological interventions show potential to improve hand function and treatment adherence. However, further research is needed to validate their predictive performance, optimize intervention protocols, and address challenges such as accessibility and long-term effectiveness.

Keywords: Hand, Multiple sclerosis, Parameterization, Rehabilitation, Technology.

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INTRODUCTION

Multiple Sclerosis (MS) is a neurodegenerative disease characterized by the demyelination within the central nervous system, in which the own immune system mistakenly attacks the myelin sheath that covers the nerve fibre (Harris et al., 2009). This damage disrupts the normal transmission of the nerve signals, resulting in impaired nerve conduction and a wide range of neurological symptoms. People with MS (pwMS) often experience motor and sensory disturbances, cerebellar dysfunction, fatigue, visual impairments, cognitive decline, speech and swallowing difficulties, as well as bladder, bowel and sexual dysfunction (Pugliatti et al., 2006, Lundy-Ekman, 2014). Among these manifestations, decreased manual dexterity and grip strength are particularly disabling, as they significantly limit the ability to perform activities of daily living (ADL) (Harris et al., 2009).

Worldwide, approximately 2,8 million people are affected by MS (Feigin, 2019), making it the leading non-traumatic cause of disability in young adults across Europe and North America (Evans et al., 2013, MSFI, 2020). Demographic data indicates that around 90% of pwMS are between 15 and 50 years old, and the female-to-male ratio has increased to almost 3:1 in recent decades (Coyle and Seeman, 2021, Ahlgren et al., 2011, Compston and Coles, 2002, Wallin et al., 2012, Orton et al., 2010). Paediatric-onset MS (<18 years) remains rare (<5% of cases), and onset after age 60 occurs in <1% of the cases (Coyle and Seeman, 2021).

Often referred to as “*the disease with a thousand faces*” due to its unpredictable course and wide variability of symptoms, MS affects various neurological functions such as strength, coordination and sensitivity (McDonald et al., 2001). Fifteen years after diagnosis, most patients experience significant hand dysfunction, forcing them to compensate with their upper limbs during everyday tasks such as buttoning clothes or handling utensils, which significantly reduces their independence, contributes to the progression of the disability and substantially increases their overall disability and loss of quality of life (Jonsdottir et al., 2019).

As a result of the wide range of neurological symptoms, pwMS tend to be significantly less physically active than healthy individuals of the same age, with up to a 30% reduction in aerobic capacity (Romberg et al., 2004, Brown and Kraft, 2005). Physically inactivity has been shown to lead to de-conditioning, which in turn contributes to the progression of disability (Motl et al., 2013). As a result, pwMS often reports difficulties in performing ADL, such as cooking or personal hygiene, which can seriously affect their self-perception and psychological well-being (Månsson and Lexell, 2004). In some cases, these limitations are associated with jog loss and reduced social integration (Chruzander et al., 2013). For these reasons, physical activity is strongly recommended as a key component of a multidisciplinary approach to MS treatment (Johansson et al., 2007).

Nowadays, advances in robotics are showing their potential in rehab, by increasing patient adherence and giving healthcare staff accurate quantitative data, which lets them personalize training and measure motor skills during therapy (Carpinella et al., 2009, Lamers et al., 2016). At the same time, telemedicine, which has been promoted since the SARS-CoV-2 pandemic in 2020, offers advantages such as greater adherence, time and cost efficiency, access without the need for travel and a reduction in the healthcare workload (P, A. J et al., 2003).

However, current devices are often limited to specific task or treat hand as a functional unit, without parameterizing the performance of each finger. This technological gap, coupled with the clinical complexity of MS, highlights the need for more versatile and personalized solutions.

The objectives of this systematic review are: (1) identify the technological devices used for the assessment and improvement of manual function in pwMS; (2) analyse how these devices address the parameterization of manual strength and dexterity, considering the specific involvement of the fingers; (3) evaluate the effectiveness of rehabilitation interventions using these devices and the reported clinical outcomes; and (4) examine healthcare professionals perspective on the implementation, execution and content of technology-assisted rehabilitation, as well as to identify recent trends and innovations in the design of tools for this purpose.

METHOD

This section explains how the research was done. The design of the same is described and it is explained how it was put into practice, justifying the choice of the methods used. This section should contain the type of quantitative research, the scope or depth of the research (exploratory, correlational and/or explanatory), population and sample, and the techniques used should be added. This section is fundamental, because it is the one that will allow the scientific community to reproduce the result. Most of this section should be written in the past tense, in a descriptive style.

Register

The systematic review was registered on the Open Science Framework platform (OSF) (https://osf.io/anjr4/?view_only=05969c336a0847028766e96f574eb63e) the 6 de February of 2026 (DOI: 10.17605/OSF.IO/ENQRK).

Procedures

The guidelines followed for the development of this systematic review were those established in the PRISMA 2020 guide (Page et al., 2021a, Page et al., 2021b).

Data sources and search strategy

Initially, four databases were to be used: Océano, Scopus, Web of Science and PubMed. However, given that Océano database draws all of its articles from the other three databases, it was decided to omit it from the final search.

The search strategy was developed by several authors (PP, NV and AM) specifically for the PubMed database (added below) and was applied to the title, abstract and keyword fields. This strategy was subsequently modified to adapt to the syntax and specific descriptions of the other databases. The bibliographic search was conducted in the PubMed, Web of Science and Scopus electronic databases, using the Boolean operator AND/OR in combination with the keywords: (((((((("multiple sclerosis"[Title/Abstract]) AND (hand[Title/Abstract])) OR ("upper limb"[Title/Abstract])) OR ("upper extremities"[Title/Abstract])) OR (finger[Title/Abstract])) OR ("hand grip"[Title/Abstract])) AND (rehab*[Title/Abstract])) OR ("hand training"[Title/Abstract])) OR ("finger training"[Title/Abstract])) NOT ("cerebral rehabilitation"[Title/Abstract])) AND ((y_5[Filter]) AND (excludepreprints[Filter]) AND (casereports[Filter] OR classicalarticle[Filter] OR clinicalstudy[Filter] OR clinicaltrial[Filter] OR clinicaltrialphasei[Filter] OR clinicaltrialphaseii[Filter] OR clinicaltrialphaseiii[Filter] OR clinicaltrialphaseiv[Filter] OR clinicaltrialprotocol[Filter] OR observationalstudy[Filter] OR patienteducationhandout[Filter] OR randomizedcontrolledtrial[Filter] OR review[Filter] OR scopingreview[Filter] OR systematicreview[Filter] AND (humans[Filter]) AND (english[Filter]) AND (alladult[Filter]))).

One author (PP) conducted the initial search, during which all collected references were uploaded to the Rayyan QCRI platform to remove duplicates. Two reviewers (PP and NV) independently assessed potentially eligible titles and abstracts, jointly resolving disagreements to minimize potential interpretation biases. The full texts of potentially eligible records were analysed according to the inclusion criteria for final selection. Reasons for exclusion were documented. In cases where articles were unavailable, authors were contacted by email.

Eligibility criteria

Original, peer-reviewed, full-text studies were included/excluded using the PICOS method (participants, interventions, comparators, outcomes and study design). The selection criteria are presented below (Table 1). To be included, a study had to have been published in a scientific journal within the last five years, to find the most recent and up-to-date evidence in the field. It was also established that the minimum number of participants in the study had to be at least 20, all of whom had to be diagnosed with MS, regardless of gender and the MS type, but with the restriction that patients had to be adults (>17 years old). This decision was made in order to have a study population large enough to produce meaningful results. One aspect that was considered when including articles, especially those on rehabilitation, was that the study used technology in the rehabilitation process, whether to enable telerehabilitation, to assist the patient or through augmented reality video games.

Table 1. Inclusion and exclusion criteria using the PICOS method.

Category	Inclusion criteria	Exclusion criteria
Participants	Adults with a confirmed diagnosis of multiple sclerosis (MS); ≥17 years; any sex; any MS subtype.	Participants without MS; paediatric samples (<16 years); mixed-age samples where adult data cannot be separated.
Interventions	Rehabilitation interventions that incorporate technology (e.g., telerehabilitation, assistive technologies, augmented reality or serious games) as part of the therapeutic process.	Rehabilitation interventions without any technological component when technology is required for inclusion.
Comparator	Any reported comparator (usual care, alternative intervention, sham, baseline, etc.).	
Outcomes	Measures of hand strength and/or dexterity, and studies that report parameterization and/or rehabilitation of these outcomes in MS patients.	Studies that do not explicitly assess or report hand strength/dexterity parameterization or rehabilitation
Study design/Other	Original, peer-reviewed, full-text studies published in scientific journals within the last 5 years; minimum sample size ≥20; sufficient methodological detail for critical appraisal	Conference abstracts, proceedings, unpublished studies; systematic reviews (not included as primary data, though screened for primary study references); studies with <20 participants or insufficient methodological detail; publications >5 years old.

Although systematic reviews were not included directly, they were examined to see if they contained references to studies that did not appear in the searches but were of interest.

Data extraction and synthesis

The process of extraction data from the final selection of articles was carried out entirely by the author of the review, which facilitates methodological consistency throughout the study. Data extraction for each article had two aspects, the first one, was to compile the main objective of the study and characterize the participating population. The second aspect involved extracting the measures and tests performed, the devices used in the study and the main conclusions reached.

RESULTS

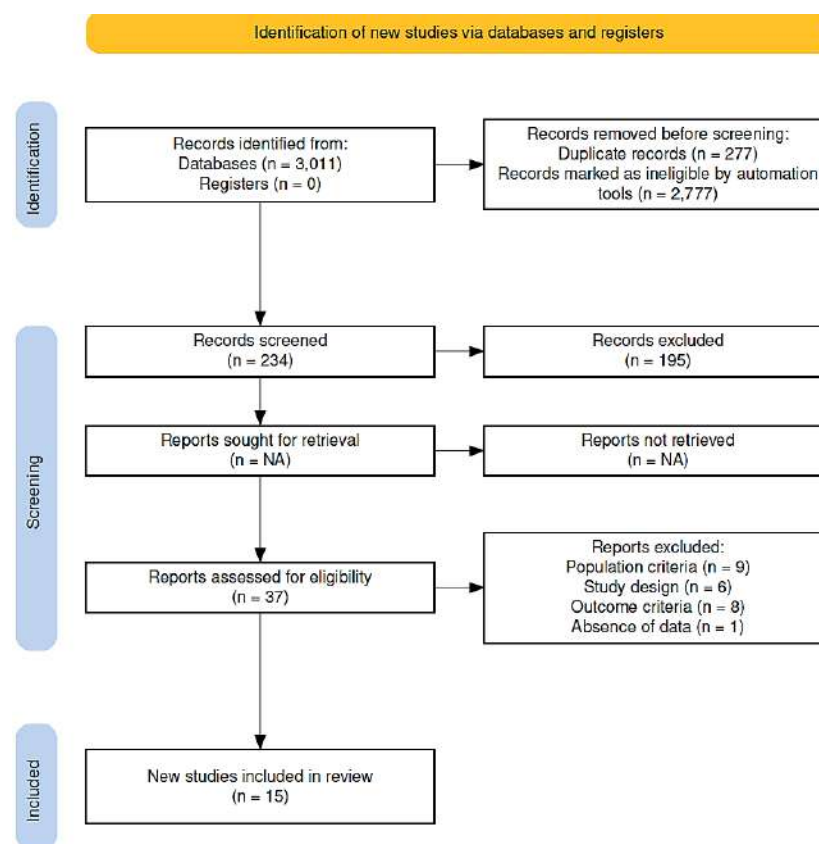
Study selection

Potentially eligible studies were exported directly from scientific databases to the Rayyan platform (<https://www.rayyan.ai/>) for duplicate removal and screening, applying the previously established inclusion

and exclusion criteria. After this initial procedure, a total of 3.037 records were identified. Figure 1 shows the flow diagram for the study selection process. Duplicate records ($n = 277$) were removed. Subsequently, after reviewing titles and abstracts, 2.777 records were discarded and 234 full texts were screened. Of these, 234 studies were excluded after applying the eligibility criteria. Finally, 15 studies were considered eligible for the systematic review.

Study presentations

The results of the selected studies are presented according to the main objectives of each study, differentiating between those focused on the parameterization of hand strength and dexterity, those addressing rehabilitation interventions and the last one focused on the execution and content of rehabilitation, but from the healthcare personnel point of view. In all cases, the information extracted is structured in two tables. The first table shows the main objective of the study and the characteristics of the participant population, while the second table summarizes the measures and test applied, the devices used and the main conclusions of each study, information on the duration and frequency of the interventions is also included. This organization allows for a clear and systematic comparison between the studies included.



Source: Page et al. (2021b).

Figure 1. PRISMA flow diagram.

Study characteristics

A total of 1105 participants information was gathered, of which 865 were pwMS, 28 healthy persons used as normative values in the study Pau et al., 2021 and 212 were healthcare professionals that participated in the survey about the implementation of rehabilitation (Rasová et al., 2020). All the studies the groups were composed of both women and men, but the number of women was higher than, involving 733 (66,33%) women.

A total of 669 people participated in the parameterization studies, of whom 65,63% were women ($n = 439$). For objective measurements, two studies used the JAMAR hand dynamometer to measure isometric grip strength (Pau et al., 2021, Grange et al., 2025), three performed fine motor skills (9-HPT) and gross motor skills tests (BBT) (Bertoni et al., 2022, Pau et al., 2022, Grange et al., 2025) and one studied positioning and opposition movements (Signore et al., 2020). Only one article used sEMG sensors to measure muscle contractions (Beretta-Piccoli et al., 2020).

In terms of results and/or subjective tests, two studies used the MAM-36 and MFIS (Prada et al., 2020, Grange et al., 2025), while those that appeared in only one study were ABILHAND (Prada et al., 2020), FIM (Prada et al., 2020), HADS (Prada et al., 2020), LSI (Prada et al., 2020), FSMC (Beretta-Piccoli et al., 2020) and SDMT (Grange et al., 2025).

In the rehabilitation group, a total of 224 people participated in the eight studies, with 48,21% ($n = 108$) belonging to the experimental groups and 51,79% ($n = 116$) to the control groups. The percentage of women were 61,54% for the total, 55,75% for the control group and 44,25% for the experimental group. As for the objective measurements taken, in half of the studies, the JAMAR hand dynamometer was used to obtain isometric grip strength (Blázquez-Fernandez et al., 2024, Pruszyńska et al., 2022, Marcos-Antón et al., 2023, Dastan et al., 2025), while in only one trial, opposition grip strength with 2 and 3 fingers and lateral pinch strength, by using the PinchGauge (Blázquez-Fernandez et al., 2024).

Seven of the eight studies chose de 9-HPT as the method for assessing fine manual dexterity (Blázquez-Fernandez et al., 2024, Cuesta-Gómez et al., 2022, Pruszyńska et al., 2022, Marcos-Antón et al., 2023, Tramontano et al., 2020, Ciatto et al., 2024, Dastan et al., 2025, Solaro et al., 2020), while four trials used de BBT for gross manual dexterity (Blázquez-Fernandez et al., 2024, Cuesta-Gómez et al., 2022, Marcos-Antón et al., 2023, Ciatto et al., 2024).

The 25% of the studies measures range of motion, one at the forearm and wrist level (Marcos-Antón et al., 2023) and the other at the wrist and each finger separately (Ciatto et al., 2024). In the subjective testing section, three studies used the MSIS-29 (Blázquez-Fernandez et al., 2024, Cuesta-Gómez et al., 2022, Marcos-Antón et al., 2023), one used the FSS (Blázquez-Fernandez et al., 2024) and two used the MFIS (Dastan et al., 2025, Solaro et al., 2020) and NRS (Ciatto et al., 2024, Solaro et al., 2020), also one quarter of the trials used the ABILHAND (Blázquez-Fernandez et al., 2024, Marcos-Antón et al., 2023).

While the tests that were only used by one of the trials were, TMT (Cuesta-Gómez et al., 2022), SCWT (Cuesta-Gómez et al., 2022), MBI (Tramontano et al., 2020), MSQIL-54 (Tramontano et al., 2020), RMI (Tramontano et al., 2020), MRC (Tramontano et al., 2020), DASH (Ciatto et al., 2024), AMSQ (Dastan et al., 2025), PBMSI (Dastan et al., 2025), IPA (Dastan et al., 2025) and BPI (Dastan et al., 2025).

Parameterization

Below are the extracted data from the six articles focused on parameterization. The first table (Table 2) show the objective to be achieved in each study and the characterization of the participant population (age, duration of illness, MS type...).

The second table (Table 3) shows the measurements and tests performed on patients, the material used in the trials and the conclusions reached in the study.

Table 2. Principal outcome and population characteristic of the parameterization studies.

Study	Principal outcome	n°	Age (X ± σ) [Range] (years)	Gender (%)	MS Type (%)	Disease duration (X ± σ) [Range] (years)	EDSS (X ± σ) [Range]
Prada et al., 2021	Compare the relationship between the MAM-36 and the ABILHAND questionnaire to detect impairments in pwMS	51	56.3 ± 10.00 [33-82]	72.55-F 27.45-M	54.94-RR 45.06-P*1	34 ± 12	5.5 ± 1.6 [1.5-7.5]
Bertoni et al., 2022	Examine alterations in bilateral fine and gross motor skills according to the degree of disability	212	54.07 ± 12.81	63.68-F 36.22-M	52.83-RR 18.87-PP 28.30-SP	18.91 ± 10.95	6.50 (5.50-7.00) *2
Signore et al., 2019	Explore the effects of aging on finger motor performance in pwMS, considering duration and phenotype	96	42.1 ± 9.5	69.80-F 30.20-M	84.40-RR 15.6-SP	[0.6-44.2] (8)*3	0-7 (2.5) *3
Pau et al., 2021	Apply methodology with two accelerometers on wrist to quantify activity, intensity and asymmetry in the upper limb	28 (28)*4	50.6 ± 9.5	71.43-F 28.57-M	67.86-RR 14.29-PP 17.86-SP	-	4.5 ± 1.9
Beretta-Piccoli et al., 2020	Quantify actual upper limb activity in terms of time, intensity and asymmetry using wrist accelerometers	21	47 ± 11	57.14-F 42.86-M	57.14-RR 14.29-PP 25.57-SP	-	4.3 ± 1.0
Grange et al., 2025	Examine alterations in bilateral fine and gross motor skills according to the degree of disability	261	51.4 ± 13.3 [19-85]	64.40-F 35.60-M	52.90-RR 18.40-PP 28.70-SP	14.61 ± 10.84 [0-53]	5.03 ± 1.9 [0.00-8.50]

Note. X = Mean/σ = Standard deviation/RR = Relapsing-Remitting/PP = Primary Progressive/SP = Secondary Progressive/EDSS = Expanded Disability Status Scale/F = Female/M = Male. *1 = Progressive type/*2Median (IQR)(Interquartile Range)/*3(Median)/*4Healthy Controls (for nominals values).

Table 3. Measurements, test, devices used and conclusion of the parameterization articles.

Study	Measures obtained	Tests performed	Devices and software used	Conclusions
Prada et al., 2020 [xx]		Manual Ability Measure-36 (MAM-36) y ABILHAND, Edinburgh Handedness Inventory, Functional Independence Measure (FIM), Hospital Anxiety and Depression Scale (HADS), Life Satisfaction Index (LSI), Modified Fatigue Impact Scale (MFIS)		Both tools, MAM-36 and ABILHAND are valid for assessing upper limb functionality in pwMS. It maintains that a multidimensional approach is necessary for a better evaluation
Bertoni et al., 2022		Fine manual dexterity (9-HPT) and gross manual dexterity (BBT)	R-Software	The study found that, in most pwMS, both fine and gross motor skills were altered with respect to normative values, with gross motor skills being more prevalent and appearing in earlier stages of the disease. Regarding the MS phenotype, gross motor skills showed more alterations and a higher prevalence.
Signore et al., 2020	Self-positioning with and without marked rhythm, sequences of opposing movements with each finger and motor performance	Finger positioning and opposition movements with marked rhythm (2Hz) and self-paced	Sensor-Engineered Glove (GAS, ETT S.p.a., Italy), hoc tool software and Stata V.14	Evidence of worsening motor performance in the finger in pwMS due to age and disease progression. Deterioration in bilateral coordination compared to normative data for healthy individuals of the same age. Relationship between age and level of disability (EDSS) with hand functions.
Pau et al., 2021	Vector magnitudes per axis, time and unilateral use ratios, mono and bilateral use index, isometric grip strength	Fine motor skills (9-HPT) and gross motor skills (BBT)	Triaxial accelerometer (Actigraph GR3X), Actilife V6.13.3 software, MATLAB and dynamometer (JAMAR®)	The use of portables devices for bilateral monitoring of the upper limb proved to be a valid tool for assessing the contribution of each limb in unilateral and bilateral movements, facilitating clinical and rehabilitation follow-up

Beretta-Piccoli et al., 2020	Maximal and submaximal contractions (20% and 60% MVC), endurance time and surface electromyography (sEMG)	Fatigue Scale of Motor and Cognitive Functions (FSMC)	Ergonomic chair (COR1), load cell, adhesive electrode mesh (MUC1), torque meter and EMG signal amplifiers (OT-Bioelettronica)	Surface electromyography (sEMG) parameters were useful for indirectly assessing fatigue and muscle performance in pwMS during submaximal contractions, especially in the biceps brachii.
Grange et al., 2025	Isometric grip strength (JAMAR®)	Fine motor skills (9-HPT), gross motor skills (BBT), Manual Ability Measure-36 (MAM-36), SDMT and MFIS-21	Dynamometer (JAMAR®) and IBM SPSS Statistics V26 software	Fatigue in pwMS is present in both subjective and objective assessments, affecting upper limb dexterity. Combined assessment of strength, dexterity and fatigue can optimize clinical interpretations and rehabilitation

Note. MAM-36 = Manual Ability Measure-36/FIM = Functional Independence Measure/HADS = Hospital Anxiety and Depression Scale/LSI = Life Satisfaction Index/ MFIS = Modified Fatigue Impact Scale/9-HPT = 9 Hole Peg Test/BBT = Block and Box Test/ FSMC = Fatigue Scale of Motor and Cognitive Functions/ SDMT = Symbol Digit Modalities Test/MFIS-21 = Modified Fatigue Impact Scale.

Rehabilitation

For those articles focused on rehabilitation, as in those on parameterization, the information extracted was separated into two groups of tables. The first one (Table 4) shows the objective of the trial and the characteristics of the study population, which in this case is composed of two groups, the control group and the experimental group. The second table (Table 5), as in the previous case, shows the measurements and tests carried out on the patients, the material used in the trials, the conclusions reached in each study and in addition, shows information on the duration and frequency of the session.

For the devices used, one article used the PowerBall, another article used the Nintendo Switch, the Pablo Tyromotion exoskeleton was also used in one trial, in other study the used the MYO Armband sensor and another used the SenseWear Armband, with their corresponding virtual environment software. This set of studies shows how conventional rehabilitation therapies combined with new technologies/devices were more effective than those that only used conventional rehabilitation techniques.

Table 6. Characteristics of the population in the survey of implementation of rehabilitation.

Study		Rasová et al., 2020				
Principal Outcome		To describe aspects of the content and delivery in MS physical therapy across Europe, analyse key factors, and evaluate general recommendations related to the implementation of physical therapies in clinical practice				
Characteristics		Total (%)	Region			
			East (%)	North (%)	South (%)	West (%)
Total respondents		212	35(16.5)	65(30.7)	91(42.9)	21(9.9)
Gender	Female	154(72.6)-F	25(71.4)-F	56(86.2)-F	63(69.2)-F	10(47.6)-F
	Male	58(27.4)-M	10(28.6)-M	58(13.8)-M	28(30.8)-M	11(52.4)-M
Age	21-30	65(30.7)	17(48.6)	15(23.1)	25(27.5)	8(38.1)
	31-50	123(58.0)	15(42.9)	38(58.5)	61(67.0)	9(42.9)
	>50	24(11.3)	3(8.6)	12(18.5)	5(5.5)	4(19.0)
Profession	Physiotherapist	201(94.8)	32(91.4)	62(95.4)	89(97.8)	18(85.7)
	Researcher	14(6.6)	3(8.6)	2(3.1)	5(5.5)	4(19.0)
	Other profession	8(3.8)	2(5.7)	4(6.2)	0(0.0)	2(9.5)
Educational level	Doctoral	18(8.5)	6(17.1)	2(3.1)	10(11.0)	0(0.0)
	Masters	69(32.5)	21(60.0)	19(29.2)	22(24.2)	7(33.3)
	Bachelor	87(41.0)	6(17.1)	39(60.0)	31(34.1)	11(52.4)
	Diploma specialist	23(10.8)	0(0.0)	3(4.6)	19(20.9)	1(4.8)
	Other education	15(7.1)	2(5.7)	2(3.1)	9(9.9)	2(9.5)
Years in practice	0-2	28(13.2)	12(34.3)	8(12.3)	6(6.6)	2(9.5)
	03-oct	63(29.7)	8(22.9)	13(20.0)	36(39.6)	6(28.6)
	>10	121(57.1)	15(42.9)	44(67.7)	49(53.8)	13(61.9)
Worktime with MS patients	0%-24%	87(41.0)	22(62.9)	18(27.7)	40(44.0)	7(33.3)
	25%-49%	40(18.9)	4(11.4)	10(15.4)	22(24.2)	4(19.0)
	50%-74%	33(15.6)	1(2.9)	15(23.1)	14(15.4)	3(14.3)
	75%-100%	52(25.5)	8(22.9)	22(33.8)	15(16.5)	7(33.3)

Table 4. Principal outcome and population characteristic of the rehabilitation studies.

Study	Principal outcome	Population (n)		Age (X ± σ) [Range](years)		Gender (%)		Disease duration (X ± σ) (years)		MS type (%)		EDSS (X ± σ) [Range]	
		Control group	Study group	Control group	Study group	Control group	Study group	Control group	Study group	Control group	Study group	Control group	Study group
Blázquez-Fernández et al., 2024	Investigate the effects of a training protocol using the Powerball® in combination with conventional physical therapy on muscle strength, coordination, fatigue, functionality and quality of life in pwMS	13	12	46,33 ±1,90	53,00 ±2,06	53,80-F 46,20-M	33,40-F 66,60-M	14,00 ±3,47	17,75 ±3,20	50-RR 50-SP	25-RR 25-PP 50-SP	5,55 ±1,09	4,38 ±2,05
Cuesta-Gómez et al., 2022	Assess the effects of NS®, combined with conventional intervention, on improving grip strength, coordination, movement speed, fine and gross motor skills, functionality, quality of life and executive function in pwMS	10	11	48,11 ±3,49	53,70 ±2,10	80-F 20-M	36,36-F 63,64-M	17,78 ±2,68	20,10 ±3,39	50-RR 10-PP 40-SP	54,55-RR 36,36-PP 9,09-SP	5,00 ±0,33	6,40 ±0,33
Pruszyńska et al., 2022	Evaluate the effectiveness of using a commercial augmented reality system in pwMS treatment	15	15	41,40 ±4,61	38,33 ±7,61	73,33-F 26,67-M	73,33-F 26,67-M	9,60 ±4,34	9,93 ±5,42	-	-	-	-
Marcos-Antón et al., 2023	Assess the effectiveness of games specially developed for the MYO Armband® capture sensor in improving forearm and wrist mobility, upper limb muscle strength, dexterity, fatigue, functionality, quality of life, satisfaction and adverse effects	15	15	47,87 ±6,70	48,67 ±7,63	66,67-F 33,33-M	40-F 60-M	13,20 ±7,60	17,27 ±10,70	53,33 RR 20,00 PP 26,67 SP	46,67-RR 13,33-PP 40,00-SP	6,0 [2,5] ^{*1}	6,0 [1] ^{*1}
Tramontano et al., 2020	Assessing the effects of sensor-based motor rehabilitation using the PABLO®-Tyromotion device as an addition to conventional rehabilitation therapy	16	14	52,30 ±5,40	46,70 ±10,40	62,50-F 37,50-M	57,14-F 42,86-M	22,40 ±9,50	17,30 ±7,60	81,25-SP 18,75-PR	71,43-SP 28,57-PR	7,10 ±1,00	6,70 ±1,80
Ciatto et al., 2024	Examine the impact of assistive training robots (Hand Tutor TM) on range of motion and manual dexterity in pwMS compared to the conventional population	15	15	46,53 ±10,91	54,73 ±7,45	60-F 40-M	66,66-F 33,33-M	-	-	53,30%RR 13,30%PP 33,30%SP	6,60%RR 93,30%SP	6,73 ±1,09	5,43 ±1,29
Dastan et al., 2025 *2	Evaluate the effects of an 8-week synchronized telerehabilitation program focused on upper limb training and hand-arm functions in pwMS and compare the results with asynchronous telerehabilitation	15	15	37 (34,0; 55,0)	46,00(41,0; 54,0)	80-F 20-M	80-F 20-M	9,75 (4,75;17)	10,20 (7,16;24,6 6)	80-PP 13,30-PP 6,70-SP	80-RR 6,70-PP 13,30-SP	2,5(2,0; 5,5)	3,5 (2,0; 5,5)
Solaro et al., 2020 *3	Compare the efficacy and tolerance of training assisted by robots with haptic technology versus sensorimotor technology in improving upper limb functions in pwMS	17	11	46±10 [26-69]	53±10 [33-67]	59-F 41-M	58-F 42-M	13±8	15±10	35-RR 24-PP 41-SP	10-RR 47-PP 42-SP	5±1	6±1

Note. X = Mean/σ = Standard deviation/RR = Relapsing-Remitting/PP = Primary Progressive/SP = Secondary Progressive/EDSS = Expanded Disability Status Scale/F = Female/M = Male. *1 = Median (IQR), Experimental group = Synchronized Telerehabilitation Treatment group, Control group = Asynchronous Telerehabilitation Treatment/*2Control group = Sensorimotor, Experimental group = Haptic.

Table 5. Measurements, test, devices used and conclusion of the rehabilitation articles.

Study	Measures obtained	Test performed	Devices and software	Sessions	Conclusions
Blázquez-Fernández et al., 2024	Isometric grip strength, two-finger opposition grip, lateral pinch grip, three-finger pinch grip	BBT, 9-HPT, MSIS-29, ABILHAND and FSS	PowerBall® 250 Hz, JAMAR® and Baseline Pinch Gauge®	2 sessions/week 45 min/session 8 weeks (16 sessions)	The Powerball® system, combined with conventional physical therapy, produced significant improvements within the group, with excellent satisfaction and adherence to the treatment. However, no significant differences were observed in comparison with the control group
Cuesta-Gómez et al., 2022	Isometric grip strength	QuickDASH, 9-HPT, BBT, MSIS-29, TMT and SCWT	Dr Kawashima's Brain Training® for the Nintendo Switch® (NS)	2 sessions/week 60 min/session 8 weeks (16 sessions)	Although the 8-week protocol showed improvements in the different measures and test performed, no significant differences were observed between the two analysis groups. While the addition of the video game showed no adverse effects and increased the subjects' level of satisfaction and compliance
Pruszyńska et al., 2022	Isometric grip strength	9- HPT and re-moving balls from a box and place them on a tray.	Neuroforma AR system y JAMAR®	5 sessions/week 40-45 min/session 4 weeks (20 sessions)*1	It emphasizes the important role that rehabilitation plays in slowing down deterioration. It highlights the value of remote rehabilitation, where patients with greater motor difficulties can undergo rehabilitation from home. Patients also showed widespread acceptance and a high degree of willingness to perform the exercise
Marcos-Antón et al., 2023	Range of motion of different joints (dorsiflexion, palmar flexion, pronation and supination) and isometric grip strength	Coordination, fatigue, functionality, 9-HPT, BBT and variables of quality of life (MSIS-29 and ABILHAND)	Sensor MYO Armband® and JAMAR®	2 sessions/week 60 min/session 8 weeks (16 sessions)	The combination of the MYO Armband® with conventional physical therapy produced positive effects in the measurements taken, in addition to demonstrating high usability and user satisfaction
Tramontano et al., 2020	-	9-HPT, MBI, MSQoL-54, RMI and MRC	PABLO®-Tyromotion and IBM SPSS Statistics Software (V 23)	3 sessions/week 40 min/session 4 weeks (12 sessions)	Visual and auditory feedback during training can be a very useful complement to pwMS. The group that used PABLO®-Tyromotion showed a higher percentage of improvement compared to the control group. Only the experimental group showed significant improvements in quality of life (MSQoL), suggesting that the use of this technology helps to motivate and generate greater enthusiasm among pwMS
Ciatto et al., 2024	Range of motion of extension and flexion movements, and frequency of cyclic	9-HPT, BBT, DASH and NRS	Hand TutorTM, Hand TutorTM device and R (V4.3.0)	6 sessions/week 45 min/session 4 weeks (20 sessions)	The rehabilitation program proved to be feasible and well received by the patients, especially those with the most severe disabilities. The experimental group achieved better results than the control group in terms of upper limb functionality after the program
Dastan et al., 2025 *2	Isometric grip strength, physical activity, energy and metabolic expenditure	9-HPT, AMSQ, PBMSI, MFIS, IPA and BPI	JAMAR®, SenseWear Armband, Skype V7.24, SenseWear Professional Software and IBM SPSS	2 sessions/week 40-60 min/session 8 weeks (16 sessions)	Found that synchronized telerehabilitation is effective in terms of fatigue, quality of life and participation of pwMS, and although, asynchronous telerehabilitation also showed improvements, they were not as significant as those in the other group
Solaro et al., 2020 *3	Resistive stiffness (kr) and tool stiffness (km)	9-HPT, Arat, MFIS and NRS	Planar robotic manipulators, eye chart and H3D API (virtual environment)	2 sessions/week 40 min/session 4 weeks (8 sessions)	The haptic modality showed slight improvement in upper limb dexterity training. Individuals with pyramidal impairments showed better adaptation to task difficulty (both for the tool and resistance stiffness) compared to those with cerebral or mixed impairments

Note. BBT = Block and Box Test/9-HPT = 9 Hole Peg Test/MSIS-29 = Multiple Sclerosis Impact Scale/FSS = Fatigue Severity Scale/TMT = The Trial Making Test/SCWT = The Stroop Colour and Word Test/MBI = Modified Barthel Index/MSQoL-54 = Multiple Sclerosis Quality of Life-54 RMI = Rivermead Mobility Index/MRC = Medical Research Council/DASH = Disabilities of the Arm Shoulder and Hand/ NRS = Neurological Rating Scale/AMSQ = Arm Function in Multiple Sclerosis/PBMSI = Patient Reported Preference-Based Multiple Sclerosis Index/ MFIS = Modified Fatigue Impact Scale/IPA = Participation and Autonomy Impact Questionnaire/BPI = Brief Pain Inventory/aRAT = Action Research Arm Test. *1Telerehabilitation sessions/*2 Experimental group = Synchronized Telerehabilitation Treatment group, Control group = Asynchronous Telerehabilitation Treatment/*3Control group = Sensorimotor, Experimental group = Haptic.

Table 7. Topics covered, devices used and conclusion of the implementation of the rehabilitation process.

Study	Rasová et al., 2020
Topics covered in the questionnaires	-Adjustments made based on the level of disability -Details of the therapy sessions (duration, frequency, intensity and composition) -Perception of the accessibility, effectiveness and sustainability of physical therapies -Therapeutics approach (how much time was spent on manual manipulation techniques, how much on giving verbal instructions and information, and how much on demonstration)
Software used in statistical analysis	-Statistical Environment R (V 3.5.0)
Conclusions	-Identify variations in therapies across Europe, where a large disparity was found between regions -Recommendations on access to treatment and adaptation based on the degree of disability -Mentions the need for standardization and/or guidelines to improve the quality and consistency of therapies for pwMS -Highlight the differences in therapeutic approaches and long-term follow-up in different European regions

Implementation of the rehabilitation

The last type of study, which was selected, was one where the purpose of it was to analyse and know better how the physical therapies were conducted across Europe. For these reasons the population of study here were the health professionals that work with pwMS. In Table 6 are shown the characteristics of the people who respond to the questionnaire, while in Table 7 is shown the topics asked, software used and the conclusions that they reached.

212 people from 26 European countries participated in the survey on the content and development of physical therapies. Of those who participated, 72,6% (n = 154) were women, with 58% aged between 31 and 50 years old. Furthermore, 94,8% of the entire group surveyed were physical therapists, with 57,1% having more than 10 years of experience in the rehabilitation of pwMS.

DISCUSSION

One of the key objectives of this systematic review was to collect and analyse studies focused on the use of non-invasive technological devices for the direct assessment of manual function and hand dexterity in pwMS following rehabilitation interventions. In addition, we set out to evaluate the impact of these interventions on grips strength, digital dexterity and functional improvement of the hand in pwMS

Parameterization (objective vs subjective measures)

When assessing the qualities and disease progression presented by pwMS, the outcomes mostly came from two types of measurements, objective and subjective.

Objective measurements provide quantitative and standardized data (Marcos-Antón et al., 2023), making possible the assess of distinct aspects, like manual dexterity (Bertoni et al, 2022), grip strength (Severijns et al., 2015). Due to the nature of been based in standardized protocols and instrument, these measurements are highly reproducible and consistent, making easier to monitor changes in physical function over time (Pau et al., 2021).

In the evaluation of fine manual dexterity, the 9-HPT is recommended as a gold standard test (Feys et al.). For the 9-HPT a clinically important worsening over time has been suggested as 20% (Goodkin et al., 1988). The protocol for this test consists of removing 9 pegs one by one from a container and insert them into a board with 9 holes, then removing them from the board and placing them back into the container (Negaresh et al., 2019). Among its advantages is the simplicity of its administration, since it only requires measuring the time it takes to complete the task. Another benefit is that the size of the pieces to be moved and board to deposit the pegs can be varied in order to make the task easier for the patient (Pruszyńska et al., 2022).

For the gross manual dexterity, the BBT is a frequently used standardized procedure, showing good responsiveness a low floor and ceiling effect when applied to pwMS (Bertoni et al., 2022; Solaro et al., 2020). The BBT evaluates gross manual dexterity by counting the number of 2.5-cm cubes a participant can transfer from one compartment of a divided box to the other within 60 s; the total number transferred is the score. The BBT is brief, easy to administer and sensitive to changes in gross hand function. The BBT test has been validated for pwMS and clinically important worsening over time has been suggested as 3,5 cubes (participant perception), 5,2 (clinical perception) or 15% (Goodkin et al., 1988).

For grip strength the common standard is the HGT that evaluates isometric force by using a hand dynamometer. To perform the HGT, the position of the arm became very important, neutral shoulders, the elbow flexed at 90°, forearm in a natural position, wrist between a dorsiflexion of 0° and 30°, and between 0° and 15° of cubital deviation (Solaro et al., 2020). For the test three measurements are made, being the score the average of the three (Solaro et al., 2020).

Subjective measures show greater heterogeneity: Patient Reported Outcomes Measures (PROMs) differ in domain coverage, item content and scoring, and some scales emphasise activities or participation while omitting aspects important to patients. These types of self-report questionnaires, like the WHODAS 2.0, investigates the subjects' level of functioning, thus allowing a more comprehensive assessment of disability by considering domains of activities and participation as well as the impact of the environmental factors on them (Curatoli et al., 2025). This heterogeneity, together with day-to-day fluctuations in patients' perceptions (influenced by mood, fatigue, etc.), can reduce concordance with objective performance tests. Therefore, and because correlations between PROMs and objective measures are often modest, it is advisable to include both types of assessment for a comprehensive evaluation of upper-limb function. Cite reviews or validation studies that document these discrepancies (Prada et al., 2021).

Disability assessment

An important factor for healthcare professionals when choosing rehabilitation treatment or tests to better monitor the disease is knowing the degree of disability. The EDSS is commonly used for this assessment in PwMS. This numerical scale ranges from 0 to 10, with the following divisions of disability levels: mild ($EDSS \leq 3,0$), moderate ($3,5 \leq EDSS \leq 5,5$) and severe ($EDSS \geq 6,0$) (Solaro et al., 2020). The EDSS focuses on ambulatory and motor skills. This scale has the disadvantage that it must be performed in person and in front of a neurologist, which in situations of mobility or economic restrictions that the patient may have (since it requires to move to a specialized centre), this can cause inconvenience and prevent the evaluation from being performed correctly. For this reason, a variation of the EDSS has been in use for several years, now being conducted by telephone and has been validated for trained personnel (Lechner-Scott et al., 2003). The PDDS is a more economical and simpler alternative to the EDSS for better monitoring of the course of the disease. For this scale, the score ranges from 0 to 8, with the following subgroups: mild ($PDDS \leq 1$), moderate ($2 \leq PDDS \leq 3$), severe ambulatory ($4 \leq PDDS \leq 6$) and severe non-ambulatory ($PDDS \geq 7$) (Bertoni et al., 2015).

Tang et al., 2022 found that upper limb tremor affects up to 50% of people with MS (Meador et al., 2016; Alusi et al., 2001) and used a scale to measure Quality of Life (QOL) in essential tremor. This scale correlates closely with EDSS-measured physical disability, similar to the MSIS-29 (Hoogervorst et al., 2004), but the QUEST scale offers a more accurate QOL assessment for MS patients with upper limb tremor. Selecting the most appropriate scale allows for precise monitoring of disability and supports tailored rehabilitation strategies.

Improvements in rehabilitation techniques

The systematic review highlights the significant role of technological advancements in the rehabilitation of hand function in pwMS, the devices and his function that appear in the selected articles is shown in Table 8.

Table 8. Devices used in the articles.

Category	Devices	Used for
Evaluation and parameterization	Dynamometers (JAMAR® and Pinch Gauge)	To measure isometric grip and pinch strength
	Tri-axial Accelerometers (Actigraph GT3X)	Monitor bilateral upper limb activity
	Sensor-Engineered Gloves	Assess finger opposition movements and positioning
	Surface Electromyography (sEMG)	Evaluate muscle fatigue and performance during contractions
Rehabilitation	PowerBall® 250 Hz	Increasing grip strength and coordination and reducing non-specific wrist pain
	Dr Kawashima's Brain Training® for the Nintendo Switch® (NS)	Infrared motion sensors for training manual dexterity
	Neuroforma AR system	Augmented reality system for arm mobility exercises
	Sensor MYO Armband®	Motion capture sensors for forearm and wrist rehabilitation
	PABLO®-Tyromotion	Sensor based exoskeleton for motor rehabilitation
	Hand TutorTM	Assistive robots for manual dexterity training
	SenseWear Armband	3-axis accelerometer to measure physiological parameters
	Planar robotic manipulators	Robot-assisted rehabilitation
Telerehabilitation	H3DAP! (virtual environment)	Virtual environment
	Skype	Conduct online meetings

On one hand, there are devices designed to perform tasks that define movement patterns and grip forces in the hand (Cuesta-Gómez et al., 2020). Digital medical metrics can be obtained and processed, resulting in objective measurements that characterized movement such as quality, speed, efficiency and delicacy, while also measuring the grip force generated (Kanzler et al., 2020).

The reviewed studies provide robust evidence of the effectiveness of technological interventions in enhancing hand function and quality of life for people with MS. The use of the PowerBall® 250 Hz in combination with conventional physiotherapy resulted in significant improvements in coordination and manual dexterity of the more affected UL as measured by the BBT (Blázquez-Fernández et al., 2024) (Table 9).

Table 9. Outcomes of the BBT test in the article Blázquez-Fernández et al., 2024.

Group	Side	Before	After	Follow-up	Two-paired comparisons		
		(X ± σ)	(X ± σ)	(X ± σ)	Pre Vs. Post	Pre Vs. Follow up	Post Vs. Follow up
		[n° of block]	[n° of block]	[n° of block]	p-value	p-value	p-value
Control	More affected	39.23 (± 10.20)	40.77 (± 10.89)	45.08 (± 11.55)	>.999	.069	.005
	Less affected	41.69 (± 10.61)	42.46 (± 11.24)	45.46 (± 10.38)	>.999	.012	.282
Experimental	More affected	44.5 (± 7.65)	49.17 (± 10.15)	52.08 (± 9.53)	.048	.001	.38
	Less affected	47.75 (± 9.55)	49.92 (± 11.97)	54.83 (± 9.93)	.312	<.001	.034

Not only are material devices being improved, but augmented reality is also introduced as a complement to conventional therapy programs for hand dexterity, achieving greater treatment intensity at affordable cost (Schwarz et al., 2019). The use of video games through virtual reality has benefits in terms of spatial-temporal organization, attention, concentration and benefits decision-making speed, memory social contact when playing in groups, spontaneity and originality (Schwarz et al., 2019, Waliño-Paniagua et al., 2019). In the reviewed literature the use of augmented reality and virtual reality systems Neuroforma AR System, allowed patients to carry out multiple arm mobility exercises remotely, with the physical therapist remotely supervising and selecting the exercises to be performed (Dastan et al., 2025). The trial showed that in the 9-HPT there

was a significant reduction in the execution time (seconds) in both sides of the body (weak and strong side) (Table 10).

Table 10. Outcomes in the 9-HPT in the article Pruszyńska et al., 2022.

Group	Side	Before ($\bar{X} \pm \sigma$)	After ($\bar{X} \pm \sigma$)	p-value	Test power
		[seconds]	[seconds]		
Control	Dominant	3.16 (± 0.28)	3.13 (± 0.29)	.279	0.0593
	Non-dominant	3.26 (± 0.29)	3.24 (± 0.31)	.7418	0.0537
Experimental	Dominant	3.25 (± 0.18)	3.10 (± 0.18)	.0002	0.6098
	Non-dominant	3.34 (± 0.19)	3.19 (± 0.21)	.0002	0.521

The benefits of telerehabilitation including interactive web-based programs, home-based systems for physical activity monitoring, or online communities (Khan et al., 2015), for instance, could monitor and motivate patients over time, whilst potentially improving the accessibility and quality of physiotherapy services (Marziniak et al., 2018).

CONCLUSIONS

This systematic review highlighted the significant potential of technology in enhancing hand rehabilitation for pwMS. Technological advancements provided accurate parameters for assessing hand function and dexterity, ensured high treatment adherence, and increased patient satisfaction. These tools also enabled more intensive exercise programs and eliminated physical barriers by allowing remote rehabilitation under professional supervision.

However, the review identified a critical gap: there was no comprehensive tool specifically designed for measuring individual finger strength in pwMS. This limitation underscored the need for future research and development to address this gap and create versatile devices that could adapt to the diverse needs of pwMS at different stages of the disease.

Regarding rehabilitation strategies, the review emphasized that combining conventional therapies with innovative technologies, such as exoskeletons, motion sensors and augmented reality systems, yielded better outcomes compared to traditional methods alone. Strategies that incorporated visual and auditory feedback, as well as engaging tools like serious games and virtual reality, were shown to improve adherence and satisfaction among patients. Telerehabilitation also emerged as a promising approach, particularly for patients with mobility challenges, as it allowed them to access therapy from home while maintaining effective supervision.

Despite these advantages, the review also highlighted certain limitations in the use and implementation of technology and telerehabilitation for pwMS. One major limitation was the lack of extensive studies demonstrating the short- and long-term effectiveness of these systems. Additionally, current devices were often focused on specific tasks and lacked versatility, while more comprehensive systems were prohibitively expensive, limiting accessibility. The review also emphasized the challenges of working with patients at different stages of the disease, as their abilities varied significantly. This highlighted the need for devices and rehabilitation strategies to be adaptable and easy to use, ensuring they could be applied to a wide range of patients without requiring excessive effort for adjustments.

Future efforts should focus on developing adaptable and personalized rehabilitation tools that could cater to the varying needs of pwMS. Additionally, further studies were required to validate the long-term effectiveness of these technologies and establish standardized guidelines for their implementation in clinical practice.

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, Pacheco Sanchez-Aguilar, PJ, Virto, N., Mendez-Zorrilla A. Methodology, Pacheco Sanchez-Aguilar, PJ, Virto, N., Mendez-Zorrilla A. Formal Analysis: Pacheco Sanchez-Aguilar, PJ, Virto, N. Investigation: Pacheco Sanchez-Aguilar, PJ, Virto, N. Writing—original draft preparation, Pacheco Sanchez-Aguilar, PJ, Virto, N. Writing—review and editing, Pacheco Sanchez-Aguilar, PJ, Virto, N., Mendez-Zorrilla A. Supervision: Mendez-Zorrilla A. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Exercise-induced lactylation: A novel mechanism regulating mitochondria-lipid droplet interaction and energy homeostasis

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ABSTRACT

The exercise-induced rise in lactate is traditionally considered a by-product of metabolism, which triggers a metabolism-regulating post-translational modification, lactylation. The dynamic properties of lactylation during physical exercise and how this biological process occurs in mitochondria-lipid droplet interactions are summarized in this review. Based on emerging evidence primarily from non-exercise models, lactylation has been proposed as a potential carrier of metabolic memory. It may facilitate phase separation to enhance communication efficiency, mediate metabolic crosstalk within the muscle-adipose axis, and add a new dimension of regulation in exercise metabolism. However, these functions remain hypothetical in the context of exercise and require validation in physiologically relevant models. These mechanisms include altered perilipin 5 (PLIN5) that facilitates contact between organelles to use fatty acids and lactylation deficiency that has adverse effects on lipid homeostasis. Lactylation is a competing mechanism with acetylation in the control of metabolic reactions. Despite some significant progress, major gaps remain in our understanding of the precise regulatory processes of lactylation, its relationships with other signalling pathways, and whether it can be used therapeutically. This research summarizes the modern results, carefully analyses the existing issues, and proposes the future research directions, which may be used as a source of extensive study in this field.

Keywords: Lactylation, Exercise metabolism, Mitochondria-lipid droplet contact, PLIN5, Post-translational modification, Metabolic memory.

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INTRODUCTION

Once considered the final metabolic end product of anaerobic glycolysis, lactate has recently been recognized as an essential molecule with additional biological functions besides energy generation (Liu et al., 2024b; Zhou et al., 2025). The main aspect of this reconceptualization is the discovery of a new post-translational modification, lactylation, in which lactyl groups derived from lactate react covalently with lysine residues of proteins, thus creating a direct relationship between the metabolic flux and epigenetic as well as proteomic regulation (Chen et al., 2025a). The lactate increase during exercise affects the lactylation of proteins, which in turn regulates key metabolic and signalling pathways, so the lactylation of RNA-binding protein, YTHDF2, in cardiomyocytes enhances physiological cardiac hypertrophy and suppresses ischemia-reperfusion injury (Li et al., 2024; Xu et al., 2024). A 2024 study published in Basic Research in Cardiology implied that exercise training universally decreases cardiac protein lactylation and YTHDF2 levels in order to alleviate ischemia-reperfusion injury through the mechanism (Xu et al., 2024). These findings are consistent with a hypothetical model proposing a spatiotemporal lactylation "*rheostat*": acute exercise-induced lactylation may serve as a protective metabolic remodelling, including improvements in mitochondrial function and insulin sensitivity, whereas chronic dysregulation could result in metabolic disorders. (Chen et al., 2025a; Wang and Zhu, 2025). This conceptual framework, while useful for integrating existing evidence, remains to be experimentally validated, particularly in human exercise models.

Despite these achievements, cognitive bias in lactylation research is substantial: most studies focus on pathological situations, which include cancer and immune regulation, and the investigation of its spatiotemporal processes during physiological processes, for instance, exercise metabolism, is insufficient (Chen et al., 2025c; Zhao et al., 2025b). In addition, the existing findings mainly rely on single models or partial evidence that lacks a detailed analysis of the patterns of regulation of different types and intensities of exercises and individual differences (Skryabin et al., 2023; Wang and Zhu, 2025). The emerging data suggest that lactylation becomes a key factor in the process of regulating the interactions between mitochondria and lipid droplets, which are crucial organelles allowing the body to manage its energy supply at the time of increased demand. But how lactylation acts in interaction with other signalling pathways, like AMPK and mTOR, and how these regulatory networks are organized hierarchically is unclear, which can make results on this topic more difficult to interpret (Gong et al., 2024). Lack of standardized measures of lactylation in skeletal muscle samples of humans has led to conflicting data on the actual prevalence and variability of lactylation during exercise (Mattingly et al., 2024; Wang and Zhu, 2025), which has complicated the issue of whether this variation is physiologically relevant or not.

LACTYLATION AS A KEY MEDIATOR OF MITOCHONDRIA-LIPID DROPLET CROSSTALK IN EXERCISE METABOLISM

Exercise-induced lactate elevation may trigger dynamic lactylation processes that potentially target proteins at mitochondria-lipid droplet interfaces, with PLIN5 and ATAD3A being candidate targets based on preliminary evidence (Chen et al., 2023a; Miner et al., 2023). The general hypothesis underlying this conceptual framework proposes that lactylation could stimulate protein binding affinity and stabilize cellular contacts between organelles, thereby potentially facilitating fatty acid transport from lipid droplets to mitochondria for β -oxidation and optimizing cellular energy metabolism during increased energy demands (Cui and Liu, 2020; Kien et al., 2022). It is important to note that this mechanism has been primarily investigated in vitro and in pathological models; direct evidence from exercise physiology remains limited. In contrast to aberrant lactylation in pathological conditions, which facilitates tumour growth and immunosuppression, physiological lactylation during exercise has been hypothesized to function as a

spatiotemporal rheostat that could dynamically govern lipid metabolism and energy homeostasis at different exercise stages and specific subcellular sites (Chen et al., 2023b; Wang et al., 2024; Ghadyani et al., 2025; Li et al., 2025a). This characterization is primarily theoretical and derives from integrating evidence across diverse experimental systems; its direct applicability to exercise metabolism requires further investigation. If validated, the proposed rheostatic activity of lactylation could ensure synchrony between organelle activity and metabolic needs in response to exercise, potentially positioning lactylation as a core regulatory activity in exercise metabolism. However, this hypothesis currently lacks direct experimental validation and should be interpreted with caution. . This working model is illustrated in Figure 1.

However, the dynamics between these two changes, be they synergetic, antagonistic, or sequential, are controversial, as a number of in vitro studies involving C2C12 myotubes showed different results with regard to their possible contribution to the stability of mitochondria-lipid droplet contact. One study suggested a complex interplay between AMPK-mediated phosphorylation of PLIN5 and its subsequent lactylation, but the precise sequence and functional hierarchy of these modifications remain unclear (Miner et al., 2023; Bovee et al., 2024). It is not yet clear that PLIN5 is functionally redundant or complementary to other members of the perilipin family (such as PLIN2 and PLIN3), and questions of whether or not there would be a specific primary target protein and decisions about the stability of the regulatory network are also raised (Shi et al., 2025). Such uncertainties highlight the need to have more systematic studies and include phosphorylation-lactylation concomitant mass spectrometry and site-specific mutation combination studies to clarify the complex interactions of lactylation with other post-translational modifications in the context of exercise.

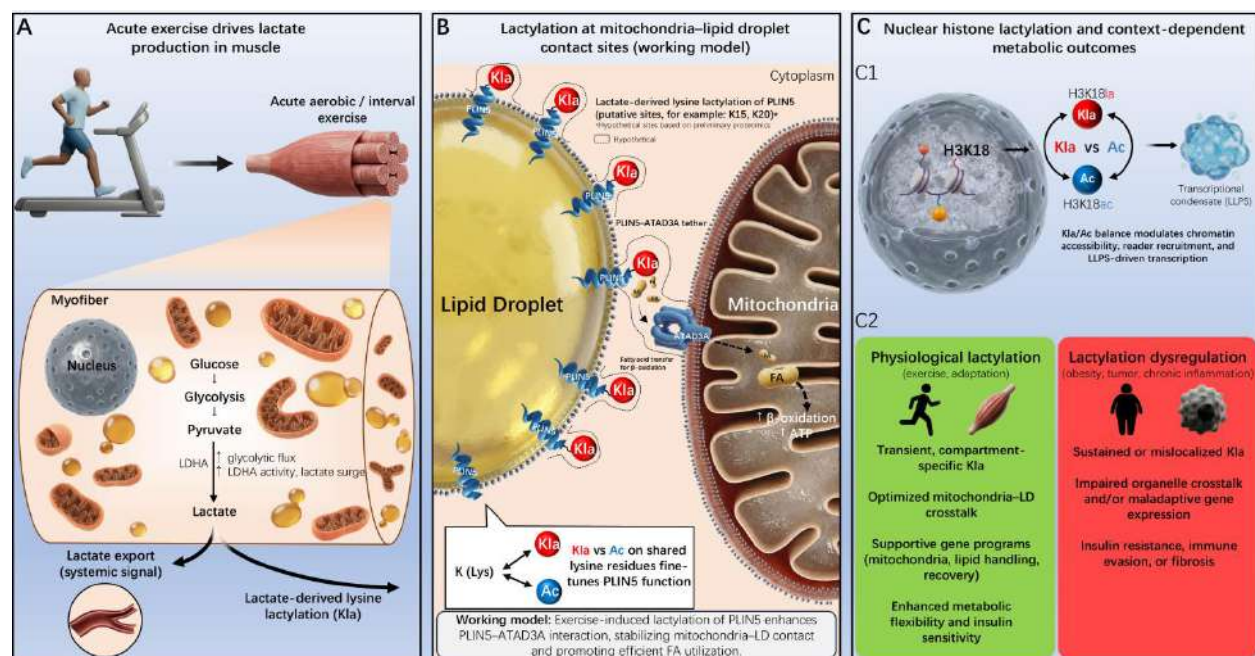


Figure 1. Exercise-induced lactylation coordinates organelle crosstalk and gene programs in skeletal muscle.

LACTYLATION OF PLIN5 PROMOTES MITOCHONDRIA-LIPID DROPLET CONTACT

Lactylation is a novel type of post-translational modification based on the lactate molecule and has emerged as a central controller of protein activity and cellular metabolism, including lipid metabolism and organelle interaction (Lu et al., 2024; Hu et al., 2025). By the operation of lactylation, a major interaction of mitochondria

and lipid droplets (LD) can be mediated by PLIN5, which is a lipid droplet-associated protein that is essential to support the biochemical and mechanical linkage between lipid droplets and mitochondria (Miner et al., 2023; Bezawork-Geleta et al., 2025). The experimental results suggest that lactylation of PLIN5 at specific, though to-be-agreed-upon lysine residues of PLIN5 (such as K15 and K20, as preliminary mass spectrometry analyses show), this augmented binding affinity to the ATAD3A mitochondrial protein is observed (Chen et al., 2022). However, the exact lactylation sites on PLIN5 remain inconsistent across studies, with differences attributed to variations in detection technologies and experimental conditions, making definitive confirmation of this process difficult. Importantly, the PLIN5 lysine lactylation can serve as a rival to acetylation on the same site, thereby specifying its binding with ATAD3A (Hu et al., 2025). This interaction is increased by simulating lactylation through the lysine site-directed alterations (i.e., like lysine to something neutral, like a K to Q) to facilitate the formation of persistent sites of mitochondria-LD contact (Liu et al., 2024a). These contact sites play a vital role in efficient delivery of fatty acids in lipid droplets to the mitochondria to undergo β -oxidation and therefore, increase cellular energy production (Wang et al., 2025a). These contact sites play a vital role in the efficient delivery of fatty acids from lipid droplets to mitochondria for β -oxidation and therefore increase cellular energy production. Thus, lactylation acts as a molecular mediator of organelle communication and increased lipid utilization during increased energy demand such as exercise. The evidence-augmented interaction between the PLIN5 and ATAD3A during lactylation underlines the idea that, along with a metabolic role, lactate is a signalling molecule and changes the important proteins to control intracellular lipid transportation and mitochondrial activity (Mandadzhiev, 2025; Wang and Zhu, 2025). It is this regulatory axis that could stimulate metabolic plasticity and energy homeostasis, clarifying the reason why exercise-triggered lactate production may control the behaviour of mitochondrial lipid droplets to meet the energy needs of the cell (Ahmadi Hekmatikar et al., 2025; Wang and Zhu, 2025).

The relevance of the research to physiological processes is limited by the experimental models used (Chen et al., 2025a; Dunzhu et al., 2025; Wang and Zhu, 2025). Most studies rely on the overexpression or mutation of PLIN5 in immortalized cell lines, which may not reliably reflect endogenous expression patterns and regulatory networks in primary muscle cells and whole tissues (Chen et al., 2025c). Furthermore, animal models using global LDHA knockouts provide metabolic phenotypes related to lactate deficiency by completely abolishing lactate production—an extreme condition that does not mimic the transient lactate elevations characteristic of human exercise physiology, thereby limiting the generalizability of results to physiological conditions (An et al., 2023; Gao et al., 2025; Li et al., 2025b). The lack of animal models with specific muscle lactylation markers has hindered proper evaluation of lactylation function in exercise metabolism; consequently, *in vitro* results should be interpreted with caution when extrapolated to *in vivo* exercise contexts (Ahmadi Hekmatikar et al., 2025; Mandadzhiev, 2025). Furthermore, the exact lysine sites of PLIN5 that are lactylated have also not been consistent across studies (Sun et al., 2022), with differences attributed to differences in detection technologies and experimental environments, which makes it difficult to confirm this process (Gong et al., 2024; Lu et al., 2024; Wu et al., 2025).

EFFECTS OF LACTYLATION DEFICIENCY ON CELLULAR METABOLISM

Lactylation plays a vital role in the maintenance of relationships between mitochondria and lipid droplets and lipid metabolism, which has been shown in the studies of the impact of lactylation deficit (Lin and Ren, 2024; Mao et al., 2024; Zhao et al., 2025a). Down-regulation of lactate dehydrogenase A (LDHA), which plays an important role in lactate production, leads to a significant drop in intracellular levels of lactylation (Hu et al., 2024; Xia et al., 2024; Chen et al., 2025b; Peng and Du, 2025). This weakens the structural integrity of contact points between mitochondria and lipid droplets, which reduces transportation of fatty acids. Metabolic diseases included and abnormal accumulation of lipid droplets in cells (Ippolito et al., 2022; Jia et al., 2023;

Mao et al., 2024; Zhao et al., 2025a). Metabolic diseases include lipid dysregulation, specifically the development of insulin resistance, which is typical of metabolic syndrome and type 2 diabetes (Feng et al., 2022; Maschari et al., 2022; Cao et al., 2025; Long et al., 2025). However, studies show that adipocyte-specific deletion of *Ldha* in obese mice paradoxically increases insulin sensitivity, indicating that the metabolic effects of lactylation modulation are context-dependent and vary by tissue (Feng et al., 2022; Lin et al., 2022). While these data suggest that lactylation contributes to lipid metabolic homeostasis under certain conditions, the divergent outcomes across different models highlight the need for caution in generalizing its role.

Representative experimental models and metabolic outcomes associated with lactylation deficiency are summarized in Table 1. As shown, the metabolic consequences of reduced lactylation vary substantially by model: global LDHA knockout causes systemic metabolic disruption, cellular LDHA knockdown impairs lipid handling and insulin sensitivity, while adipocyte-specific LDHA deletion in obese mice improves insulin sensitivity. These divergent outcomes indicate that the effects of lactylation modulation are highly tissue-specific and context-dependent. Rather than uniformly disrupting cellular homeostasis, lactylation appears to exert distinct metabolic effects depending on the specific tissue manipulated and the completeness of lactylation ablation. This complexity highlights the need for cautious interpretation of lactylation function in metabolic health.

Table 1. Representative models of reduced lactylation and their metabolic consequences.

Model / manipulation	Tissue / system	Change in lactate / lactylation	Mitochondria-LD contact / lipid phenotype	Metabolic outcomes	References
Global LDHA knockout (whole-body KO)	Whole organism (multiple tissues)	Near-complete loss of lactate production; broad reduction of protein lactylation	Not specifically reported; global disturbance of lipid and energy metabolism is implied	Systemic metabolic phenotypes associated with lactylation deficiency; considered an extreme model that does not mimic transient exercise-induced lactate elevation in humans	(Yang et al., 2021; Li et al., 2025b)
LDHA knockdown in cultured cells	In vitro cellular models (for instance, immortalized cell lines)	↓ intracellular lactate production; ↓ global protein lactylation	Disruption of mitochondria-lipid droplet (LD) contact sites; impaired fatty acid trafficking; abnormal lipid droplet accumulation	Cellular lipid dysregulation linked to insulin resistance-like disturbances, highlighting the role of lactylation in maintaining lipid metabolic homeostasis and insulin sensitivity	(Nian et al., 2022; Yao and Li, 2023; Dong et al., 2024)
Adipocyte-specific LDHA deletion in obese mice	Adipose tissue (adipocyte-specific KO; obese models)	↓ adipocyte lactate production and protein lactylation; reduced lactate signalling to the microenvironment	Not directly reported; alterations in adipose lipid handling and inflammatory milieu are implicated	Paradoxical improvement of systemic insulin sensitivity and reduced adipose macrophage inflammation, illustrating that reduced lactylation can have beneficial effects in specific tissue and metabolic contexts	(Feng et al., 2022; Galle et al., 2022; Lin et al., 2022)

Note: This table summarizes experimental contexts in which lactylation is reduced or impaired and highlights that the metabolic consequences are highly tissue- and context-dependent.

COMPETITIVE REGULATORY MECHANISMS BETWEEN LACTYLATION AND ACETYLATION

Lactylation and acetylation are both lysine-based post-translational modifications that may compete for the same lysine sites (for instance, histone H3 lysine 18, H3K18), based primarily on evidence from non-exercise models (Wang et al., 2022; Xin et al., 2022; Xie et al., 2025; Xu et al., 2025b). Whether this competitive relationship operates similarly during exercise remains to be determined. In addition, lactylation of specific lysine residues has been proposed to facilitate biomolecular condensate formation through liquid-liquid phase separation of metabolic signalling proteins and transcriptional regulators, potentially enhancing signal transduction and transcriptional activation (Dai et al., 2025; Ma et al., 2025; Wang et al., 2025b). The relevance of phase separation to exercise-induced lactylation requires further investigation. The process contributes to the formation of transcriptional machinery and chromatin remodelling complexes at target gene loci, which increase gene expression responses to metabolic stress, including exercise (Dai et al., 2025; Ma et al., 2025; Wang et al., 2025b).

Current research on this competitive interaction is subject to important limitations that affect the reliability of prevailing conclusions (Nitsch et al., 2021; Bao et al., 2025; Xie et al., 2025; Xu et al., 2025b). Most evidence supporting the lactylation-acetylation competition derives from in vitro experiments or static cell models, which may not reflect the dynamic metabolic changes and complex environment of in vivo exercise conditions (Xin et al., 2022; Bao et al., 2025; Xu et al., 2025a). Whether competitive priority between lactylation and acetylation exists during exercise, and how exercise intensity and duration might affect it, remains unknown. Additionally, whether other lysine-targeted modifications (for example, succinylation and malonylation) interfere under exercise-induced metabolic stress has not been investigated (Nitsch et al., 2021; Yao et al., 2024; Ma et al., 2025). Analytical methods currently lack sufficient resolution to reliably distinguish sequential or simultaneous changes in lactylation and acetylation at shared sites (Artiukhov et al., 2021; Ma et al., 2025). Mass spectrometry, despite being considered the gold standard, often shows insufficient sensitivity to detect transient and low-abundance lactylation events induced by acute exercise. Furthermore, commercial lactylation antibodies may cross-react with acetylation, potentially leading to inaccurate quantification (Artiukhov et al., 2021; Yao et al., 2024; Ma et al., 2025). These technical limitations should be considered when interpreting the current evidence base.

The above-mentioned technical issues have contributed to inconsistent findings across research groups. Some reported predominance of lactylation under exercise stress conditions (Wang et al., 2022; Merkuri et al., 2024; Bao et al., 2025; Hou et al., 2025), while others found no obvious competition (Xin et al., 2022; Xie et al., 2025; Xu et al., 2025b, 2025a). These discrepancies highlight that the existence and nature of lactylation-acetylation competition during exercise remain unresolved. Standardized detection protocols and more physiologically relevant models are needed to clarify whether this competitive relationship is consistently present under exercise conditions.

CONCLUSIONS AND PERSPECTIVES

This review summarizes previous research exploring a potential role for exercise-induced lactylation in metabolic regulation and organelle communication. Lactylation has been associated with changes in mitochondrial function, lipid metabolism, and gene expression across diverse models, and may compete with other lysine acylations, such as acetylation, at shared sites, though this competition remains to be confirmed in exercise contexts. We propose a hypothetical model in which the lactylation of essential proteins, such as PLIN5, could enhance interactions between mitochondria and lipid droplets by modulating protein-protein interactions (for example, with ATAD3A), thereby potentially promoting fatty acid utilization during exercise.

In this proposed framework, loss or dysregulation of lactylation might impair organelle communication and disrupt lipid homeostasis, potentially contributing to insulin resistance in a tissue- and context-specific manner, rather than as a global, unidirectional process. The competitive cross-talk between lactylation and acetylation, if confirmed during exercise, could function as a regulatory switch for protein function and gene expression in response to metabolic stress. Within this model, lactylation is conceptualized as a spatiotemporal rheostat for exercise metabolism, potentially adapting to changes in exercise intensity and the spatial positioning of metabolic organelles as a proposed mechanism for energy balance regulation. Even though recent research has found lactylation as an additional process of organelle communication in exercise metabolism, gaps in understanding and controversy still exist.

More sensitive and specific detection methods are required to provide support and confirm the precise spatiotemporal details of lactylation at different exercise intensities and durations, particularly in human skeletal muscle (Meng et al., 2025). Secondly, the cross-regulation of lactylation and other signalling pathways (such as AMPK and mTOR) and post-translational modifications also needs to be analysed carefully in order to clarify the hierarchical structure of the regulatory network, that is, whether the AMPK-mediated phosphorylation and lactylation of PLIN5 are synergistic or sequential (Hagihara et al., 2021). As existing experimental models (global LDHA deletion, immortalized cell lines) have limitations, tissue-specific and conditional models of these modifications are needed to accurately assess the physiological role of lactylation.

The potential clinical relevance of lactylation for exercise interventions and metabolic disease treatment remains a subject of future inquiry, given current technical and conceptual limitations. A fundamental unanswered question is whether lactylation is a cause of metabolic adaptation or merely a consequence of exercise-induced metabolic stress (Zhang et al., 2024). Exogenous manipulation of lactylation levels, whether through lactate supplementation or potential inhibitors, risks disrupting endogenous metabolic balance and producing unanticipated outcomes. Furthermore, targeting PLIN5 lactylation therapeutically faces specific limitations, including the difficulty of separating lactylation from competing modifications such as acetylation to avoid off-target effects, which currently limits clinical feasibility (Shang et al., 2022).

The therapeutic application of lactylation-related mechanisms would require substantial advances in selective regulation and safety verification. Accordingly, near-term clinical translation should be regarded as a long-term perspective rather than an immediate possibility. Future studies should prioritize developing more sensitive and specific detection tools, establishing physiologically relevant models, and systematically exploring regulatory mechanisms. These foundational advances are needed to determine whether lactylation holds physiological significance in exercise metabolism and, if so, whether it may eventually have relevance for metabolic disease research.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. J. Z.: Conceptualization, Investigation, Data Curation, Writing – Original Draft, Validation, Formal Analysis, Methodology. Z. M.: Formal Analysis, Methodology, Validation, Investigation. J. L.: Supervision, Project Administration, Funding Acquisition, Conceptualization, Writing – Review & Editing. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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A bibliometric analysis of knowledge structure and research trends in swimmer's shoulder (2015-2025)

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ABSTRACT

Shoulder pain remains one of the most common and persistent problems in competitive swimming. Unlike acute traumatic injuries, swimmer's shoulder usually develops gradually through the combined effects of repetitive stroke motion, fluctuating training load, movement compensation, and insufficient recovery. Although an expanding body of research has examined this topic from the perspectives of biomechanics, training load, muscle function, and rehabilitation, the overall knowledge structure and developmental trajectory of the field remain insufficiently clarified. To address this gap, the present study conducted a bibliometric analysis of swimmer's shoulder research using the Web of Science Core Collection. A total of 195 publications published between 2015 and 2025 were included. Publication trends, core authors, leading journals, country-level contributions, relative growth rate, doubling time, field-normalised citation score, and keyword co-occurrence patterns were analysed with CiteSpace and VOSviewer. The results show a sustained increase in research output and the emergence of a relatively stable but heterogeneous academic network. Clear differences were observed between high-output and high-impact contributors, particularly at the journal and country levels. Keyword co-occurrence, clustering, and timeline analyses indicate a transition from symptom-oriented research toward mechanism-based and intervention-oriented approaches, with increasing attention to biomechanics, functional assessment, monitoring, prevention, and rehabilitation. The study proposes a three-level framework of symptom identification, mechanism explanation, and intervention-oriented management. This framework integrates fragmented findings and clarifies how swimmer's shoulder research has evolved from describing pain to explaining mechanisms and informing applied prevention and rehabilitation strategies.

Keywords: Swimmer's shoulder, Competitive swimming, Shoulder injury, Biomechanics, Injury prevention, Bibliometric analysis.

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INTRODUCTION

Shoulder-related problems have long been among the most frequently discussed and complex issues in competitive swimming. Although many studies appear to focus on shoulder pain, overuse injury, or swimmer's shoulder, the field addresses a broader set of questions concerning how training load is organised, how stroke technique develops, how physical function adapts, and how rehabilitation strategies are implemented. Swimmer's shoulder should therefore not be interpreted only as a local joint complaint, but as the outcome of interacting factors within the training system of competitive swimming (Hill et al., 2015; Struyf et al., 2017). Swimming involves highly repetitive upper-limb motion, and the shoulder repeatedly moves through large ranges while producing force over long periods of training. Among competitive swimmers, symptoms often do not follow a single identifiable injury event. Instead, they tend to emerge gradually through repeated exposure, accumulated workload, altered movement patterns, and insufficient recovery. Recent reviews have continued to associate shoulder pain with workload-related factors, musculoskeletal dysfunction, and other interacting risk factors in competitive swimmers (Feijen et al., 2020; McKenzie et al., 2023). Because this process is complex, research has expanded in several directions. Some studies emphasise training volume and workload progression, whereas others focus on stroke mechanics, scapular control, strength imbalance, functional assessment, exercise therapy, preventive training, and rehabilitation management. These lines of work provide valuable evidence, but together they also reveal a broad field whose internal structure is not yet fully synthesised (Struyf et al., 2017; Feijen et al., 2020; Yoma et al., 2022). This diversity is not necessarily a limitation. Rather, it suggests that swimmer's shoulder is no longer a narrowly defined clinical label but an interdisciplinary topic linking training practice, injury risk identification, biomechanical explanation, and rehabilitation management. The challenge is that, as the literature broadens, researchers may focus on isolated segments and overlook the connections among themes. Recent reviews have mainly synthesised evidence within specific subtopics, such as risk factors, workload, or exercise intervention, which further highlights the need for a broader perspective on the knowledge structure of the field (McKenzie et al., 2023; Feijen et al., 2020; Yoma et al., 2022). Bibliometric analysis provides a useful approach for examining this broader structure. Unlike traditional narrative reviews, bibliometric analysis can reveal publication trends, influential authors, core journals, country-level contributions, citation patterns, and keyword co-occurrence relationships, thereby clarifying how research themes are organised and how they evolve over time. The present study therefore uses the Web of Science Core Collection to analyse English-language literature published between January 1, 2015 and December 31, 2025. By mapping publication patterns, leading contributors, national differences, bibliometric indicators, and thematic networks, this study aims to reposition swimmer's shoulder from a single injury category to a structured research field within competitive swimming, sports medicine, and rehabilitation science.

Literature review

Mechanisms of training load, repetitive motion, and overuse

In competitive swimming, the training load is widely recognised as one of the primary factors associated with shoulder pain and overuse injuries. Swimming is characterised by highly repetitive upper limb motion, where athletes may perform thousands of stroke cycles within a single training session. Such repetitive exposure places continuous mechanical stress on the shoulder joint, particularly on the rotator cuff and surrounding soft tissues (McKenzie et al., 2023; Stella et al., 2024).

Prior studies have consistently associated excessive training volume, sudden workload increases, and insufficient rest with the onset of swimmer's shoulder. The association between training load and shoulder injury appears to be multifactorial rather than linear. Some swimmers may tolerate high training volumes without symptoms, whereas others may develop shoulder pain under comparable workloads. This

inconsistency indicates that training load interacts with various aspects, including technique, strength, and individual adaptability (McKenzie et al., 2023; Tavares et al., 2025).

Furthermore, contemporary research frequently depends on cross-sectional or short-term observations, which constrains the comprehension of cumulative load effects over time. Consequently, whereas training load is a critical element, it cannot solely account for the emergence of swimmer's shoulder (Takayama et al., 2024; McKenzie et al., 2023).

Biomechanics, stroke technique, and control of the scapula

Biomechanical analysis provides an important framework for understanding the mechanisms underlying swimmer's shoulder. A substantial body of research has examined stroke technique, joint kinematics, scapular movement patterns, and shoulder loading. Efficient stroke mechanics require coordinated motion between the glenohumeral joint and the scapulothoracic articulation. Disruption of this coordination may alter load distribution across the shoulder complex and increase injury risk (Kennedy et al., 2024; Stella et al., 2024).

Swimmers with shoulder pain often present altered movement patterns, including scapular dyskinesis, changes in stroke timing, and modified rotation angles. These findings suggest that shoulder symptoms may arise not only from excessive training volume but also from movement compensation, impaired neuromuscular control, and inefficient force transfer during repetitive swimming motion (Kennedy et al., 2024; Yoma et al., 2022).

Nevertheless, many biomechanical studies are conducted in laboratory settings, which may not fully reflect the complexity of daily training environments. The causal relationship between altered movement patterns and shoulder injury also remains uncertain. Field-based and longitudinal biomechanical research is therefore needed to clarify how stroke mechanics, fatigue, workload, and recovery interact over time (Kennedy et al., 2024).

Strength, balance of muscles, and functional

Muscle strength and functional capacity are essential for maintaining shoulder stability during repetitive swimming motion. The rotator cuff and scapular stabilisers help maintain joint alignment and support force transfer throughout the stroke cycle (McKenzie et al., 2023; Stella et al., 2024). Previous studies have associated shoulder pain with muscle weakness, neuromuscular deficits, strength imbalance, limited range of motion, and reduced dynamic stability. These factors may increase movement compensation and contribute to local overload (McKenzie et al., 2023; Tavares et al., 2025). However, there is still no consensus regarding optimal assessment methods or strength-training protocols. Many studies examine isolated variables, which limits the development of integrated functional models that could guide comprehensive screening, training, and rehabilitation strategies (Yoma et al., 2022; Kennedy et al., 2024).

Management of training, prevention, and rehabilitation

As prevention oriented thinking has developed, research has increasingly moved toward intervention and management strategies. Preventive programmes commonly include strength training, flexibility exercises, technique correction, workload monitoring, and recovery management. These strategies aim to reduce injury risk while preserving swimming performance. Rehabilitation studies have also focused on restoring function and supporting return to training. However, intervention protocols vary considerably across studies, which makes it difficult to formulate generalisable recommendations. In addition, many intervention studies are conducted under controlled conditions and may not fully represent the variability of real training environments,

athlete responses, and competition schedules. This limits the direct transferability of some findings to applied swimming practice.

From fragmented evidence to knowledge mapping: The need for bibliometric analysis

Overall, existing research on swimmer's shoulder covers multiple dimensions, including training load, biomechanics, muscle function, monitoring, prevention, and rehabilitation. These studies provide important insights, but they are often conducted within separate subfields, resulting in a fragmented understanding of the literature (McKenzie et al., 2023; Yoma et al., 2022). Most reviews focus on specific subtopics, such as risk factors or rehabilitation, and therefore provide limited information about the overall intellectual structure and thematic evolution of the field. Bibliometric analysis can integrate these diverse research themes by identifying publication patterns, influential contributors, keyword relationships, and emerging topics. It therefore offers a structured basis for clarifying the knowledge structure of swimmer's shoulder research and for identifying future research directions (Donthu et al., 2021; Öztürk et al., 2024).

DATA SOURCES AND METHODS

Data source and search strategy

This study adopted a bibliometric design to examine the knowledge structure, publication patterns, and thematic evolution of swimmer's shoulder research. Bibliometric analysis is suitable for mapping the development of a research field when the aim is to identify publication trends, influential contributors, major journals, country-level contributions, and conceptual relationships among research themes (Donthu et al., 2021). Recent methodological discussions have also emphasised that bibliometric studies should clearly report the search strategy, database selection, inclusion and exclusion criteria, data cleaning procedures, and analytical tools to ensure transparency and reproducibility (Öztürk et al., 2024).

The Web of Science Core Collection was selected as the primary data source for this study. This database was chosen because it provides standardised bibliographic records, citation information, subject classifications, and export formats that are widely used in bibliometric and scientometric studies. In addition, the Web of Science Core Collection is described by Clarivate as a publisher-independent global citation database, which makes it appropriate for tracing publication output and citation relationships across disciplines (Clarivate, 2024).

The literature search was conducted in the Web of Science Core Collection using the topic search field. The search period was limited to publications from January 1, 2015 to December 31, 2025. This time frame was selected to capture the most recent decade of swimmer's shoulder research and to examine how the field has developed from symptom-oriented studies toward mechanism-based, prevention-oriented, and rehabilitation-related research. The search was performed using the following search query:

TS = ("swimmer's shoulder" OR ("swimming" AND "shoulder pain") OR ("competitive swimmers" AND "shoulder injury") OR ("swimmers" AND "shoulder" AND "risk factor") OR ("swimmers" AND "shoulder" AND "prevention") OR ("swimmers" AND "shoulder" AND "rehabilitation")).

The search terms were designed to cover the major expressions used in swimmer's shoulder research, including the direct term "swimmer's shoulder" and related expressions referring to swimming-related shoulder pain, shoulder injury, risk factors, prevention, and rehabilitation. The use of Boolean operators was intended to balance sensitivity and specificity, ensuring that relevant studies were captured while limiting records that were only generally related to the shoulder or to swimming.

The initial search retrieved 269 records. A stepwise screening procedure was then applied to improve topical relevance and analytical reliability. First, Web of Science subject categories were used to retain records in sports science, sports medicine, rehabilitation, biomechanics, physical therapy, orthopaedics, health sciences, and closely related areas; records from unrelated categories were removed, leaving 201 records. Second, titles, abstracts, keywords, and Web of Science citation topic information were reviewed to determine whether each record addressed swimming-related shoulder pain, swimmer's shoulder, shoulder injury in swimmers, risk factors, biomechanics, prevention, or rehabilitation. Studies that mentioned swimming or shoulder terms only incidentally were excluded, leaving 198 records. Third, the sample was restricted to English-language articles and review articles because these document types provide complete bibliographic records, abstracts, keywords, and cited references suitable for bibliometric analysis. After this process, 195 valid publications were retained.

Eligibility criteria

To strengthen methodological transparency and improve the reproducibility of the bibliometric analysis, explicit inclusion and exclusion criteria were applied. In bibliometric research, the use of predefined filtering criteria is important because database searches may retrieve records that are outside the actual conceptual scope of the study. Therefore, researchers are expected to clarify how the final sample was identified and why certain records were excluded (Öztürk et al., 2024).

Publications were included if they met all of the following criteria:

1. The publication focused on swimmer's shoulder, swimming-related shoulder pain, shoulder injury, shoulder injury risk, prevention, rehabilitation, biomechanics, functional assessment, training load, or training-related shoulder problems in swimmers.
2. The research population or research context was directly related to swimmers, competitive swimmers, elite swimmers, or swimming training.
3. The publication was indexed in the Web of Science Core Collection.
4. The publication was written in English.
5. The document type was classified as an article or review article.
6. The publication year fell within the period from 2015 to 2025.

Publications were excluded if they met any of the following criteria:

1. The publication focused on general shoulder pain or general shoulder injury without a clear connection to swimming.
2. The study examined shoulder injuries in other sports or general athletic populations without providing direct relevance to swimming-related shoulder problems.
3. The publication was a conference abstract, editorial, letter, book chapter, correction, news item, or other non-research document type.
4. The publication was not written in English.
5. The bibliographic record was incomplete, duplicated, or lacked sufficient information for bibliometric analysis.
6. The publication contained broad terms such as "*shoulder*" or "*swimming*" but did not make a meaningful contribution to understanding swimmer's shoulder, swimming-related shoulder pain, risk factors, prevention, biomechanics, or rehabilitation.

These criteria were applied to ensure that the final dataset represented the core literature of swimmer's shoulder research rather than a broad and heterogeneous set of studies on shoulder problems or swimming in general.

Screening procedure

The screening procedure was conducted in four stages. In the first stage, the topic search identified 269 potentially relevant records. In the second stage, subject-category filtering excluded records outside sports science, sports medicine, rehabilitation, biomechanics, physical therapy, orthopaedics, health sciences, and related fields, reducing the dataset to 201 records. In the third stage, titles, abstracts, keywords, and citation topic information were reviewed for topical relevance. Records were retained only when the swimming context and shoulder-related problem were both explicit. Studies on general shoulder pain, other sports, non-athlete populations, or general swimming performance without a shoulder-injury focus were removed, leaving 198 records. In the final stage, language and document-type restrictions were applied. Only English-language articles and review articles were retained, resulting in the final dataset of 195 valid publications.

This screening procedure was designed to improve the reproducibility of the study and to reduce the risk of including irrelevant records. Similar to reporting principles used in systematic and bibliometric reviews, the screening process was presented in a transparent format so that readers can understand how the final analytical dataset was constructed (Page et al., 2021; Montazeri et al., 2023).

Table 1. Literature search, screening, and eligibility process

Screening stage	Criterion applied	Records retained	Records excluded	Main reason for exclusion
Initial search	Topic search in Web of Science Core Collection	269	—	Initial retrieval
Subject category filtering	Records related to sports science, sports medicine, rehabilitation, biomechanics, physical therapy, and related health sciences were retained	201	68	Irrelevant subject categories
Citation topic and relevance screening	Citation topic information, titles, and abstracts were checked for topical relevance	198	3	Weak relevance to swimmer's shoulder or swimming related shoulder problems
Language and document type filtering	English language articles and review articles were retained	195	3	Non eligible language or document type
Final dataset	Publications included in bibliometric analysis	195	—	Final valid publications

Data extraction, cleaning, and keyword normalisation

After screening, the full records and cited references of the 195 eligible publications were exported from the Web of Science Core Collection for bibliometric analysis. The exported information included titles, authors, journal names, publication years, countries or regions, institutional affiliations, abstracts, author keywords, Keywords Plus, citation counts, and cited references. These fields were used to examine publication output, research collaboration, citation influence, and thematic relationships within swimmer's shoulder research.

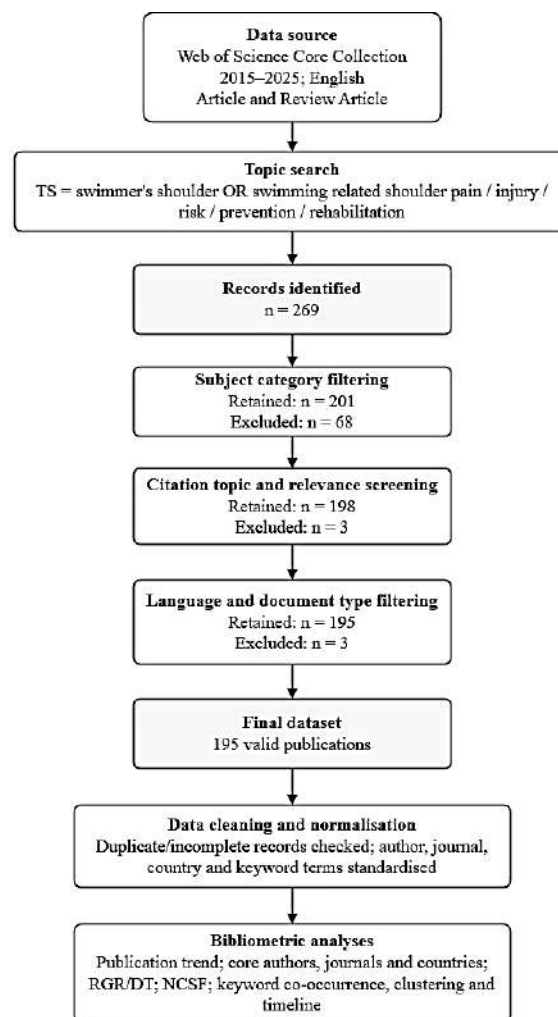
Before the bibliometric analysis, the dataset was cleaned to improve consistency and reduce errors. Data cleaning is a necessary step in bibliometric research because bibliographic databases may contain inconsistencies in author names, institutional names, journal titles, keywords, and cited references. Recent methodological work has stressed that insufficient preprocessing may lead to inaccurate network structures and misleading bibliometric interpretations (Lim et al., 2024; Nowakowska, 2025).

The cleaning process included checking for duplicate and incomplete records, standardising author and journal names where necessary, verifying publication years, and reviewing country and institutional

information. Keyword normalisation was also performed to reduce fragmentation caused by spelling differences, plural forms, hyphenation, abbreviations, and semantically equivalent terms. For example, closely related expressions such as "risk factor" and "risk factors" were unified, and terms referring to the same anatomical or functional concept were merged when appropriate. Ambiguous terms were retained only when their meaning could be confirmed from the title, abstract, or keyword context. This procedure ensured that the keyword network reflected the conceptual structure of swimmer's shoulder research rather than inconsistencies in terminology.

Bibliometric analysis and visualisation

This study used CiteSpace and VOSviewer to analyse and visualise the final dataset. CiteSpace was used to identify knowledge structures, keyword clusters, citation patterns, and thematic evolution. CiteSpace has been widely used to detect and visualise emerging trends and structural patterns in scientific literature (Chen, 2006). VOSviewer was used to construct and visualise bibliometric networks, including author collaboration and keyword co-occurrence networks. VOSviewer is particularly useful for constructing and displaying large bibliometric maps in an interpretable visual format (van Eck & Waltman, 2010).



Note. RGR = Relative Growth Rate; DT = Doubling Time; NCSF = Field-Normalised Citation Score.

Figure 1. Workflow of the bibliometric analysis and literature screening process for swimmer's shoulder research.

The analysis focused on the following dimensions: annual publication output, core authors, core journals, core countries, relative growth rate, doubling time, field-normalised citation score, high-frequency keywords, keyword co-occurrence networks, keyword clustering, and keyword timeline evolution. These indicators were selected not only to describe the publication characteristics of swimmer's shoulder research but also to clarify the intellectual and thematic development of the field.

In this study, performance analysis was used to identify publication output, influential authors, journals, and countries. Science mapping was used to examine relationships among keywords, clusters, and research themes. This combination of performance analysis and science mapping is consistent with established bibliometric approaches, which recommend integrating descriptive indicators with network-based visualisation to obtain a more complete understanding of a research field (Donthu et al., 2021; Öztürk et al., 2024).

The bibliometric results were further interpreted in relation to the conceptual development of swimmer's shoulder research. Specifically, keyword co-occurrence, clustering, and timeline analyses were used to examine whether the field has evolved from symptom identification toward mechanism explanation, functional assessment, prevention, and rehabilitation management. This interpretive step was included to avoid limiting the study to descriptive statistics and to strengthen the conceptual contribution of the bibliometric findings.

The overall workflow of literature retrieval, eligibility screening, data cleaning, keyword normalisation, and bibliometric analysis is presented in Figure 1. This workflow clarifies how the initial 269 records retrieved from the Web of Science Core Collection were processed into the final dataset of 195 valid publications. It also shows the subsequent analytical procedures, including data cleaning, bibliometric mapping, and thematic interpretation. By presenting both the screening process and the analytical pathway, the workflow strengthens the transparency and reproducibility of the study.

RESULTS

Descriptive statistics

This study collected a total of 195 publications. These papers were written by 826 authors from 423 institutions across 41 countries and were published in 64 journals. Together, these publications cited 4,708 references from 1,251 different journals.

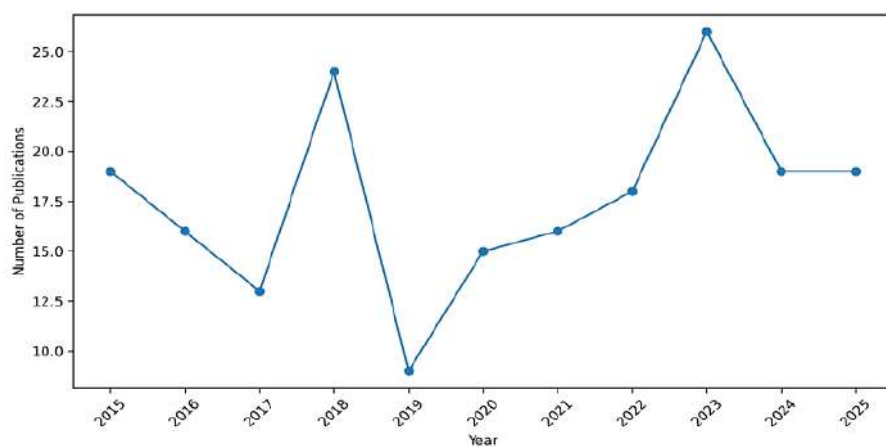


Figure 2. Annual number of publications from 2015 to 2025.

Core author analysis

Studying the writers of the literature can teach us about the main researchers and experts in this subject of study. The eminent researcher Price (1963) noted that within the same subject, fifty percent of the articles were authored by a cohort of exceptionally prolific writers, with the size of this group being roughly equivalent to the square root of the total number of authors. In his work, Egghe accurately determined the correlation between Price's Law and Lotka's Law, providing a mathematical demonstration of the law's applicability (Egghe, 2005). Nicholls objectively examined the validity of Price's square root law and investigated its correlation with Lotka's Law (Nicholls, 1988). That is:

$$\sum_{m+1}^I n(x) = \sqrt{N}$$

In this study, the most productive author published 9 papers ($N_{MAX} = 9$). According to Price's Law, the minimum number of papers required for a core author is $m = 0.749 \sqrt{N} \max \approx 2.247$. Therefore, authors who have published three or more papers were classified as core authors in this field.

$$m = 0.794 \times N_{MAX} \approx 2.38$$

A total of 34 core authors published 144 papers, accounting for 73.8% of the total number of publications. This proportion exceeds the 50% threshold proposed by Price, indicating that a relatively stable core author group has emerged in swimmer's shoulder research.

Table 2. Bibliometric analysis of core authors in swimmer's shoulder research.

Rank	Author	Documents	Citations	Average citation/Publication
1	Tate, Angela	9	216	24
2	Kaneoka, Koji	7	76	10.9
3	Akuzawa, Hiroshi	6	76	12.7
4	Feijen, Stef	6	186	31
5	Kuppens, Kevin	6	186	31
6	Matsuura, Yuiko	6	68	11.3
7	Struyf, Filip	6	186	31
8	Ginn, Karen A.	5	99	19.8

Table 2 presents the most productive and influential authors in swimmer's shoulder research. Angela Tate ranked first, with 9 publications, 216 citations, and an average of 24 citations per publication, indicating both sustained productivity and substantial citation influence. Koji Kaneoka ranked second with 7 publications and 76 citations, showing an important contribution to publication output. Feijen, Stef; Kuppens, Kevin; and Struyf, Filip each published 6 papers and received 186 citations, with an average of 31 citations per publication, suggesting strong citation influence relative to output. Overall, the author-level findings indicate that a relatively stable core author group has emerged, while productivity and citation impact remain unevenly distributed across researchers.

Figure 3 presents the author collaboration network generated by VOSviewer. The size, colour, and connections of the nodes indicate the relative contribution of authors and the collaborative relationships among research groups. The overall network shows several connected clusters rather than a single dominant group, suggesting that swimmer's shoulder research has gradually moved from isolated studies toward a more organised but still heterogeneous collaborative structure. Angela Tate occupies a central position in the

network and is connected with several author groups, which is consistent with her high publication output and citation count. Kaneoka, Koji and Feijen, Stef also hold prominent positions. Kaneoka contributes strongly to research productivity, whereas Feijen shows high citation influence. These findings indicate that the field contains both productive contributors and influential authors whose work shapes the academic direction of swimmer's shoulder research.

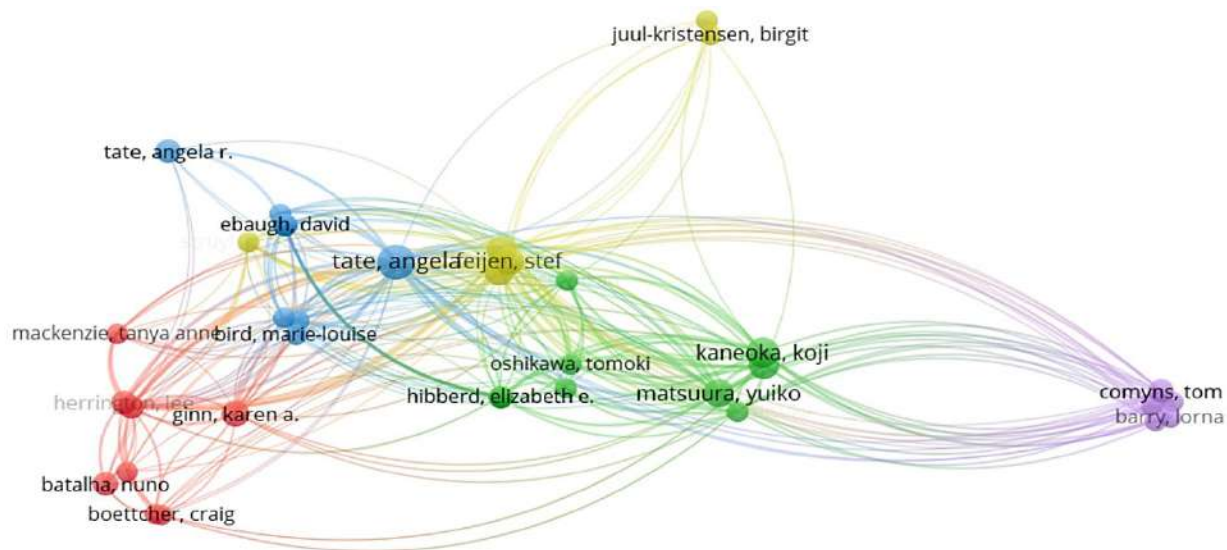


Figure 3. Author collaboration network in swimmer's shoulder research.

Several collaboration clusters can be identified in the network. One cluster includes Mackenzie, Tanya Ann; Herrington, Lee; Ginn, Karen A.; Batalha, Nuno; and Boettcher, Craig, indicating a relatively stable internal collaboration pattern. Another cluster, represented by Tate, Angela R.; Ebaugh, David; and Bird, Marie-Louise, is more centrally positioned and connects with multiple parts of the network. A third cluster includes Kaneoka, Koji; Matsuura, Yuiko; Oshikawa, Tomoki; and Hibberd, Elizabeth E., representing another important research pathway. The group represented by Feijen, Stef and Juul-Kristensen, Birgit appears smaller but may contribute to knowledge integration across related themes. These patterns suggest three complementary roles in the field: authors who sustain publication growth, authors whose studies receive high citation attention, and bridging authors who connect different research communities.

Core journal analysis

Table 3. Ranking of influential core journals in swimmer's shoulder research.

Rank	Source	Documents	Citations	Average citation/Publication
1	Physical Therapy in Sport	17	301	17.7
2	Journal of Athletic Training	13	171	13.1
3	International Journal of Sports Physical Therapy	12	95	7.9
4	Journal of Sport Rehabilitation	10	73	7.3
5	American Journal of Sports Medicine	7	394	56.3
6	Journal of Science and Medicine in Sport	7	112	16
7	Orthopaedic Journal of Sports Medicine	7	83	11.8
8	British Journal of Sports Medicine	6	1370	228.3
9	Sports Biomechanics	6	64	10.7
10	Sports Health: A Multidisciplinary Approach	6	77	12.8

The core journal analysis in Table 3 shows that swimmer's shoulder research is mainly published in journals related to sports rehabilitation, athletic training, sports medicine, physical therapy, and biomechanics. This distribution indicates that the topic is no longer limited to swimming technique alone but has developed into a broader research concern involving injury prevention, functional evaluation, training management, and rehabilitation intervention. Physical Therapy in Sport published the largest number of articles (17), received 301 citations, and achieved an average of 17.7 citations per article, suggesting that it is both a major publication venue and a stable source of applied research in this field. The Journal of Athletic Training, International Journal of Sports Physical Therapy, and Journal of Sport Rehabilitation also contributed substantially, reflecting the practical orientation of current swimmer's shoulder research.

Highly prolific journals and highly influential journals were not identical. Although Physical Therapy in Sport published the largest number of papers, the British Journal of Sports Medicine and the American Journal of Sports Medicine showed stronger citation impact. The British Journal of Sports Medicine published 6 articles but received 1,370 citations, with an average of 228.3 citations per article. The American Journal of Sports Medicine published 7 articles and received 394 citations, with an average of 56.3 citations per article. These findings suggest that some high-impact sports medicine journals publish fewer swimmer's shoulder studies, but those studies are more visible within broader debates on sports injury prevention, clinical assessment, and athlete health.

The Journal of Science and Medicine in Sport, the Orthopaedic Journal of Sports Medicine, Sports Biomechanics, and Sports Health: A Multidisciplinary Approach also ranked among the top ten journals. Their presence shows that swimmer's shoulder research is informed by sport science, orthopaedic sports medicine, biomechanics, and multidisciplinary athlete health management. The Journal of Science and Medicine in Sport published 7 papers and received 112 citations, with an average of 16 citations per article. The Orthopaedic Journal of Sports Medicine published 7 papers and received 83 citations, with an average of 11.8 citations per article. Sports Biomechanics published 6 articles and received 64 citations, with an average of 10.7 citations per article. Sports Health: A Multidisciplinary Approach published 6 papers and received 77 citations, with an average of 12.8 citations per article. These journals further demonstrate that contemporary swimmer's shoulder research has developed clear interdisciplinary characteristics through the integration of rehabilitation science, clinical medicine, biomechanics, and training science.

Overall, the journal distribution shows a clear dual structure. High-output publications are mainly concentrated in sports rehabilitation and athletic training journals, indicating that the field is strongly oriented toward functional recovery, preventive intervention, and practical application. By contrast, highly influential findings are often published in internationally recognised sports medicine journals, suggesting that swimmer's shoulder has gradually been incorporated into broader discussions of sports injury and clinical management. This pattern reflects the disciplinary characteristics of the publication platforms and indicates that future research is likely to develop through deeper integration between sports rehabilitation and sports medicine.

Core country analysis

The distribution of academic output and citation impact illustrates the contributions and influence of various countries within this research domain. By analysing the number of publications, total citations, and average citations per publication (CPP) of the top ten countries, a clearer picture of each country's research performance in this field can be obtained.

The data in Table 4 reveal a clear concentration in the national distribution of swimmer's shoulder research. The United States ranked first with 68 publications, 1,360 citations, and an average of 20 citations per

publication. This indicates a broad and sustained research base, likely supported by extensive sports medicine, athletic training, physical therapy, and university-based clinical research infrastructure. The high output of the United States suggests that swimmer's shoulder has been examined across multiple institutional and professional settings, including athlete health management, injury prevention, functional assessment, and rehabilitation intervention.

Table 4. Ranking of core countries by publication output and academic influence in swimmer's shoulder research.

Rank	Source	Documents	Citations	Average citation/Publication
1	USA	68	1360	20
2	Australia	27	1967	72.8
3	England	22	320	14.5
4	Brazil	15	219	14.6
5	Canada	13	238	18.3
6	Japan	13	106	8.2
7	Belgium	10	216	21.6
8	Portugal	10	189	18.9
9	Spain	9	149	16.6
10	Iran	8	83	10.4

Australia ranked second with 27 publications. Although its publication output was lower than that of the United States, its total citation count reached 1,967, the highest among all countries, and its average citation count per article was 72.8. This indicates a pattern of concentrated and highly visible research influence. The Australian contribution may be associated with strong traditions in competitive swimming, sports physiotherapy, athlete monitoring, and applied sport science. In bibliometric terms, Australia therefore represents a high-impact profile: fewer publications than the United States, but stronger normalised citation influence and international visibility.

England ranked third with 22 publications, 320 citations, and an average of 14.5 citations per publication. Brazil ranked fourth with 15 publications, 219 citations, and an average of 14.6 citations per publication. Canada and Japan each published 13 papers, but their citation influence differed. Canada received 238 citations, with an average of 18.3 citations per article, whereas Japan received 106 citations, with an average of 8.2 citations per article. These differences show that publication volume does not necessarily correspond to citation influence and that national contributions should be interpreted through both productivity and impact.

Belgium and Portugal each published 10 papers and ranked among the top eight countries. Belgium received 216 citations, with an average of 21.6 citations per article, while Portugal received 189 citations, with an average of 18.9 citations per article. Although their publication output was moderate, their average citation performance was relatively strong. This suggests that swimmer's shoulder research is not limited to a small number of dominant countries but also includes meaningful contributions from countries with established expertise in sports medicine, rehabilitation science, biomechanics, and training science.

There are two clear patterns in the national distribution in this field. First, most of the publications come from Europe, North America, and English-speaking countries, especially the US, Australia, England, and Canada. This suggests that the development of swimmer's shoulder research is closely related to the long-term accumulation of these countries in competitive swimming, sports medicine, and sports rehabilitation. Second, highly productive countries and highly influential countries are not exactly the same. The United States has an absolute advantage in publication scale, whereas Australia performs more prominently in both total

citations and average citations per article, indicating that its research outcomes are more representative and influential within the field. This difference suggests that publication quantity can only reflect research activity but cannot fully represent academic influence, and both dimensions should be considered together.

This outcome underscores the robust interdisciplinary nature of swimmer's shoulder research. This subject is intricately associated not only with competitive swimming but also with research domains such as sports injury prevention, clinical evaluation, functional recovery, and rehabilitation interventions. Consequently, nations with more robust foundations in sports medicine, rehabilitation science, and advanced athletic training systems are more likely to yield enduring and significant research findings in this area. In the future, as research methodologies evolve and international collaboration intensifies, the national distribution of swimmer's shoulder research may become increasingly varied. Nevertheless, European and North American countries are expected to retain a predominant position for an extended period, primarily due to their established research institutions, funding prospects, and access to elite athletes for study purposes.

RGR, DT and NCSF

The data on the relative growth rate (RGR) and doubling time (DT) reveal the growth trend and maturity of literature in a particular field. RGR reflects the growth speed of publications within a specific time interval, while DT indicates the time required for the number of publications to double (Mahapatra, 1994; Javed & Liu, 2018).

1.Relative Growth Rate (RGR)

The Relative Growth Rate (RGR) is used to measure the growth rate of publications, and its calculation formula is as follows:

$$RGR = \frac{W2 - W1}{T2 - T1}$$

Among them, W1 and W2 respectively represent the natural logarithms of the cumulative number of publications at time T1 and T2. T1 and T2 are adjacent years.

2.Doubling Time (DT)

The doubling time (DT) represents the time needed for the number of publications to double. The relationship between DT and RGR is as follows:

$$DT = \frac{0.693}{RGR}$$

Among them, $\ln(2) \approx 0.693$ is the constant of the natural logarithm, and RGR is the relative growth rate.

3.Relative growth rate(RGR) and Doubling time(DT) of publications

As shown in Table 5, although the annual number of publications fluctuated across individual years, the cumulative number of publications showed a steady upward trend during the observation period. This indicates that swimmer's shoulder has remained a sustained research topic rather than a short-term or temporary academic concern. The publication output was relatively active in several years, particularly after 2020, suggesting that shoulder-related problems in swimmers have continued to attract attention in sports medicine, rehabilitation, biomechanics, and training science.

Table 5. Relative growth rate and doubling time of publications.

Years	Publications	Cumulative Sum	W1	W2	RGR	Mean (R)	DT (P)	Mean (DT)
2015	19	19	2.944	3.555	0.611		1.134	
2016	16	35	3.555	3.871	0.316		2.194	
2017	13	48	3.871	4.277	0.405		1.709	
2018	24	72	4.277	4.407	0.130		5.329	
2019	10	82	4.407	4.575	0.168		4.125	
2020	15	97	4.575	4.727	0.153	0.297	4.539	3.172
2021	16	113	4.727	4.875	0.148		4.688	
2022	18	131	4.875	5.056	0.181		3.828	
2023	26	157	5.056	5.170	0.114		6.066	
2024	19	176	5.170	5.273	0.103		6.760	
2025	19	195	5.273	—	—	0.136	—	5.336

The RGR results further reveal that the growth speed of swimmer's shoulder research gradually slowed over time. In the earlier stage, the mean RGR was higher, indicating a period of relatively rapid expansion in which the basic clinical problem, injury characteristics, and research boundaries of swimmer's shoulder were being established. In the later stage, the mean RGR decreased, while the mean DT increased. This pattern suggests that the field has moved from rapid growth toward a more stable and mature phase of development. A decline in RGR and an increase in DT should not be interpreted as a reduction in academic value. Rather, these indicators may reflect the gradual consolidation of the research field, in which the number of publications grows more slowly but the research questions become more focused and specialised.

This interpretation is consistent with the keyword timeline analysis. Earlier studies were mainly concerned with shoulder pain, injury occurrence, diagnosis, and epidemiological characteristics, whereas later studies increasingly addressed biomechanics, muscle strength, range of motion, scapular control, monitoring, prevention, and rehabilitation management. Therefore, the RGR and DT results do not only describe publication growth; they also reflect the intellectual development of the field. Swimmer's shoulder research appears to have shifted from problem recognition toward mechanism explanation and practical management, which indicates a more mature stage of knowledge development.

4. Field-Normalized Citation Score (NCSF)

The Field-Normalized Citation Score (NCSF) is used to measure the relative academic impact of different countries within a specific field. An NCSF value of 1.0 indicates that the number of citations of a country's or institution's publications is at the average level for that field. An NCSF greater than 1.0 means that the citations exceed the average for the field, indicating a higher level of impact; whereas an NCSF below 1.0 suggests lower-than-average citation levels within the field.

The NCSF (Field-Normalized Citation Score) is calculated using the following formula:

$$NCSF = \frac{CPP}{CI}$$

Where:

CPP represents the average number of citations per paper.

CI (Citation Impact) is the benchmark citation impact for the field. Here, $CI = 4708 / 195 \approx 24.14$ is calculated from the WoS (Web of Science) data source, which reflects the average number of citations for all related publications in the field of swimmer's shoulder.

The CI value is used to normalize citation rates across different subfields, allowing for a comparison of the academic performance of different countries and journals in the field of swimmer's shoulder with this benchmark.

The top 10 journals ranked by NCSF are shown in Table 6:

Table 6. NCSF values of core journals in swimmer's shoulder research.

Nº	Journal	Documents	Citations	NCSF
1	British Journal of Sports Medicine	6	1370	9.46
2	American Journal of Sports Medicine	7	394	2.33
3	Physical Therapy in Sport	17	301	0.73
4	Journal of Science and Medicine in Sport	7	112	0.66
5	Journal of Athletic Training	13	171	0.54
6	Sports Health: A Multidisciplinary Approach	6	77	0.53
7	Orthopaedic Journal of Sports Medicine	7	83	0.49
8	Sports Biomechanics	6	64	0.44
9	International Journal of Sports Physical Therapy	12	95	0.33
10	Journal of Sport Rehabilitation	10	73	0.30

Table 6 shows that journal level NCSF values were not fully consistent with publication output. Some journals, such as Physical Therapy in Sport, Journal of Athletic Training, International Journal of Sports Physical Therapy, and Journal of Sport Rehabilitation, published a relatively large number of swimmer's shoulder studies. These journals represent important and continuous publication platforms for research on functional assessment, rehabilitation strategies, preventive training, and clinical management. Their contribution is therefore reflected mainly in sustaining the development and accumulation of applied research in this field.

However, journals with fewer publications, such as the British Journal of Sports Medicine and the American Journal of Sports Medicine, showed much higher normalised citation influence. This indicates that publication quantity and citation impact represent different dimensions of journal contribution. A journal may publish fewer studies but still exert stronger academic influence if those studies are widely cited and connected to broader debates in sports medicine, injury prevention, and clinical rehabilitation. Therefore, the journal distribution of swimmer's shoulder research should be interpreted from both output and influence perspectives.

The journal level NCSF results suggest that swimmer's shoulder research has developed through two complementary knowledge dissemination channels. One channel is represented by rehabilitation and physical therapy-oriented journals, which provide stable publication space for applied and clinically relevant studies. The other channel is represented by high-impact sports medicine journals, which disseminate influential findings to a wider academic community. This dual structure indicates that swimmer's shoulder research is both an applied rehabilitation topic and an issue of broader relevance within sports medicine and athlete health management.

The top 10 countries ranked by NCSF are shown in Table 7. As shown in this table, the country-level NCSF results also demonstrate that publication output and citation influence are not identical. The United States produced the largest number of publications, which suggests a broad and active research base in sports medicine, athletic training, physical therapy, and university-based rehabilitation research. This high output may reflect the strong institutional foundation and research capacity of the United States in athlete injury prevention and clinical sport science.

Table 7. NCSF data table ranked by country.

Nº	Country	Documents	Citations	NCSF
1	Australia	27	1967	3.02
2	Belgium	10	216	0.89
3	USA	68	1360	0.83
4	Portugal	10	189	0.78
5	Canada	13	238	0.76
6	Spain	9	149	0.69
7	Brazil	15	219	0.60
8	England	22	320	0.60
9	Iran	8	83	0.43
10	Japan	13	106	0.34

Australia, although producing fewer publications than the United States, showed stronger normalised citation influence. This pattern suggests that Australian research may have contributed more concentrated and highly visible findings in competitive swimming, sports physiotherapy, athlete monitoring, and clinically relevant injury prevention. In this sense, the United States and Australia represent two different forms of contribution to swimmer's shoulder research. The United States reflects research scale and institutional breadth, whereas Australia reflects citation concentration and international influence.

The NCSF results therefore help clarify the difference between productivity and impact. A country with a larger publication base may contribute to the breadth and continuity of the field, while a country with higher normalised citation influence may play a stronger role in shaping the conceptual, methodological, or practical direction of the research area. This distinction is important because evaluating national contribution only by publication counts may underestimate the influence of countries that produce fewer but more highly cited studies.

Taken together, RGR, DT, and NCSF provide evidence that swimmer's shoulder research is entering a more mature stage. The field is no longer defined only by increasing publication numbers. Instead, its development is reflected in the consolidation of research themes, the differentiation between output and impact, and the growing integration of symptom identification, biomechanical explanation, functional assessment, prevention, and rehabilitation. These findings strengthen the scientific value of the bibliometric analysis by connecting quantitative indicators with the intellectual evolution of the field.

Keyword analysis

Table 8 shows that swimmer's shoulder research is concentrated around several primary themes: swimming-specific context, shoulder symptoms, injury prevention, and functional management. The keyword "swimming" appeared 75 times, indicating that the literature is strongly grounded in swimming-specific settings. "Shoulder pain" appeared 64 times, followed by "shoulder" and "pain" with 55 and 53 occurrences, respectively. These findings confirm that shoulder symptoms remain the central problem domain of the field. At the same time, the presence of prevention, risk factors, strength, and competitive swimmers among the high-frequency keywords indicates that research has extended beyond symptom description toward risk identification and functional management.

From the perspective of injury and risk identification, both "injuries" and "risk factors" appeared 40 times, indicating that research in this field has moved beyond simply describing pain and has gradually extended to the investigation of injury mechanisms and contributing factors. In particular, the fact that "risk factors" ranked among the top ten keywords suggests that recent studies have increasingly recognised that swimmer's shoulder is not caused by a single factor but is more likely related to the combined influence of training load,

movement patterns, local stability, muscle strength, and recovery status. This indicates that the research perspective in this field is shifting from merely identifying pain to explaining why it occurs and how risks can be recognised at an early stage.

Table 8 High Frequency Keywords in Swimmer's Shoulder Research

Rank	Keyword	Occurrences
1	swimming	75
2	shoulder pain	64
3	shoulder	55
4	pain	53
5	injuries	40
6	risk-factors	40
7	strength	38
8	swimmers	36
9	competitive swimmers	34
10	impingement	31

The keyword "*strength*" ranked seventh with 38 occurrences, indicating that strength-related factors occupy an important position in swimmer's shoulder research. This finding reflects increasing attention to shoulder muscular strength, muscle balance, rotator cuff function, and functional support capacity in both prevention and rehabilitation. The prominence of strength-related terms suggests that the field is moving beyond pain description and toward a more functional understanding of shoulder health in swimmers.

In addition, "*swimmers*" and "*competitive swimmers*" appeared 36 and 34 times, respectively, further indicating that current studies are mainly focused on swimming athletes, especially competitive swimmers. This suggests that a swimmer's shoulder is not simply a general shoulder problem but rather a sports injury issue closely associated with specialised training. Because competitive swimmers perform high frequency and repetitive stroke movements over long periods, their shoulders are exposed to substantial demands in both range of motion and workload, making them a key population for related research. This finding also suggests that future studies should continue to examine the specific influence of training patterns, performance level, and training stage on shoulder problems in relation to the particular characteristics of competitive swimming.

The keyword "*impingement*" appeared 31 times and remained among the top ten keywords. This indicates that shoulder impingement and related clinical mechanisms continue to be important topics in swimmer's shoulder research. Its frequent occurrence suggests that the field is concerned not only with subjective pain or general injury description, but also with specific pathological mechanisms and clinical interpretation. This further confirms the interdisciplinary nature of swimmer's shoulder research, particularly the integration of sports rehabilitation, biomechanics, and clinical medicine.

Overall, the distribution of high-frequency keywords indicates that swimmer's shoulder research has developed a relatively clear thematic structure. It is grounded in the specific context of swimming, centred on shoulder pain and injury manifestations, and extended through important directions such as risk factor identification, muscle strength and functional analysis, and the exploration of impingement mechanisms. This suggests that the field has gradually evolved from simply describing shoulder symptoms to a more comprehensive stage that also addresses injury mechanisms, functional assessment, and preventive intervention. It can be expected that, with the continued development of training monitoring, functional screening, and rehabilitation management research, future hotspots in swimmer's shoulder research will increasingly focus on risk warning, precise intervention, and the integrated analysis of multiple factors.

Keyword co-occurrence analysis

Figure 4 shows that the keyword co-occurrence network generated with CiteSpace has a multicentre structure with dense connections among major terms. This indicates that swimmer's shoulder research is not organised around a single issue, but around an interconnected set of themes including shoulder pain, swimming, injuries, prevention, strength, biomechanics, and functional assessment. The network structure therefore supports the view that the field has developed from an isolated injury topic into a broader knowledge system linking symptoms, mechanisms, and applied management.

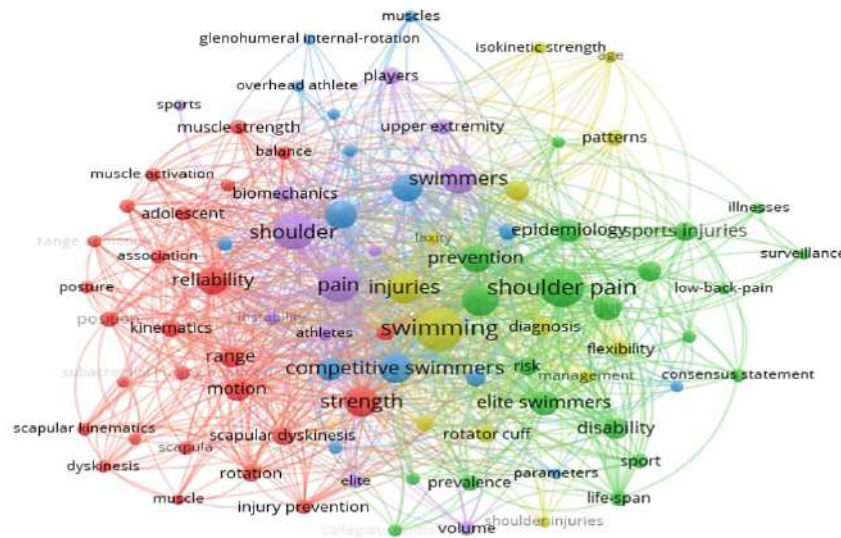


Figure 4. Keyword co-occurrence network of swimmer's shoulder research.

Table 9. Characteristics and academic significance of key keywords.

Thematic node	Node characteristics	Academic role
Shoulder pain	Keywords such as swimming, injuries, pain, epidemiology and diagnosis, and serves as one of the core nodes in the network	Closely connected with Forms the core problem domain of swimmer's shoulder research and provides the basis for shoulder problem identification, injury analysis, and rehabilitation research
Swimming	Widely co-occurs with swimmers, competitive swimmers, shoulder pain, prevention, and injuries, and is located in the central area of the network	Clarifies the sport specific nature of the field and shows that the research is consistently grounded in swimming training and competition contexts
Injuries/epidemiology	Shows strong links with sports injuries, prevalence, risk, diagnosis, and surveillance	Helps reveal the occurrence patterns, epidemiological characteristics, and risk distribution of shoulder injuries and provides evidence for prevention strategies
Biomechanics	Frequently co-occurs with kinematics, motion, scapular dyskinesis, rotation, and muscle activation	Provides theoretical support for explaining the movement mechanisms and functional imbalance involved in swimmer's shoulder
Strength	Closely related to muscle strength, rotator cuff, isokinetic strength, muscles, and upper extremity	Highlights the importance of strength level and local functional support in injury prevention and rehabilitation
Prevention	Forms a clear cluster with risk, injury prevention, management, and elite swimmers	Promotes the shift of research from problem description to risk management and preventive intervention
Competitive swimmers	Closely associated with swimmers, elite swimmers, volume, risk, and shoulder pain	Emphasizes the specific nature of the study population and provides a basis for examining the relationship between training load and shoulder problems
Scapular dyskinesis	Strongly linked with scapular kinematics, rotation, and motion	Provides an important entry point for understanding movement compensation and functional imbalance in the development of shoulder pain
Rotator cuff	Closely connected with strength, prevention, and shoulder pain	Reflects the key role of rotator cuff function in local stability, preventive training, and rehabilitation management

The thematic nodes in swimmer's shoulder research are closely connected and jointly form a field centred on shoulder-related problems in swimming, while also addressing mechanical explanation and practical intervention. The terms "shoulder pain," "swimming," and "injuries" occupy central positions in the network, indicating that the main research concern remains shoulder symptoms and injury occurrence in competitive swimming. Strong links among nodes such as swimmers and competitive swimmers further confirm the sport-specific nature of the field. At the same time, connections among biomechanics, motion, rotation, scapular dyskinesis, and muscle activation suggest that current research has moved beyond pain description toward explanations based on movement mechanisms, functional imbalance, and scapular control.

In addition, the frequent appearance of nodes such as rotator cuff and upper extremity indicates that muscle strength and local stabilisation have received substantial attention in relation to injury prevention and rehabilitation. The clustering of prevention with risk, injury prevention, and management further suggests that the field is moving from problem identification toward risk management and preventive intervention. Overall, swimmer's shoulder research has developed a framework centred on shoulder pain and injury, explained through biomechanical and functional mechanisms, and extended toward prevention and rehabilitation.

Keyword clustering relationships

Figure 5 shows that the keyword clustering structure in swimmer's shoulder research is relatively clear, mainly forming thematic groups such as monitoring, athletes, muscle strength, range of motion, forward head posture, taekwondo, neck, lower limbs, and freestyle swimming. Overall, the links among these clusters are relatively close, indicating that research in this field is concerned not only with shoulder pain and injury itself but has also gradually expanded to related topics such as muscle strength, joint range of motion, postural characteristics, training monitoring, and sport-specific movement patterns. Among these clusters, monitoring, muscle strength, strength, and range of motion are particularly prominent, suggesting that current research places greater emphasis on functional assessment, risk monitoring, and preventive intervention. Overall, swimmer's shoulder research has shown a clear trend toward developing from a simple description of injury to a more balanced focus on functional mechanism analysis and comprehensive management.

To further clarify the thematic structure of swimmer's shoulder research, the major clusters identified in the keyword clustering map were summarized in terms of topic name, representative keywords, and research direction, as shown in Table 10.

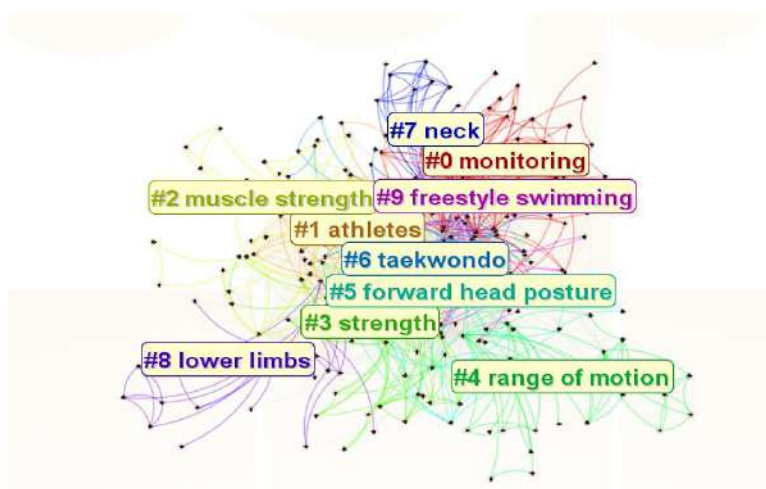


Figure 5. Keyword clustering map of swimmer's shoulder research.

Table 10. Swimmer's shoulder research keywords clustering analysis and research directions.

Cluster	Theme	Keywords	Research direction
#0	Monitoring and risk management	monitoring; injury monitoring; risk; management; surveillance	Tracks shoulder problems, training load, risk identification, and early-warning management.
#1	Athletes and population characteristics	athletes; swimmers; competitive swimmers; elite swimmers	Clarifies population-specific patterns among competitive and elite swimmers.
#2	Muscle strength and functional support	muscle strength; muscles; upper extremity; isokinetic strength	Highlights upper-extremity strength, local stability, and functional assessment.
#3	Strength training and injury prevention	strength; injury prevention; rotator cuff; training	Links strength-based intervention with shoulder stability, prevention, and rehabilitation.
#4	Range of motion and functional assessment	range of motion; flexibility; shoulder injuries; volume	Identifies mobility and flexibility as indicators of dysfunction, adaptation, and risk.
#5	Forward head posture and postural control	forward head posture; posture; alignment; biomechanics	Examines postural alignment and its influence on shoulder mechanics.
#6	Cross-sport comparison and functional transfer	taekwondo; athletes; strength; biomechanics	Uses cross-sport evidence to enrich interpretation of shoulder function.
#7	Neck and upper-body kinetic chain	neck; upper extremity; muscles; posture	Connects shoulder symptoms with cervical and proximal upper-body interactions.
#8	Lower limbs and whole-body coordination	lower limbs; motion; coordination; biomechanics	Extends analysis from local shoulder factors to integrated body mechanics.
#9	Freestyle swimming and stroke-specific features	freestyle swimming; stroke pattern; swimmers; technique	Emphasises stroke mechanics, repetitive technique, and style-specific loading.

Table 10 indicates that swimmer's shoulder research includes not only shoulder pain and injury, but also monitoring, muscle strength, range of motion, posture, stroke technique, and whole-body coordination. This thematic distribution shows that the field is gradually moving from symptom description toward a more comprehensive framework that includes mechanism explanation, functional assessment, risk monitoring, prevention, and rehabilitation management.

Keyword timeline analysis

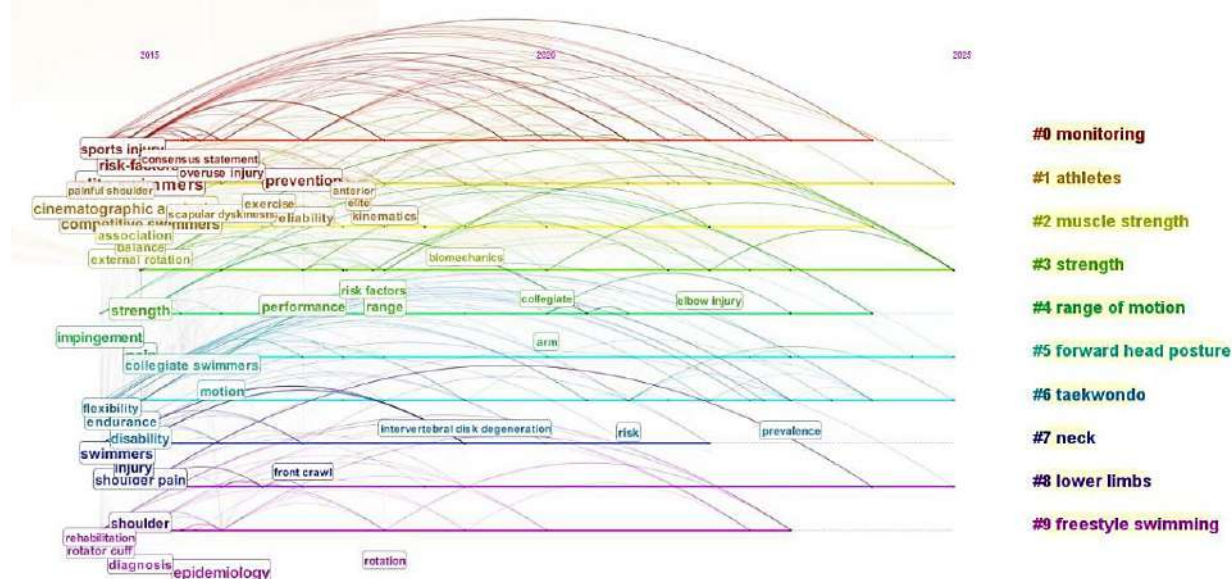


Figure 6. Keyword timeline view of swimmer's shoulder research.

Figure 6 shows how keyword clusters in swimmer's shoulder research changed between 2015 and 2025. Overall, the timeline suggests a coherent developmental pathway rather than a set of isolated topics. Early themes were mainly concerned with problem identification, whereas later themes increasingly focused on mechanisms, monitoring, prevention, and management. This temporal pattern supports the interpretation that swimmer's shoulder research has gradually evolved from recognising shoulder pain as a common problem toward explaining its causes and developing applied strategies to manage risk.

In the earlier stage, the research mainly focused on keywords such as swimmers, shoulder pain, injury, shoulder, diagnosis, and epidemiology. These topics suggest that the initial concerns of the field were centred on identifying the existence of shoulder problems in swimmers, describing their clinical manifestations, and clarifying their occurrence in athletic populations. In other words, early studies were mainly devoted to recognising shoulder pain and injury as a common and meaningful issue in competitive swimming.

As the field advanced, terms such as strength, muscle strength, range of motion, biomechanics, kinematics, and scapular dyskinesis gained prominence. This transition signifies a shift in research focus from merely describing pain and injury to investigating the functional and mechanical underpinnings of swimmer's shoulder. During this period, there was an increased emphasis on muscle support, joint mobility, movement pattern alterations, and scapular control, indicating a concerted effort to elucidate the aetiology of shoulder issues rather than solely documenting their existence.

In recent years, clusters such as monitoring, prevention, risk factors, performance, and forward head posture have remained active and become increasingly important. Monitoring appears to be one of the most active recent topics, suggesting growing interest in training surveillance, risk identification, and early management. This trend indicates a shift from retrospective injury description toward process-oriented management and preventive strategies. The timeline also includes themes such as freestyle swimming, neck function, and lower-limb coordination, indicating that the field is extending toward stroke-specific characteristics, kinetic-chain influences, and whole-body coordination.

The timeline view indicates that swimmer's shoulder research has progressed from describing pain and injury to interpreting these problems through functional and biomechanical mechanisms, and more recently to monitoring, prevention, and integrated management. This shift suggests a deepening of the field. Shoulder pain is increasingly understood not as an isolated symptom, but as the outcome of interacting factors within the training, performance, and recovery system.

DISCUSSION

Overall development pattern of swimmer's shoulder research

The present bibliometric findings indicate that swimmer's shoulder research has developed into a relatively mature and structured field over the past decade. Rather than focusing solely on shoulder pain as an isolated clinical symptom, current research increasingly situates swimmer's shoulder within a broader system that integrates training load, movement mechanics, functional capacity, and rehabilitation management (McKenzie et al., 2023; Kennedy et al., 2024).

From a developmental perspective, the discipline demonstrates a clear progression from phenomenon identification to mechanism exploration, ultimately resulting in process-oriented management. Early research primarily addressed the prevalence and characteristics of shoulder pain, while later studies shifted toward

biomechanical explanations and functional assessment. More recent work has emphasised monitoring, risk management, and preventive strategies (McKenzie et al., 2023; Yoma et al., 2022).

This transition reflects a broader paradigm shift in sports injury research, where complex conditions are no longer explained by single factors but are increasingly understood through integrated, multifactorial frameworks (McKenzie et al., 2023).

Structural and institutional interpretation of bibliometric patterns

The author, journal, and country analyses suggest that swimmer's shoulder research has developed through a relatively stable but uneven knowledge production structure. The author collaboration network indicates that the field is not organised around a single dominant research group. Instead, several partially connected clusters have emerged, each contributing to different dimensions of swimmer's shoulder research. Some authors appear to contribute mainly through sustained publication output, whereas others exert stronger influence through highly cited studies on risk factors, biomechanics, functional assessment, or rehabilitation. This distinction is important because productivity and academic influence do not necessarily represent the same form of contribution in bibliometric analysis (Donthu et al., 2021; Öztürk et al., 2024).

The collaboration network also suggests that swimmer's shoulder research has entered a stage of partial consolidation. The presence of stable author groups indicates that the field has moved beyond scattered individual studies and has begun to form recognisable research communities. However, the network remains heterogeneous, with several clusters showing stronger internal connections than external links. This pattern may reflect the interdisciplinary nature of swimmer's shoulder research. Researchers from sports medicine, physical therapy, biomechanics, athletic training, and rehabilitation science may address related but not identical research questions. As a result, knowledge development in this field is characterised by both specialisation and partial fragmentation. Future studies would benefit from stronger collaboration among biomechanical researchers, clinicians, rehabilitation specialists, and swimming performance scientists.

The core journal analysis further supports this interpretation. High-output journals such as *Physical Therapy in Sport*, *Journal of Athletic Training*, *International Journal of Sports Physical Therapy*, and *Journal of Sport Rehabilitation* indicate that swimmer's shoulder research is strongly rooted in applied sports rehabilitation, clinical assessment, and injury management. These journals provide important publication platforms for studies focused on functional evaluation, training-related shoulder problems, preventive exercise, and rehabilitation strategies. In contrast, journals with fewer publications but higher citation impact, such as the *British Journal of Sports Medicine* and the *American Journal of Sports Medicine*, appear to function as high-impact dissemination channels for studies with broader clinical or theoretical significance. This contrast indicates a dual publication structure in the field: rehabilitation-oriented journals support continuous topic development, while high-impact sports medicine journals amplify findings that influence the wider sports injury and clinical research community.

Country-level differences also require interpretation beyond simple publication counts. The United States produced the largest number of publications, suggesting a broad and active research base in sports medicine, athletic training, physical therapy, and university-based rehabilitation research. This high output may be partly associated with the extensive institutional infrastructure of sports science and clinical research in the United States, where shoulder injuries in athletes are studied across multiple professional contexts. Australia, by contrast, produced fewer publications but showed stronger citation influence. This pattern suggests that Australian research may be more concentrated in influential studies related to competitive swimming, sports physiotherapy, athlete monitoring, and clinically relevant injury prevention. Therefore, the national distribution

of swimmer's shoulder research should be understood through two dimensions: publication volume and citation influence.

The contrast between the United States and Australia is particularly important. A high number of publications reflects research activity and institutional breadth, whereas a high citation impact reflects international visibility and knowledge influence. The present findings suggest that swimmer's shoulder research is shaped not only by the amount of research produced but also by the degree to which this research is integrated into broader discussions on sports injury prevention, biomechanics, rehabilitation, and athlete health management. This interpretation strengthens the analytical value of the bibliometric findings and responds to the need to move beyond descriptive reporting.

Overall, the author, journal, and country analyses show that swimmer's shoulder research has become a structured and interdisciplinary field. Its development is supported by several stable author groups, a combination of rehabilitation-oriented and high-impact sports medicine journals, and a country level pattern in which publication output and citation influence are not always aligned. These findings suggest that future research should not only increase publication volume but also promote cross-group collaboration, international cooperation, and stronger integration between clinical, biomechanical, and training-related perspectives.

Conceptual contribution: A three level framework of swimmer's shoulder research

A central contribution of this study is the development of a three level framework for understanding the knowledge structure of swimmer's shoulder research. Previous reviews have examined specific aspects of swimmer's shoulder, such as training volume, injury risk factors, or exercise therapy interventions (Feijen et al., 2020; McKenzie et al., 2023; Yoma et al., 2022). However, these reviews generally focus on particular subtopics rather than the overall intellectual structure of the field. The present bibliometric analysis provides a broader view by showing how these subtopics are connected within the development of swimmer's shoulder research. Based on the keyword co-occurrence, clustering, timeline, author, journal, and citation results, swimmer's shoulder research can be organised into three interrelated levels: symptom identification, mechanism explanation, and intervention-oriented management.

The first level is symptom identification. At this level, the research focus is on shoulder pain, injury occurrence, epidemiology, diagnosis, and the recognition of swimmer's shoulder as a common problem in competitive swimming. The high frequency of keywords such as "*shoulder pain*," "*pain*," "*injuries*," "*swimming*," and "*competitive swimmers*" indicates that the field remains grounded in the practical problem of shoulder symptoms among swimmers. This level provides the clinical and sport-specific foundation for the field. Without the identification of shoulder pain and injury as persistent problems in swimming, later research on mechanisms and interventions would lack a clear problem base.

The second level is mechanism explanation. At this level, research moves beyond the description of pain and injury and attempts to explain why swimmer's shoulder occurs. The bibliometric findings show that keywords and clusters related to biomechanics, strength, range of motion, scapular dyskinesis, rotator cuff function, muscle activation, and stroke mechanics play an important role in the knowledge structure of the field. These themes indicate that swimmer's shoulder is increasingly understood as a multifactorial condition involving training load, movement patterns, local shoulder function, scapular control, muscular support, and individual adaptation. This mechanism-oriented level reflects a deeper scientific understanding of swimmer's shoulder and helps explain why similar training loads may lead to symptoms in some swimmers but not in others.

Table 11. Three-level framework of swimmer's shoulder research.

Level	Main focus	Bibliometric evidence	Scientific and practical meaning
Symptom identification	Shoulder pain, injury, diagnosis, epidemiology, competitive swimmers	High-frequency keywords such as "shoulder pain," "pain," "injuries," "swimming," and "competitive swimmers"	Establishes swimmer's shoulder as a persistent clinical and sport-specific problem
Mechanism explanation	Biomechanics, strength, range of motion, scapular dyskinesis, rotator cuff, stroke mechanics	Keyword co-occurrence and clustering around biomechanics, strength, movement, scapular control, and functional assessment	swimmer's shoulder as a multifactorial condition involving load, movement, function, and adaptation
Intervention-oriented management	Prevention, monitoring, rehabilitation, risk management, training modification	Recent timeline activity in monitoring, prevention, management, and rehabilitation-related themes	Connects bibliometric evidence with prevention, rehabilitation, training modification, and long-term athlete health management

The third level is intervention-oriented management. At this level, research focuses on prevention, monitoring, rehabilitation, training modification, risk management, and return-to-training strategies. The keyword timeline and clustering results suggest that recent research has become increasingly concerned with monitoring and prevention, indicating a shift from retrospective injury description toward proactive management. This level has strong practical value because it connects research findings with applied sport science, coaching, clinical assessment, and rehabilitation practice. In this sense, swimmer's shoulder research is no longer limited to identifying the existence of shoulder pain or explaining its mechanisms; it is increasingly concerned with how to reduce risk, guide training, support recovery, and protect long-term athlete health.

This framework advances current understanding in three ways. First, it integrates fragmented research themes into a coherent structure. Instead of treating shoulder pain, biomechanics, strength, prevention, and rehabilitation as separate topics, the framework shows that they represent different stages of knowledge development within the same field. Second, it clarifies the developmental trajectory of swimmer's shoulder research. The field has progressed from identifying symptoms to explaining mechanisms and then to developing prevention-oriented and rehabilitation-oriented approaches. Third, it strengthens the practical relevance of bibliometric findings. The framework can help researchers identify underdeveloped areas, clinicians design more comprehensive assessment and rehabilitation models, and coaches better understand the relationship between training load, movement quality, and shoulder health.

The three-level framework also highlights future research directions. At the symptom level, more longitudinal epidemiological studies are needed to clarify the incidence, recurrence, and severity of shoulder problems across different competitive levels and training stages. At the mechanism level, future studies should further examine how training load, stroke mechanics, scapular control, strength, range of motion, and recovery interact over time. At the intervention level, more field-based and longitudinal intervention studies are needed to test whether monitoring systems, preventive exercise programmes, and rehabilitation strategies can reduce shoulder symptoms while maintaining swimming performance. Therefore, the proposed framework does not simply summarise existing literature; it provides an organising model for future research and applied practice in swimmer's shoulder.

Overall, the present bibliometric study contributes to the field by transforming a dispersed body of literature into an integrated knowledge structure. The symptoms–mechanisms–intervention framework shows that swimmer's shoulder research has evolved from a symptom-focused topic into a multidisciplinary research area involving sports medicine, biomechanics, rehabilitation science, training monitoring, and athlete health

management. This conceptual contribution strengthens the originality of the study and demonstrates how bibliometric evidence can be used not only to describe a field but also to explain its intellectual development and practical significance.

Interdisciplinary integration and knowledge convergence

The findings demonstrate that swimmer's shoulder research exhibits strong interdisciplinary characteristics, involving sports science, biomechanics, clinical medicine, and rehabilitation science. The presence of both high-output rehabilitation journals and high-impact sports medicine journals indicates a bifurcated knowledge framework: one focused on practical application and the other on clinical and theoretical progress.

This interdisciplinary convergence enhances the explanatory capacity of the field and allows swimmer's shoulder to be understood within a more comprehensive framework that integrates training systems and clinical perspectives (McKenzie et al., 2023; Yoma et al., 2022).

Practical implications for training and rehabilitation

The findings of this study have important practical implications for training and rehabilitation in competitive swimming. Swimmer's shoulder should be managed through integrated prevention and rehabilitation rather than isolated symptom treatment. Coaches, clinicians, and practitioners should consider training load, stroke technique, shoulder strength, scapular control, range of motion, and recovery as interdependent components. Early identification of risk factors through monitoring and functional assessment is critical for preventing symptom progression. Strength training and movement correction should therefore be emphasised not only during rehabilitation but also as part of long-term injury prevention and athlete health management (Yoma et al., 2022; Tavares et al., 2025; Takayama et al., 2024).

Limitations and future directions

Despite its contributions, this study has several limitations. First, the analysis was based only on the Web of Science Core Collection, which may have excluded relevant studies indexed in other databases such as Scopus, PubMed, or SPORTDiscus. Second, the study included only English-language articles and review articles, which may have introduced language and document-type bias. Third, bibliometric analysis can reveal publication trends, citation relationships, and thematic structures, but it cannot directly evaluate the methodological quality or clinical effectiveness of individual studies. Future research should combine bibliometric analysis with systematic or scoping review methods to provide a more comprehensive understanding of swimmer's shoulder research. More longitudinal and intervention-based studies are also needed to clarify how training load, stroke mechanics, shoulder function, and recovery interact over time (Kennedy et al., 2024; Takayama et al., 2024; Tavares et al., 2025).

CONCLUSION

Main findings

This study conducted a bibliometric analysis of swimmer's shoulder research from 2015 to 2025 based on the Web of Science Core Collection. The findings reveal that the field has developed into a relatively structured and interdisciplinary research domain over the past decade. Research output showed a steady upward trend. A relatively stable yet heterogeneous academic network has emerged, with noticeable differences between high-output and high-impact contributors. Keyword and clustering analyses further indicate a transition from symptom-orientated research toward mechanism-based and intervention-orientated approaches.

Theoretical contributions

This study contributes to the literature by providing a structured bibliometric overview of swimmer's shoulder research from 2015 to 2025. By identifying publication patterns, citation differences, keyword relationships, and thematic evolution, the study shows how the field has shifted from symptom-oriented research toward mechanism-based and intervention-oriented approaches. The proposed three-level framework, comprising symptom identification, mechanism explanation, and intervention-oriented management, offers an integrative model for understanding the internal organisation and developmental trajectory of the field.

Practical implications

The findings have significant implications for training and rehabilitation practices in competitive swimming. Swimmer's shoulder should be regarded as a multifactorial issue resulting from the interplay of training load, technique, functional capacity, and recovery management, rather than as a singular clinical condition. Consequently, coaches and practitioners should implement an integrated approach that amalgamates workload regulation, technical optimization, strength development, and recovery monitoring (Yoma et al., 2022; Tavares et al., 2025).

Limitations and future research

Future research should integrate multiple databases and combine bibliometric analysis with systematic or scoping review methods to provide a more comprehensive understanding of the field. Increased focus should be directed towards tailored training and rehabilitation approaches, sophisticated monitoring technologies, and cohesive models that integrate biomechanics, physiology, and workload management (Kennedy et al., 2024; Tavares et al., 2025).

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: Ming Lou. Methodology: Ming Luo. Formal analysis: Thariq Khan Bin Azizuddin Khan. Investigation: Bo Wang. Data curation: Bo Wang. Writing – original draft: Changqing Guo. Writing – review & editing: Changqing Guo. Supervision: Thariq Khan Bin Azizuddin Khan.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Nordic hamstring exercise asymmetries do not influence change of direction abilities

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ABSTRACT

Multidirectional demands in team sports emphasise eccentric hamstring strength, as the hamstrings play a critical role in modulating ground reaction forces during deceleration and change of direction (COD). A common method to assess limb asymmetry is the Nordic Hamstring Exercise (NHE), an eccentric movement which derives metrics such as maximum force and impulse which are associated with improved linear acceleration in team-sport athletes. The primary aim was to examine how NHE-derived symmetries and limb differences influence COD sprint performance metrics. Forty-six university-level athletes (28 males, 18 females; age 20.37 ± 1.47 years) underwent 30-m linear and COD sprints, alongside bilateral NHE on the VALD Nordbord measuring maximum force, average force, and impulse. Non-parametric data were analysed using ART followed by general linear models in SPSS, with fixed factors of symmetry grouping, limb, and direction (for directional metrics) and a significance of $p < .05$. No significant effects or interactions emerged for symmetry grouping across metrics including MDSA area, area percentage, acceleration, directional velocity and directional acceleration, and NHE forces and impulse. Limb grouping showed significant effects on area percentage ($p = .02$; left higher) and maximum force ($p = .05$; right higher), while directional grouping revealed highly significant effects ($p < .001$) with sharper angles yielding lower acceleration and velocity. These findings suggest NHE symmetries do not substantially influence COD performance in this cohort, whereas limb-specific differences influence area percentage and maximum force, and sharper turn angles substantially reduce acceleration and velocity.

Keywords: Performance analysis, Change of direction, Nordic hamstring exercise, Asymmetry.

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INTRODUCTION

Multidirectional sprinting in field- and court-based sporting codes plays a pivotal role in match performance due to the athletes being required to evade opponents, respond to dynamic game scenarios, and execute tactical manoeuvre effectively (Brughelli *et al.*, 2008; Sheppard & Young, 2006). These actions, including acceleration, deceleration and change of direction (COD), require an athlete to produce and absorb forces rapidly, particularly from lower extremities in which strength asymmetries as well as neuromuscular control can influence their multidirectional efficiency (Bishop *et al.*, 2019; Dos'Santos *et al.*, 2019). Athletes which undergo repetitive sport specific pivoting or unilateral loading may experience asymmetrical inter-limb differences exceeding 10-15% which may compromise specific tasks which require bilateral coordination (Bishop *et al.*, 2021; Kocak *et al.*, 2023; Loturco *et al.*, 2022).

Eccentric tasks during a deceleration are controlled by the hamstrings which moderate ground reaction forces (GRFs) in order to regulate momentum as well as facilitating re acceleration during a COD (Harper *et al.*, 2022; Morin *et al.*, 2015). To isolate and strengthen eccentric hamstring capabilities, the Nordic hamstring exercise (NHE) is commonly used with studies finding that team sport athletes that perform the NHE have found to have improved linear acceleration and reduced hamstring asymmetry (Freitas *et al.*, 2019; Kocak *et al.*, 2023; Loturco *et al.*, 2019; Opar *et al.*, 2015). Although the research is under explored when considering how NHE derived asymmetries may affect multidirectional sprints as these imbalances may not only impair functions slightly but also accumulate over time (Bishop *et al.*, 2022; Ličen & Kozinc, 2023).

A COD task will increase the demands required during sprinting as the athletes are required to, decelerate, redirect their path and re accelerate in that direction which can all be influenced by the turn angle, entry velocity as well as the limb dominance of the athlete (Dos'Santos *et al.*, 2018; Jones *et al.*, 2016). When performing a change of direction with a sharper angle, such as at 90° or 135°, greater braking impulses and eccentric control is required compared to that of narrower angles, which may lead to asymmetries in velocity and acceleration capabilities between limbs (Hader *et al.*, 2016; Arboix-Alió, Buscà *et al.*, 2024). Additionally, biomechanical research has found that COD sprints with larger turns will intensify braking impulses and additionally decrease momentum after the pivot, which negatively effects the reacceleration due to the increased demands for eccentric muscle regulation as well as GRF adjustments (Dos'Santos *et al.*, 2018; Dos'Santos *et al.*, 2021; Harper *et al.*, 2019).

However, even while considering these insights, tradition assessments will test linear sprint and COD capabilities separately, thus limiting the insight into an athlete's holistic multidirectional sprint ability (Nimphius *et al.*, 2018; Graham-Smith *et al.*, 2018). The multidirectional sprint area (MDSA) is a novel method in which the velocities from a linear sprint, deceleration and multiple COD sprints are used to create a holistic metric to determine an athlete's multidirectional sprint ability (Gordon & Green *et al.*, 2026). This method enables evaluation of proportional contributions, revealing how asymmetries in velocity or acceleration might stem from underlying strength disparities, as seen in comparisons between NHE and COD performance (Bishop *et al.*, 2021; Gordon & Green, 2026). Furthermore, athletes' training loads and recovery times vary, particularly in university athletes, while understanding these links could assist in informing interventions due to the paucity in comparing NHE symmetries with COD metrics across multiple angles in male and female groups (Freitas *et al.*, 2022; Loturco *et al.*, 2022).

In addition, due to the inconsistent relationship between COD speed and drop jumps as well as isokinetic tests, task specific evaluations are required to further understand the relationships for multidirectional ability (Bishop *et al.*, 2022; Dos'Santos *et al.*, 2019). While previous research has shown that hamstring demands

will increase as the angle in a COD increases, it remains unclear how NHE metrics differ when comparing the specific angles, particularly when including the MDSA method for the athletes (Gordon & Green, 2026; Harper *et al.*, 2022). This may assist coaches and practitioners with profiling their athletes, where early detection of their imbalances could support their development of their multidirectional sprint ability (O'Cain *et al.*, 2025; Arboix-Alió *et al.*, 2024).

The primary aim of this study is to investigate the relationships between NHE symmetries, limb differences, and COD sprint performance metrics—including MDSA areas, accelerations, and velocities—across 45°, 90°, and 135° turns in university-level athletes.

METHODOLOGY

Research design and participants

This study followed an observational cross-sectional approach in order to compare the NHE symmetry/asymmetry classifications of the athletes and their sprint and COD metrics. The assessments were conducted over two sessions, conducted on separate days interspersed by a minimum of 48 hours, to limit fatigue accumulation. Sprint and COD tests were performed on grass surface to mimic competition setting. The testing procedure was varied between individuals within the groups to mitigate sequencing bias, however the athletes followed a fixed schedule for consistency in measurement.

A sample of 46 university-level athletes (age: 20.37 ± 1.47 years; mass: 65.14 ± 8.22 kg; height: 169.15 ± 8.67 cm) who volunteered from team sports including football, rugby, and hockey. The sample comprised 28 males (age: 20.86 ± 1.62 years; mass: 67.38 ± 8.03 kg; height: 173.21 ± 8.53 cm) and 18 females (age: 19.61 ± 0.7 years; mass: 61.66 ± 7.7 kg; height: 162.83 ± 4.2 cm). All athletes completed written informed consent forms prior to participation, and the study received institutional ethical approval (REC-1359-2022).

Linear maximal sprint

The velocity of a 30 m maximal straight-line sprint was captured using a Stalker ATS II radar device (Stalker Pro, Radar Sales Inc., Richardson, TX, USA). Each sprint was split into the first 15 m and the second 15 m to reach the overall 30 m distance performed. Acceleration was subsequently calculated from the velocity measurements from the sprints. Athletes were instructed to use a split start stance, with their lead foot placed 30 cm behind the start line to ensure they started at the correct position and were encouraged to continue running at maximal effort past the end point. Three attempts were performed by each athlete with a minimum of 2-minute intervals between attempts to allow for optimal performance during each attempt. Data processing was conducted through Stalker ATS 5.0 software (Stalker Pro, Radar Sales Inc., Minneapolis, MN, USA) (Cronin & Templeton, 2008).

Change of direction

COD capabilities were measured through 30-m sprints incorporating pivots at the midpoint (15 m) with turn angles of 45°, 90°, and 135° executed bilaterally, yielding six variant conditions. Interval timings at 15 m and 30 m were obtained using Fusion Smartspeed timing gates (Fusion Sports, Coopers Plains, Queensland, Australia) accurate to 0.01 s. Commencing from a static split stance akin to the sprint test, athletes propelled maximally to the pivot point, braked optimally for redirection, and accelerated to completion. Each variant allowed three repetitions separated by no less than 3-minutes of recovery. The attempt with the fastest 15-30 m interval was used to for the velocity and acceleration data.

Multidirectional Sprint Area (MDSA)

The MDSA method is a novel method which is used to quantify a holistic multi directional sprint performance of an athlete by measuring linear sprint, deceleration and COD velocities across eight equidistant directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) (Gordon & Green, 2026). The MDSA method can present an athlete's MDSA in directional sections, including forward, backward, right and left. The protocol established for this method used velocity data from the 15-30 m interval of the various tests which forms an octagonal polygon on a graph (Gordon & Green, 2026). A shoelace formula, defined as $0.5 | \sum (x_i y_{i+1}) - x_{i+1} y_i |$, was used to calculate the total area as well as the segmented areas derived from the velocity data captured (Gordon & Green, 2026). Furthermore, the segmented areas of the right and left direction can be used to assess the athlete's directional dominance with both a relative percentage value as well as the actual value calculated from the segmented area.

Nordic curls

A Nordic hamstring curl was used to evaluate the hamstring eccentric capacity of the athletes using a VALD Nordbord (VALD Performance, Newstead, Australia). The athletes were instructed to set themselves in a knelling position on the VALD Nordbord with their lower legs fixed with restraints that are positioned onto the ankle joints, with each attempt having a 30 second rest interval. Each athlete attempted the NHE three times and were instructed to have a controlled forward descent against the resistance while also ensuring their hips and torso stay aligned as well as their arms folded across their torso. The attempts were considered acceptable if a clear and distinct force apex was succeeded by an abrupt reduction during the assessment. The metrics recorded for this test included peak force (N), mean force (N) and peak impulse (N·s) for each leg.

Identification of asymmetry

Symmetry and asymmetry were evaluated bilaterally for NHE metrics (right and left limbs) and directionally for COD accelerations and velocities. For NHE, symmetry was determined by comparing absolute differences using maximum force, with asymmetry defined as a difference exceeding 10% of the stronger limb's value (Kocak *et al.*, 2023). Data were grouped into symmetry (symmetrical vs. asymmetrical) and limb (right vs. left) categories, with directional added for COD-specific analyses to capture turn-side effects.

Statistical analysis

Participants were grouped by a symmetrical grouping, which was examined by the symmetry and asymmetry metrics from their max force outputs of their NHE for comparative analysis. Additionally, the limb groupings were made according to the directional (left and right) tests as well as directional grouping which were grouped by the different angles of the COD tests (45°, 90° and 135°).

Shapiro-Wilk tests confirmed non-parametric data distribution, necessitating aligned rank transformation (ART) for ANOVA-type analyses using the ARTTool. ART-transformed data were analysed in SPSS (Version 30, IBM Corp., Armonk, NY, USA) using general linear models (GLM) and univariate procedures. Fixed factors included symmetry grouping and limb grouping for all metrics, with direction added as a third factor for directional acceleration and velocity datasets. Dependent variables comprised ART-transformed MDSA area, MDSA area percentage, acceleration, directional velocity, directional acceleration, NHE maximum force, NHE average force, and NHE maximum impulse. Significance was set at $p < .05$, with post-hoc tests adjusted for multiple comparisons where applicable. Multiple comparisons ($n = 18$) resulted in an adjusted p -value of .00278.

RESULTS

When comparing the directional acceleration and velocity of the athletes during each change of direction sprint, the data indicates that CODs with greater angles of change exhibit lower acceleration and velocity than those with lesser angles, consistent with biomechanical demands of sharper turns (Table 1). For the MDSA method, minor differences between left and right segments were revealed (Table 2). Finally, the Nordic hamstring curl metrics, the median average force, maximum force and maximum impulse showed differences between the symmetrical and directional groupings (Table 2).

Table 1. Descriptive data (median and interquartile range (IQR)) for the COD tests for 46 field team-sport athletes, based on allocated groups.

	Asymmetrical (n = 21)	Symmetrical (n = 25)	Left (n = 46)	Right (n = 46)	45 (n = 92)	90 (n = 92)	135 (n = 92)
Velocity [†]	5.84 (1.932)	5.94 (1.98)	5.94 (2.01)	5.87 (1.94)	7.52 (2.04)	6.47 (1.72)	5.12 (1.19)
Acceleration [†]	2.27 (1.59)	2.43 (1.69)	2.36 (1.70)	2.30 (1.63)	3.94 (1.93)	2.80 (1.40)	1.76 (0.80)

Note. [†] $p < .00278$.

Table 2. Descriptive data (median and interquartile range (IQR)) values for the symmetry and directional data

	Asymmetrical (n = 21)	Symmetrical (n = 25)	Left (n = 46)	Right (n = 46)
Area	55.26 (25.05)	59.72 (25.68)	58.51 (26.96)	58.91 (24.77)
Area percentage*	50.00 (2.77)	50.00 (2.38)	49.57 (3.99)	50.44 (3.99)
Max force*	294.63 (121.25)	336.00 (133.19)	299.88 (112.88)	338.63 (147.81)
Avg. force	284.71 (103.72)	313.28 (111.75)	284.71 (105.57)	314.91 (123.40)
Max impulse	3055.03 (3522.30)	3242.66 (3113.25)	2906.83 (2944.98)	3644.33 (3581.14)

Note. * $p < .05$.

Symmetrical grouping

The ART, followed by GLM analyses for symmetrical grouping, revealed no significance or interactions across most metrics. Specifically, no significant effects of symmetrical grouping were observed on acceleration, area, area percentage, average force, maximum force, or maximum impulse.

Limb grouping

ART-GLM analyses for limb grouping indicated limited significant effects, with no significant interactions across metrics (Table 2). No significant effects of limb grouping were found on acceleration, area, average force, or maximum impulse. However, a significant effect of limb grouping was observed on area percentage ($p = .02$), with the left limb contributing to a higher proportional area compared to the right. In addition, a significant difference was observed on the maximum force ($p = .05$), in which the right limb exhibited greater peak values when compared to the left.

Directional grouping

The directional grouping analysis was only conducted for the directional acceleration and velocity metrics. The results observed revealed highly significant difference for directional however no significant interactions were found (Table 1). Additionally, for the directional acceleration, a significant difference was found ($p < .001$) while the directional velocity also showed a significant difference with the direction ($p < .001$) where lower acceleration occurred at sharper angles compared to that at smaller angles. No significant differences were found in both the directional acceleration and velocity for direction by symmetrical grouping interaction, direction by limb interaction, or direction by symmetrical grouping by limb interaction.

DISCUSSION

The primary aim of the study was to investigate the NHE symmetry and limb specific differences exerted on COD sprint performance among university athletes, with no significant effects or interactions observed for symmetrical grouping across all metrics. Furthermore, limb grouping yielded significant effects limited to area percentage (greater left limb contribution) and maximum force (higher right limb peaks). In contrast, directional grouping demonstrated significant main effects specific to acceleration and velocity, with sharper angles imposing progressively greater biomechanical demands, independent of symmetry or limb factors.

The findings from the symmetrical grouping analyses indicate that there were no significant effects or interactions on any of the COD and NHE metrics. These suggest that asymmetry in NHE metrics, as assessed via the VALD Nordbord, does not substantially differentiate COD sprint performance in university level athletes performing 30 m sprints with turns at 15 m. Similar observations have been reported in studies examining asymmetries in COD tasks, where inter limb differences in strength related metrics do not consistently impair overall performance, potentially because athletes can compensate through technical adjustments or bilateral contributions during multi directional movements (Bishop *et al.*, 2021; Dos'Santos *et al.*, 2019). Additionally, the lack of significance may stem from the relatively homogeneous sample of university athletes, who may not exhibit the extreme asymmetries seen in elite populations, thereby reducing the detectable impact of symmetrical grouping on COD outcomes (Loturco *et al.*, 2019). Although performing the NHE primarily targets eccentric hamstring strength of an individual, which could be seen as vital in the deceleration phase of the COD, this may not necessarily translate to their maximal sprinting velocity (Harper *et al.*, 2022; Morin *et al.*, 2015). The method of using the ART GLM may indicate the inability to subtle symmetrical differences within a non-parametric distribution due to the non-significant findings (Bishop *et al.*, 2021). Subsequently, these limitations may be even greater with regards to asymmetry from high intensity actions derived from COD protocols (Dos'Santos *et al.*, 2019). The results from this research reveal that aiming for perfect symmetry in the NHE may not assist in improving the athletes COD performance within this sample, which aligns with previous research which signify that moderate asymmetries can be present in athletes with strong COD ability (Bishop *et al.*, 2022; Loturco *et al.*, 2022).

Conversely, this research found that limited significant differences within the limb-grouping indicates that the asymmetries in the NHE may not directly influence the overall performance of left and right COD directions. When considering the MDSA area percentage of the athletes, it was found that the left segment contributed to more to the overall multidirectional sprint ability. This finding suggests the athletes' sprinting ability was impacted more from the left proportion of the MDSA in addition to the force distribution towards to the left CODs, particularly the deceleration and reacceleration during these tasks. This may be the case due to limb specific adaptations in sport in which the non-dominant limb will act as a stabilising or braking mean when turning (Dos'Santos *et al.*, 2021; Jones *et al.*, 2016). The contribution of the left segment of the MDSA aligns with previous literature where the inner leg, which is usually the left, generates larger braking forces during the COD turn by ensuring efficient deceleration and minimising the turn radius and therefore enhancing the task efficiency (Arboix-Alió *et al.*, 2024). These adaptations underscore the functional utility of moderate left-limb emphasis in force contributions; however, they may also signal a need for bilateral monitoring to prevent compensatory overload. Maximal force also was revealed to be significantly larger with the right limb compared to the left during the peak values of the task. This may be an indication that the right limb is the dominant limb in force production during the NHE, which is similar to previous findings in movements such as sprinting or pivoting (Bishop *et al.*, 2019; Loturco *et al.*, 2022). Acceleration and impulse did not have significant results, and this may be a result of compensatory mechanisms between limbs. Furthermore, this may allow athletes to maintain their performance despite these asymmetries, which can also be found when

strength asymmetries do not correlate with their speed deficits (Freitas *et al.*, 2019; Morin *et al.*, 2015). The limb grouping also showed non-significant results for directional metrics, suggesting that these unilateral tasks may not alter the acceleration or velocity of the athlete's turning performance due to its bilateral nature (Bishop *et al.*, 2019; Dos'Santos *et al.*, 2020).

Moreover, the directional grouping analyses, applied specifically to directional acceleration and velocity, demonstrated highly significant effects of direction. In contrast, no significant interactions involving symmetrical or limb groupings were found with these metrics. When performing sharper angles, lower acceleration and velocity was present compared to that of shallower angles. This further demonstrates the demands of acute COD necessitating a greater need for deceleration and reacceleration by the athlete. Additionally, the greater requirement of amplified braking forces, extended ground contact times, reduced post-turn momentum and velocities, and compromised reacceleration via enhanced eccentric control and GRF modulation is essential for the ability of an efficient COD performance (Dos'Santos *et al.*, 2018; Harper *et al.*, 2019; Dos'Santos *et al.*, 2021). Due to the needs of these demands, deceleration reliance on hamstring efficiency increases, and furthermore the comparisons of NHE confirm the critical role of eccentric strength in the turn of a COD task (Harper *et al.*, 2022; Morin *et al.*, 2015). In addition, greater posterior chain energy expenditure is required by the athlete when turning sharper angles and thus have elevated metabolic costs (Hader *et al.*, 2016). The lack of interactions in this research indicates that the directional results are consistent across symmetrical and limb groupings, suggesting that angle specific challenges in COD are not controlled by baseline NHE symmetry or limb preferences of the athletes. Thus, the 15 m entry distance performed in this research may not reach the approach velocities which may significantly reveal differential impacts as COD biomechanics have been known to influence under greater variable sprint conditions (Dos'Santos *et al.*, 2018; Dos'Santos *et al.*, 2021).

Regarding the non-significant findings for symmetrical grouping, it is pertinent to consider that symmetries in athletic performance are inherently test specific. Previous research has found this by indicating how bilateral asymmetries in one metric or task do not necessarily correlate with those in another (Bishop *et al.*, 2022). Such as the asymmetries observed in the eccentric hamstring strength from the NHE may not directly relate to the dynamic COD task or the MDSA method. This emphasises the task dependency of inter-limb balance as well as the potential limitation of generalising symmetry from isolated tests to multi-planar movements (Virgile & Bishop, 2021). This is consistent with the results of this study, where NHE-derived symmetries failed to influence COD outcomes, suggesting that practitioners should assess symmetries across multiple modalities to capture a comprehensive profile rather than assuming transferability. University athletes with less experience as compared to elite athletes, may have greater masked interaction effects in which asymmetries impair angle-related deficits (Bishop *et al.*, 2022; Loturco *et al.*, 2022). The findings in this study emphasise the importance of angle specific training in COD programs, which particularly should focus on sharper turns that demand superior deceleration capabilities. Moreover, this is consistent with recommendations for incorporating high-intensity braking drills to mitigate performance losses (Harper *et al.*, 2019; Jones *et al.*, 2016).

Finally, the findings in this study emphasise the efficiency and proficiency of using the ART-GLM method for examining skewed athletic performance datasets. The ART preprocessing step aligns and ranks data to facilitate factorial ANOVA-like analyses on non-parametric distributions. Previous research has used a similar approach in order to evaluate relationships in non-normal data, particularly within factorial designs for repeated measures (Elkin *et al.*, 2021; Wobbrock *et al.*, 2011). This method was vital to identify the main effects and relationships across the non-parametric data. Moreover, this ensured this research was able to bypass any restrictive requirements of traditional parametric assumptions.

Practical implications

The current study further emphasises that training protocols should prioritise functional output rather than the attempt to achieve absolute bilateral symmetry (Bishop *et al.*, 2021; Dos'Santos *et al.*, 2019). Furthermore, moderate eccentric strength imbalances appear entirely compatible with refined COD ability. Practitioners and coaches should use COD drills which involve smaller angles to maximise deceleration abilities in order to mimic match requirements as well as emphasise eccentric posterior chain strength (Dos'Santos *et al.*, 2021; Harper *et al.*, 2019; Jones *et al.*, 2016). In addition, the limb-specific variances examined in this study, suggest using individual monitoring technologies such as the VALD Nordbord allow for identifying functional adaptations and mitigating compensatory overload (Bishop *et al.*, 2019; Loturco *et al.*, 2022; Arboix-Alió *et al.*, 2024). Moreover, by using a holistic method such as the MDSA along with the NHE assessments provides valuable evaluations to optimise training efficiency as well as evidence-based training for the athletes.

Limitations

Although the use of the ART preprocessing provides a robust framework for evaluating non-parametric data, the relatively small sample size of this study may lack the statistical power to successfully identify the subtle relationships in the groupings. In addition, university populations have been found to have moderate asymmetries when compared to more elite populations, in which more definite imbalances are known to degrade COD abilities (Bishop *et al.*, 2022). By utilising isolated NHE metrics, the contributions of the hamstrings and cognitive load of unanticipated turns may not be fully encompassed, which can lead to the role of limb symmetry being amplified (Dos'Santos *et al.*, 2020; Morin *et al.*, 2015). Lastly, physiological sex differences and differing sports participation experience within this mixed-gender group may have influenced the outcomes. Future studies may incorporate stratified sampling techniques to improve real-world application of the MDSA metric.

CONCLUSION

The primary objective of this study was to examine the relationships between NHE symmetry, limb-specific variances and COD sprint performance in university athletes. This research observed that limb-specific groupings yielded isolated significant differences such as higher left limb contributions to area percentage and higher peak maximum force in the right limb. This suggests that functional adaptations in force distribution may not fundamentally change an athlete's overall multidirectional ability. However, the directional grouping results showed significant differences in both acceleration and velocity, which propose increased mechanical demands are required to change direction at sharper angles. This effect seems to be independent of the athlete's symmetry profile as well as limb dominance. While a lack of significant differences in the symmetrical grouping may indicate that for university-level athletes, the bilateral symmetry in their eccentric hamstring strength may not be a primary determinant of MDSA performance.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. G.G. and A.G. were responsible for the conceptualisation of the project. Data collection was conducted by G.G., while data analysis and interpretation were carried out by both G.G. and A.G. The manuscript draft was completed by G.G. Both authors contributed to the review and incorporation of comments. Supervision of the project was provided by A.G. All authors have read and agreed to the published version of the manuscript. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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 work the author(s) used Google Gemini in order to assist with finding redundancies and refining sections. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

INSTITUTIONAL REVIEW BOARD STATEMENT

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Faculty of Health Sciences, Research Ethics Committee) of The University of Johannesburg (REC-1359-2022, 26 January 2022).

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study.

DATA AVAILABILITY STATEMENT

The original contributions presented in this study are included in the article. Data are available upon reasonable request from the corresponding author.

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Effects of a general warm-up on anaerobic exercise performance in power and endurance athletes

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ABSTRACT

Purpose: The purpose of this study was to compare the effects of a general warm-up (GWU) on anaerobic exercise performance between power and endurance athletes. **Methods:** Twenty male power athletes and twenty male endurance athletes participated in this study. The participants performed 20 minutes of cycling at 60% of their predicted maximum heart rate as a GWU. Their anaerobic exercise (countermovement jump [CMJ] and 6-second sprint cycling [SC]) performance was assessed before and after the GWU. **Results:** A significant interaction effect (group $\times$ time) was observed in CMJ height ($p = .041$). The endurance athletes showed a significant improvement in CMJ height after the GWU ($p < .001$), whereas the power athletes did not ($p = .794$). No significant interaction effects were observed in mean power ($p = .957$) and peak power ($p = .197$) during the SC. **Conclusion:** These results suggest that training history influences the effect of a GWU on anaerobic exercise performance, and endurance-trained individuals may benefit more from the GWU consisting of continuous cycling. Furthermore, these findings demonstrate that a one-size-fits-all warm-up cannot optimize an athlete's performance and emphasize the necessity of designing warm-up programs tailored to their training history.

Keywords: Performance analysis, Countermovement jump, Sprint cycling, Performance enhancement.

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INTRODUCTION

It is widely accepted that athletes need to warm up before competitive exercise to optimize their performance. A typical physiological effect of a warm-up is an increase in muscle temperature, which has been associated with increased muscle metabolism (Gray et al., 2011) and muscle fibre conduction velocity (Pearce et al., 2012). Enhanced performance after a warm-up is primarily attributed to physiological mechanisms resulting from this elevated muscle temperature. In anaerobic exercise such as vertical jump and sprint cycling, a 1°C increase in muscle temperature has been reported to enhance the performance by 2–5% (Racinais & Oksa, 2010).

However, it has been noted that there is substantial inter- and intra-individual variability in responses to warm-up (Afonso et al., 2024). Thus, for athletes and their coaches, understanding the individual characteristics that influence the effect of warm-up on exercise performance is crucial for designing individualized warm-up programs. Post-activation performance enhancement, observed shortly after brief, high-force contractions (Cuenca-Fernández et al., 2017), has been shown to be greater in individuals with more extensive training experience (≥ 2 years) (Xu et al., 2025). In contrast, there is limited information on the individual characteristics that influence the effect of a general warm-up (GWU). A GWU typically involves light-intensity aerobic exercise (e.g., cycling and jogging) and is intended to increase the temperature of the major muscle groups involved in the primary exercise (Bishop, 2003). Given that a GWU is one of the most widely performed routines for enhancing athletic performance, it is meaningful to investigate individual characteristics that influence its effect.

Skeletal muscle fibre composition may be an important individual characteristic that modulates the effect of a GWU on anaerobic exercise performance. In high cadence (160–180 rpm) cycling exercise, passively increasing muscle temperature enhances the utilization of creatine phosphate and adenosine triphosphate in type IIA fibres, leading to improved maximum power (Gray et al., 2008). In addition, the temperature coefficients of maximum and average power reportedly correlate with the percentage of type IIA fibres (Gray et al., 2006). This suggests that in exercises demanding fast muscle contractions, individuals with a greater percentage of type IIA muscle fibres may derive greater benefits from passive muscle warming. This is likely because type II fibres contribute more to power output than type I fibres during high-speed movements (Sargeant, 1994). Furthermore, continuous endurance training increases the percentage of type I fibres and decreases type IIA fibres (Bathgate et al., 2018). Conversely, sprint and resistance training have been shown to increase the percentage of type IIA fibres while decreasing or maintaining type I fibres (Andersen et al., 1994; Liu et al., 2003). Consequently, power athletes, who typically possess a high percentage of type IIA muscle fibres due to long-term sprint and resistance training, are more likely to benefit from a GWU that increases muscle temperature compared to endurance athletes.

However, to our knowledge, no studies have directly investigated the influence of training history on anaerobic exercise performance after a GWU. Previous research related to this issue has shown that, after performing 10 minutes of intermittent contractions at 50% of the maximum voluntary contraction (MVC) of the knee extensor muscles, power athletes exhibited a more significant decrease in knee extension force during the MVC than endurance athletes (Morana & Phane Perrey, 2009). These results likely occur because endurance athletes have a higher percentage of type I fibres, which are more resistant to fatigue (Tesch & Karlsson, 1985). On the other hand, minimizing fatigue is important for an effective warm-up, and a GWU of 10–20 minutes at an intensity less than 60% of maximum oxygen intake (VO_{2max}) has been proposed (Bishop, 2003). Thus, further research is needed to clarify the effect of a GWU with appropriate intensity on anaerobic exercise performance of individuals with different training histories.

Therefore, this study investigated the influence of training history on anaerobic exercise performance after a GWU at an appropriate intensity. We hypothesized that power athletes would show a greater improvement in anaerobic exercise performance than endurance athletes after the GWU.

MATERIAL AND METHODS

Participants

Twenty male power athletes (age: 19.5 years [19.0–20.0 years], height: 1.74 m [1.70–1.78 m], body mass: 68.5 kg [64.6–71.1 kg], body mass index: 22.6 [21.6–23.2]) and twenty male endurance athletes (age: 20.5 years [19.8–22.0 years], height: 1.71 m [1.67–1.72 m], body mass: 57.7 kg [55.9–60.0 kg], body mass index: 19.9 [19.2–20.6]) without musculoskeletal and cardiovascular injuries participated in the study. The power athletes were competitive sprinters in the 100 m, 200 m, or 110 m hurdles (sprint training experience: 7.0 years [5.8–8.0 years], average training frequency in the last 3 months: 5.0 times/week [5.0–5.0 times/week], average duration of single training session in the last 3 months: 180 min/session [150–180 min/session], World Athletics score (Spiriev & Spiriev, 2025): 922 points [888–984 points]), while the endurance athletes were competitive runners in the 5000 m and 10000 m (long-distance running training experience: 9.0 years [6.8–10.0 years], average training frequency in the last 3 months: 13.0 times/week [13.0–13.0 times/week], average duration of single training session in the last 3 months: 95 min/session [90–120 min/session], World Athletics score: 827 points [729–889 points]). All participants had experience with jumping and cycling exercises. Prior to the experiment, the participants were informed of the procedures, benefits, and potential risks of the study. They then signed an institutionally approved informed consent document to participate in the study. This study was approved by the Ethics Review Committee of the University of Tsukuba (No. 024-59, approval date: December 20, 2024).

Measures

The participants performed the countermovement jump (CMJ) and the sprint cycling (SC) twice each before and after the GWU. The CMJ was performed on a force plate (Ex-Jumper, DKH Co., Tokyo, Japan), and ground reaction force data were sampled at 1000 Hz. Jump height was calculated from the ground reaction force data using an Excel analysis file created by Chavda et al. (Chavda et al., 2018). After completing the CMJ trials, the participants performed the SC on a cycle ergometer (Power Max VIII, KONAMI Co., Ltd., Tokyo, Japan). The average and peak power values shown on the ergometer display after the SC were recorded.

Heart rate data during the GWU was collected by attaching a heart rate monitor (Polar H10, Polar Electro Oy., Kempele, Finland) to the chest at a sampling frequency of 1 Hz. The average power during the GWU shown on the cycle ergometer (Wattbike Pro, Wattbike Ltd., Nottingham, United Kingdom) display was recorded. The participants rated their perceived exertion (RPE) for the lower limb muscles (RPE-LM) and respiratory system (RPE-RS) on a scale of 1 to 10 (Foster et al., 2001; Romarateabala et al., 2018) after the GWU.

Procedures

All procedures were conducted in a temperature-controlled laboratory (room temperature $21.3 \pm 0.75^{\circ}\text{C}$) between 8:00 AM and 7:00 PM. The participants were instructed to avoid strenuous physical activity, caffeine and alcohol for 24 hours prior to the test. After arriving at the laboratory and receiving a thorough explanation of the anaerobic exercise performance tests and the GWU, the participants put on athletic shoes and clothing. Their anaerobic exercise performance was then assessed before and after the standardized GWU.

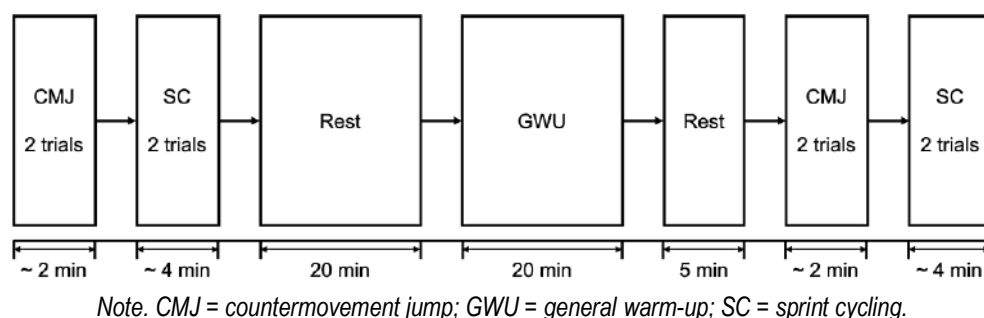


Figure 1. Schematic representation of the study design and testing procedures.

The participants performed the CMJ and the SC twice each before and after the GWU. Each CMJ was performed with the participant's hands on their hips to eliminate the influence of arm swing. The depth of squatting during the CMJ was not restricted. Before the first CMJ trial, the participants were given a visual demonstration and instructed to jump as high as possible. To establish a baseline force for each CMJ trial, the participants were instructed to stand still on the force plate for two seconds after data collection began. The participants rested for one minute between the first and second CMJ trials. At each time point, the trial with the greater CMJ height was analysed. Three minutes after completing the two CMJ trials, the participants performed the SC on a cycle ergometer with the load set at 7.5% of body mass (Gray et al., 2006). The saddle was adjusted to an optimal position for each participant and maintained at this height for all subsequent trials. Both feet were secured to the foot pedals with belts. The participants were instructed to remain seated and pedal at maximum effort for six seconds. A three-minute rest period was provided between the first and second SC trials. At each time point, the trial with the higher average power was analysed.

After completing the anaerobic exercise performance tests, the participants rested in a seated position for 20 minutes. Following the rest period, the participants adjusted the saddle of the cycle ergometer (Wattbike Pro, Wattbike Ltd., Nottingham, United Kingdom) in preparation for the GWU. During the GWU, the participants cycled for 20 minutes at a pedalling cadence of 60–70 rpm, targeting an intensity of approximately 60% of their predicted maximum heart rate ($HR_{max} = 208 - [0.7 \times \text{age}]$) (Tanaka et al., 2001). While maintaining this cadence, the pedal load was adjusted to achieve the target intensity of 60% HR_{max} . The duration and intensity of the GWU were selected based on previous studies showing that it caused minimal depletion of high-energy phosphates (Karlsson et al., 1970) and increased muscle temperature by 2–3°C (Cunha et al., 2010; Saltin et al., 1968). Five minutes after completing the GWU, the participants rated their RPE-LM and RPE-RS.

Analysis

G*Power software (version 3.1.9.6, University of Kiel, Kiel, Germany) was used to calculate the sample size needed for this mixed-design study (Faul et al., 2007). A minimum sample size of 17 per group was required to reach a statistical power level ($1 - \beta$) of 0.80 based on an α level of .05 and a predicted effect size of .25. The Shapiro-Wilk test was used to evaluate the distribution of all variables. As some variables were not normally distributed, a two-way (group $\times$ time) mixed-design nonparametric analysis of variance was used to examine changes in anaerobic exercise performance variables before and after the GWU between the power and endurance athletes (Wobbrock et al., 2011). When a significant interaction effect was found, the Wilcoxon signed-rank test was used to compare anaerobic exercise performance variables before and after the GWU within each group. The Mann-Whitney U test was used to examine the differences in average power during the GWU and RPE between the two groups. The intraclass correlation coefficient (ICC) was calculated to assess the reliability of the data obtained from the anaerobic exercise performance tests at each time point.

within each group. The statistical significance level was set at $p < .05$. All data are presented as medians (interquartile ranges). Effect size (r) was calculated to assess the magnitude of change within groups and differences between groups. The Hodges–Lehmann estimator was calculated to determine the median differences between the first and second attempts both before and after the GWU, along with their corresponding confidence intervals. In addition, the estimator was used to quantify the median difference between the before and after the GWU and its confidence interval. All statistical analyses were performed using statistical software (IBM SPSS Statistics ver. 28.0, IBM Corporation, Armonk, USA).

RESULTS

Table 1 shows the results of the within-group reliability tests for the anaerobic exercise performance variables at each time point. All performance variables showed high reliability (ICC = 0.879–0.965).

Table 1. Reliability of anaerobic exercise performance tests.

Test	Variables	Groups	Before		After	
			ICC (95%CI)	Hodges–Lehmann estimator (95%CI)	ICC (95%CI)	Hodges–Lehmann estimator (95%CI)
CMJ	Jump height (m)	Power athletes	0.917 (0.807–0.966)	0.011 (0.001–0.020)	0.879 (0.725–0.950)	0.008 (0.003–0.013)
		Endurance athletes	0.931 (0.836–0.972)	0.009 (0.002–0.014)	0.948 (0.876–0.979)	0.004 (-0.003–0.010)
SC	Average power (W)	Power athletes	0.858 (0.682–0.811)	32 (11–51)	0.893 (0.753–0.956)	18 (2–33)
		Endurance athletes	0.800 (0.568–0.915)	25 (8–43)	0.966 (0.917–0.986)	7 (-3–17)
	Peak power (W)	Power athletes	0.914 (0.799–0.965)	32 (24–40)	0.965 (0.914–0.986)	18 (12–23)
		Endurance athletes	0.949 (0.878–0.979)	22 (13–28)	0.957 (0.897–0.983)	7 (2–14)

Note. 95%CI = 95% confidence interval; CMJ = countermovement jump. ICC = intraclass correlation coefficient; SC = sprint cycling.

Table 2. Changes in anaerobic exercise performance variables after the GWU.

Test	Variables	Groups	Before	After	ES	Hodges–Lehmann estimator (95%CI)	p -value (η^2)		
			Median (IQR)	Median (IQR)			G	T	G x T
CMJ	Jump height (m)	Power athletes	0.41 (0.39–0.45)	0.42 (0.40–0.44)	0.06	0.001 (-0.007–0.010)	< .001†	.003†	.041†
		Endurance athletes	0.25 (0.23–0.30)	0.27* (0.26–0.32)	0.72	0.013 (0.006–0.023)	(.754)	(.207)	(.106)
SC	Average power (W)	Power athletes	761 (681–791)	770 (695–813)	0.40	16 (-3–32)	< .001†	.041†	.957
		Endurance athletes	501 (467–552)	506 (474–585)	0.50	12 (1–23)	(.680)	(.105)	(.000)
	Peak power (W)	Power athletes	889 (854–954)	912 (860–961)	0.37	10 (-3–26)	< .001†	< .001†	.197
		Endurance athletes	601 (564–650)	629 (589–672)	0.88	22 (15–26)	(.719)	(.336)	(.043)

Note. CI = confidence interval; CMJ = countermovement jump; ES = effect size; G = group. IQR = Interquartile range; SC = sprint cycling; T = time. * A significant difference before and after the general warm-up ($p < .05$). † A significant interaction effect, main effect of group, or main effect of time ($p < .05$).

The average power during the GWU was significantly higher in endurance athletes (136 W [119–147 W]) than in power athletes (99 W [89–115 W]) (absolute average power: $p < .001$, $r = .67$; average power relative to body mass: $p < .001$, $r = .84$).

No significant differences between groups were observed in the average heart rate during the GWU ($p = .134$, $r = .24$, power athletes: 114.6 bpm [113.8–116.2 bpm], endurance athletes: 114.0 [112.5–115.0]). The results of the anaerobic exercise performance tests are shown in Table 2.

In CMJ height, a significant interaction effect (group $\times$ time) and main effects of group and time were observed. Post hoc tests revealed that the endurance athletes showed a significant increase in CMJ height after the GWU ($p = .001$, $r = .72$), whereas no significant change was observed for the power athletes ($p = .794$, $r = .06$).

Both average and peak power during the SC showed significant main effects of group and time, but no significant interaction effects.

No significant differences between groups were observed in RPE-LM ($p = .819$, $r = .04$) and RPE-RS ($p = .932$, $r = .01$).

DISCUSSION

The purpose of this study was to investigate the influence of training history on anaerobic exercise performance following cycling at an intensity appropriate for a GWU. The hypothesis that the power athletes would show greater improvement in anaerobic exercise performance than the endurance athletes following the GWU was not supported. Instead, the endurance athletes showed greater improvement in CMJ height. Furthermore, no significant differences between groups were observed in average and peak power during the SC. These results suggest that factors other than muscle fibre composition have a greater influence on the performance-enhancing effect of a GWU.

Many studies have demonstrated the positive effect of increasing muscle temperature on anaerobic exercise performance (Bergh & Ekblom, 1979; Sargeant, 1987; Tsurubami et al., 2020). Additionally, a study examining internal factors that modulate changes in exercise performance associated with increases in muscle temperature reported that individuals with a higher percentage of type IIA fibres showed greater improvements in anaerobic exercise performance with increases in muscle temperature (Gray et al., 2006). However, this finding was observed when muscle temperature was passively increased using hot water and electric blankets, and no studies have investigated whether similar results can be observed when muscle temperature is increased through active warm-up. To our knowledge, the present study is the first to address this issue.

A potential factor explaining the discrepancy between our results and the hypothesis may be the varying resistance to motor pattern interference caused by continuous exercise. Previous studies reported that preceding movement tasks have a negative impact on the performance of a subsequent task (Kay & Blazeovich, 2009; Marquez et al., 2009). Specifically, there was no decrease in isometric ankle joint moment after MVC, but the peak concentric moment was significantly reduced (Kay & Blazeovich, 2009). This reduction was accompanied by, and correlated with, significant reductions in peak triceps surae electromyographic amplitude. In addition, it has been reported that CMJ height decreased after 15 minutes of cycling at an intensity of approximately 140 bpm, which may be due to changes in the activation pattern of the lower limb muscles (Marquez et al., 2009). To our knowledge, there are no studies showing that endurance athletes are less affected by motor pattern interference than power athletes. However, a previous study on triathletes suggested that changes in respiratory and circulatory responses and running patterns after cycling vary depending on the competitive level of the participants (Millet et al., 2000). Furthermore, it has been reported

that when marathon runners completed a 30 km trial and performed CMJ every 5 km, the CMJ height was highest at the 25 km point (Del Rosso et al., 2016). This suggests that well-trained endurance athletes may be resistant to motor pattern interference caused by continuous exercise, ensuring that the positive effect of the GWU on CMJ performance is not obscured. However, to our knowledge, there is no direct evidence that endurance training can suppress motor pattern interference after continuous exercise. Thus, further research is warranted to elucidate the effect of endurance training on changes in movements and muscle activation patterns during anaerobic exercise after continuous exercise.

Based on previous research found no difference in maximum heart rate between power athletes and endurance athletes (Whyte et al., 2008), this study applied the same estimation formula (Tanaka et al., 2001) to calculate maximum heart rate for all participants, setting the relative intensity of the GWU equally for both groups. In fact, there was no significant difference between the groups in RPE after the GWU. However, the average power during the GWU was higher in endurance athletes than in power athletes. This difference in power output could have led to different changes in muscle temperature between the two groups. In addition, a previous study (Racinais & Oksa, 2010) has demonstrated a strong association between muscle temperature and anaerobic exercise performance. Therefore, if the difference in average power during the GWU affects muscle temperature, this could adequately explain why the endurance athletes show greater improvements in anaerobic exercise performance than the power athletes. However, some studies have shown that muscle temperature increases depending on relative exercise intensity rather than absolute exercise intensity (Saltin et al., 1968; Saltin & Hermans, 1966). Therefore, although we could not measure muscle temperature due to equipment limitations, it is unlikely that the difference in average power during the GWU caused a significant difference in muscle temperature changes between the groups.

This study has several limitations. First, the study was limited to verifying the effect of a cycling warm-up. Additional studies for other types of dynamic warm-ups would contribute to designing individualized warm-up programs. Furthermore, since the study was limited to male sprinters and long-distance runners, it is unclear whether the results can be applied to athletes in other sports or to female athletes. Conducting research on them could deepen our understanding of the influence of training history on warm-up effectiveness.

CONCLUSIONS

This study demonstrates that an individual's training history influences the effect of the GWU on anaerobic exercise performance, and individuals who regularly engage in endurance training may benefit more from the GWU. These findings suggest that the performance-enhancing effect of the GWU is not solely determined by muscle fibre composition but may also be associated with neuromuscular factors, such as resistance to motor pattern interference induced by continuous exercise. These findings indicate that a one-size-fits-all warm-up cannot optimize athletes' performance and emphasize the importance of individualized warm-up according to an athlete's training history. This research provides the fundamental knowledge necessary to shift from a uniform approach to designing individualized warm-up programs.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. N. Ushirooka, K. Muratomi, H. Maemura, S. Tanigawa contribute to the research concept and study design; N. Ushirooka, K. Muratomi, S. Tanigawa performed literature review and the experiment data collection; N. Ushirooka performed statistical analysis; N. Ushirooka, K. Muratomi, H. Maemura, S. Tanigawa contribute to data

interpretation; N. Ushirooka wrote the manuscript; K. Muratomi, H. Maemura, S. Tanigawa revised the manuscript. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Anticipation performance and perceptual-cognitive training effect on anticipation skills in tennis serve return across youth age groups: A pilot exploratory study

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ABSTRACT

While perceptual training can be effective in developing anticipation skills, it is not commonly incorporated into tennis practice sessions, especially for young players. This pilot exploratory intervention study aimed to assess the effect of perceptual-cognitive training based on video recordings of tennis serves modified by temporal occlusion on development of anticipatory skills in expert tennis players of various age categories, i.e. U12, U14, U18 and adults. A total of 19 participants were divided into intervention and control group based on the age. We used pre and post-test design with temporal occlusion design. The intervention group underwent a 3-week video-based perceptual-cognitive training program. Pre-tests results revealed that adults and U18 category reached better response rate compared to U14 and poor result of U12. After applying the perceptual-cognitive training, the results demonstrate its effect and improvement across all age categories. The U12 category showed considerable improvement, with both the U12 and U14 categories reaching the performance level of the U18 and adult participants in the post-test under the T4-T6 occlusion condition. Respecting the sample size, video-based perceptual training could be effective way to improve anticipation skills and performance even in young tennis players. However, further investigation in this area is needed to gain a deeper understanding.

Keywords: Performance analysis, Advance information, Temporal occlusion, Visual search, Perception, Decision-making.

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INTRODUCTION

Players across different ages and skill levels develop varying degrees of perceptual and anticipatory abilities, which can significantly influence their overall performance in sport games (Abernethy & Zawi, 2007; Shim et al., 2006). In tennis and other fast-paced sports, the speed of the ball imposes strict time constraints on athletes' sensory perception and motor responses. Decisions must be made within milliseconds, with high accuracy, and under constantly changing temporal and spatial conditions (Müller et al., 2006). Perceptual-cognitive training can serve as a standard training method that provides athletes with repeated exposure to specific situations, both on the field and off it (e.g., when physical training is not possible due to injury or illness).

Perceptual-cognitive training involves using sport-specific visual information to make decisions, thereby enhancing performance through improved visual anticipation—predicting outcomes based on advance information, such as an opponent's movements (Broadbent et al., 2015). Beyond anticipation and decision-making, this training also develops additional perceptual-cognitive skills, including pattern recognition and the perception of contextual and situational information, which inform decision processes (Abernethy et al., 2005). During competition, athletes must extract relevant information while ignoring irrelevant details (Goldstone, 1998). Compared to novices, expert players can better detect and use both contextual and kinematic information to make accurate predictions (Abernethy & Zawi, 2007; Shim et al., 2006; Williams & Jackson, 2019). Contextual information may be visual (e.g., opponent positioning) or non-visual (e.g., score, wind) (Vernon et al., 2018). Kinematic information during a tennis serve includes movements of the server's body segments, the racket, or the ball toss. These cues appear before racket-ball contact, followed by key kinematic information from the initial ball-flight phase (Morris-Binelli et al., 2020).

Perceptual-cognitive training frequently uses video simulations of sport-specific situations, such as the tennis serve-return. After watching these videos, athletes are required to predict or decide the next event based on the observed visual information. The footage is typically filmed from the player's perspective and edited using temporal occlusion (Brenton et al., 2019). Temporal occlusion interrupts the video at predefined kinematic moments (e.g., during the server's motion or early ball flight), limiting access to visual information at critical points. Its purpose is to control the timing of available visual cues and determine when athletes extract information needed for anticipation (Williams et al., 2011).

The effectiveness of temporal-occlusion-based perceptual training on anticipation skills has been demonstrated in various sports games (Abernethy et al., 1999; Fadde, 2006; Murgia et al., 2014). Athletes undergoing visuomotor or visual-perception interventions were able to capture advance information and showed improved anticipation by identifying key details earlier in post-tests and transfer tests (Brenton et al., 2019). These findings indicate that players can benefit from video-based training and that the skills learned can transfer to real-game performance. Moreover, the research supports extensive evidence showing that experts are better than novices at extracting information from advance cues to make predictions.

Despite evidence that expert players use the opponent's early movement patterns, including the ball toss during the serve (Murray & Hunfalvy, 2017; Ward et al., 2002; Williams et al., 2002) to anticipate actions, there is a lack of research focusing on highly skilled younger athletes in temporally constrained situations such as the serve-return in tennis. Weissensteiner et al. (2008) has shown that athletes under 15 years old can extract advance information for prediction, yet there is limited evidence of how highly skilled younger athletes use such information in practice. Moreover, it remains unclear whether these abilities can be systematically enhanced through structured perceptual-cognitive training in junior expert populations.

Underdeveloped ability to detect and apply advance information from an opponent's movements may be a performance-limiting factor for younger players, highlighting the need to address this component of performance in training. Previous studies (Gabbett et al., 2007; Hopwood et al., 2011; Maman et al., 2011; Williams et al., 2003) have demonstrated the effectiveness of video-based perceptual training with temporal occlusion in enhancing anticipation skills, but they primarily included adult populations, leaving the developmental trajectory and trainability of junior experts (U12–U18) largely unexplored. Consequently, age-related differences in responsiveness to perceptual-cognitive training remain insufficiently examined. The aim is to assess the effect of perceptual-cognitive training based on video recordings of tennis serves modified by temporal occlusion on development of anticipatory skills in expert tennis players of various age categories, i.e. U12, U14, U18 and adults. Given the pilot nature of the study, it was expected that the intervention group would show greater pre–post improvements in anticipatory performance than the control group, with possible age-related differences.

MATERIAL AND METHODS

Participants

Nineteen participants (ten male and nine female) voluntarily agreed to take part in this experiment, based on convenience sampling. The study was designed as a pilot-controlled pre–post intervention. Participants were allocated to intervention (IG) and control (CG) groups using age-stratified assignment procedures to ensure a balanced distribution across age categories: U12, U14, U18, and adults. Both groups completed pre- and post-testing, while the intervention group additionally undertook a three-week perceptual-cognitive training program. The IG consisted of 3 U12 participants, 2 U14, 2 U18, and 2 adults. The CG included the same number of participants in each age category, except for the U12 group, which had 4 participants. The mean age of all participants was 16.5 ± 6.4 years, and they had been playing tennis for 10.4 ± 6.2 years. These participants had represented in international performance tennis or were national players playing in international tournaments. Their mean ranking in the national ranking of the Czech Republic in their age category was 33.0 ± 40.6 . An a priori power analysis using G*Power indicated that a total of 34 participants would be required to detect a medium effect ($f = .25$) for the group $\times$ time interaction with $\alpha = .05$ and power = .80. The present sample of 19 participants therefore represents a pilot-level investigation. The Ethics Committee at the Faculty of Physical Education and Sport, at Charles University approved this study in accordance with the Declaration of Helsinki. All participants or their adult representatives were informed of the risks and benefits of the study and provided written informed consent prior to participating.

Methods and procedures

The pretest, perceptual training, and post-test involved watching edited video recordings of tennis serves from the perspective of the receiving player. Temporal occlusion was applied by prematurely ending the video recordings—blacking out the screen at predefined moments (Figure 1)—to create video sequences of varying durations that provided differing amounts of visual information related to the server's action kinematics.

We created two sets of video sequences: one for testing (pretest and post-test) and one for training (intervention). Two 17-year-old right-handed servers, each with over 12 years of tennis experience and regular participation in international tournaments (mean ITF Juniors ranking 228.5 ± 67.5), were recorded using an iPhone 14 Pro Max (30 fps) and a Canon EOS 4000D (30 fps). A tripod-mounted camera was positioned at the typical location and mean body height of a receiving player (these recordings served only as feedback for the intervention group). A second camera was placed on the server's side, 1 m inside the service line toward the net, aligned between the server and the first camera. This second camera captured the server's full action and the ball's trajectory.

From 58 recorded serves from the deuce court, 12 representative serves (six per server) were selected by an expert tennis coach with over 10 years of coaching experience and prior competitive playing experience at the national level. The selected serves included all three types of first serves (flat, slice, kick), landing legally within the service box either close to the T (junction of the service line and centre line) or wide (near the sideline). Each video was edited to begin with the server's preparation phase and initial stance and then was prematurely terminated at one of the designated occlusion moments with a five-second blackout. Each serve type was occluded at six specific moments (Figure 1). In total, 72 video sequences (12 serves $\times$ 6 occlusion conditions) were created. Video files containing these sequences were then assembled in an identical randomized order for the pretest and post-test, and in a different randomized order for the intervention training.

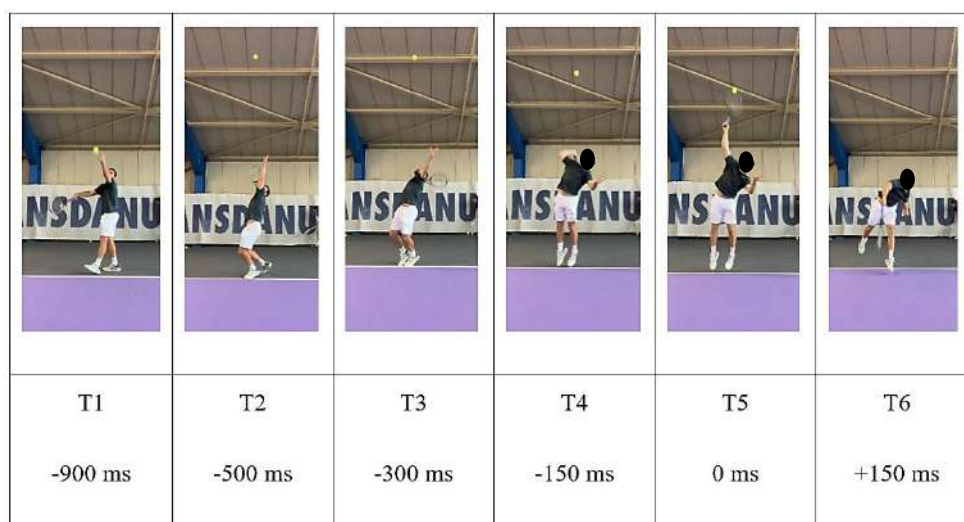


Figure 1. Occlusion points in the video sequences. The T5 (0 ms) condition represents the moment of racket–ball contact.

Pretest

After receiving instructions about the tasks and testing conditions, participants completed the pretest. They were not familiar with the servers featured in the video recordings. The pretest included four practice trials with occlusion and four without occlusion to familiarize participants with the task requirements. The pretest consisted of 72 sequences presented in random order and without sound. Participants were required to watch the videos and respond as quickly as possible by simulating either a forehand return shot (if the serve was aimed wide) or a backhand return shot (if the serve was aimed to the T).

The video sequences were displayed on a screen with a 139 cm diagonal. Participants stood in their normal receiving position with a tennis racket, 4 m from the screen, ensuring that the viewing angle was approximately 6°, corresponding to an in-situ spatial situation. A 6-minute break was provided after 36 trials (i.e., halfway through the test). Participants' responses were recorded on prepared response sheets. The entire pretest lasted approximately 20 minutes.

Intervention

Participants assigned to the intervention group completed 12 perceptual-cognitive training sessions (four times per week over three weeks) in addition to their regular tennis and fitness training between the pretest and post-test (Brenton et al., 2019; Farrow et al., 2005; Müller & Abernethy, 2014). Perceptual training

consisted of watching pretest videos on a tablet or TV screen, supplemented with serve-outcome feedback (i.e., after each occluded sequence, the full server action was shown without occlusion, including the ball trajectory and landing point in the service box). Each training session lasted 14 minutes and included 144 video sequences (72 occluded trials plus full-length feedback videos for each occlusion condition). Before starting the intervention, participants were instructed to: i) watch the video recordings on a screen with a diagonal of at least 25 cm; ii) perform a motor response to each occluded sequence by simulating a forehand or backhand return shot based on the predicted serve outcome (T or wide). By completing all 12 training sessions, participants in the intervention group viewed a total of 864 occluded video sequences, including 144 sequences for each occlusion condition.

Post-test

Two days after completing the intervention, all participants undertook the post-test, which was identical to the pretest.

Statistical analysis

The dependent variable was the response accuracy of participants' motor responses when estimating the correct location of the tennis serve in each occlusion condition. A correct motor response involved simulating a forehand or backhand return shot corresponding to the server's intended direction. Relative correctness was calculated as the proportion of correct responses out of all responses for a given occlusion condition for each participant. This value ranged from 0 to 1 (e.g., 0.60 = 60% accuracy). Due to the small subgroup sizes and potential violations of normality assumptions, non-parametric statistical procedures were applied.

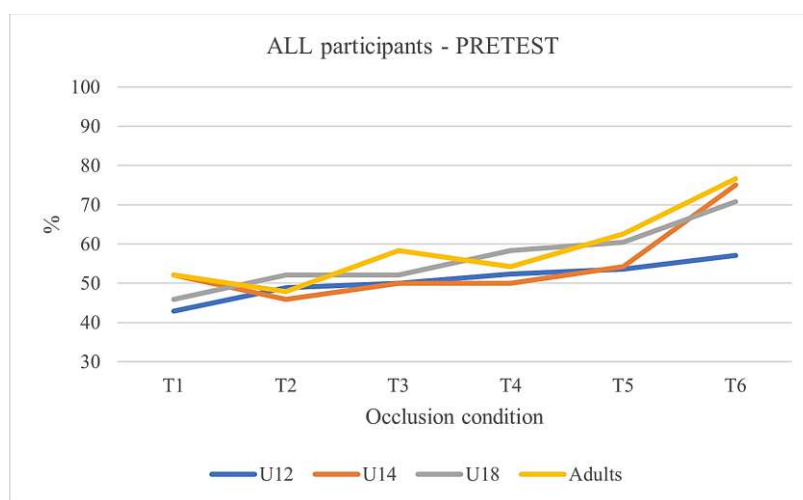
To examine differences in pretest performance across age categories (U12, U14, U18, adults), pooled results from T1–T6 were analysed using the Kruskal–Wallis test. Where appropriate, exploratory pairwise comparisons were conducted using Mann–Whitney U tests. Within-group pre–post comparisons (intervention and control groups separately) were performed using the Wilcoxon signed-rank test. To assess the group $\times$ time interaction effect, change scores (post-test minus pretest values) were calculated for each participant and compared between the intervention and control groups using the Mann–Whitney U test. The data were compared against a 50% guessing level, as only two response options were available. Effect sizes (r) were reported for Mann–Whitney U and Wilcoxon signed-rank tests to support interpretation of practical relevance. Additionally, performance accuracy was descriptively compared against a 50% guessing level, reflecting chance performance when only two response options were available. Due to the small subgroup sizes, statistical findings were interpreted alongside effect sizes and descriptive patterns.

RESULTS

As an initial overall performance of anticipation skills, we present the pretest results of both CG and IG together, with the respect to specific age categories. We observe (Figure 2) comparable correct responses in the early occlusion conditions T1–T4 across all age categories, adults who achieved most successful results in T3 condition from all categories and improved performance in T5 and T6 conditions except U12 category. Although the overall Kruskal–Wallis test was not statistically significant, exploratory pairwise Mann–Whitney U comparisons indicated a possible difference between the U12 and adult categories ($U = 669.5$, $p = .023$, $r = .27$). Given the exploratory and pilot nature of the study, these findings should be considered preliminary.

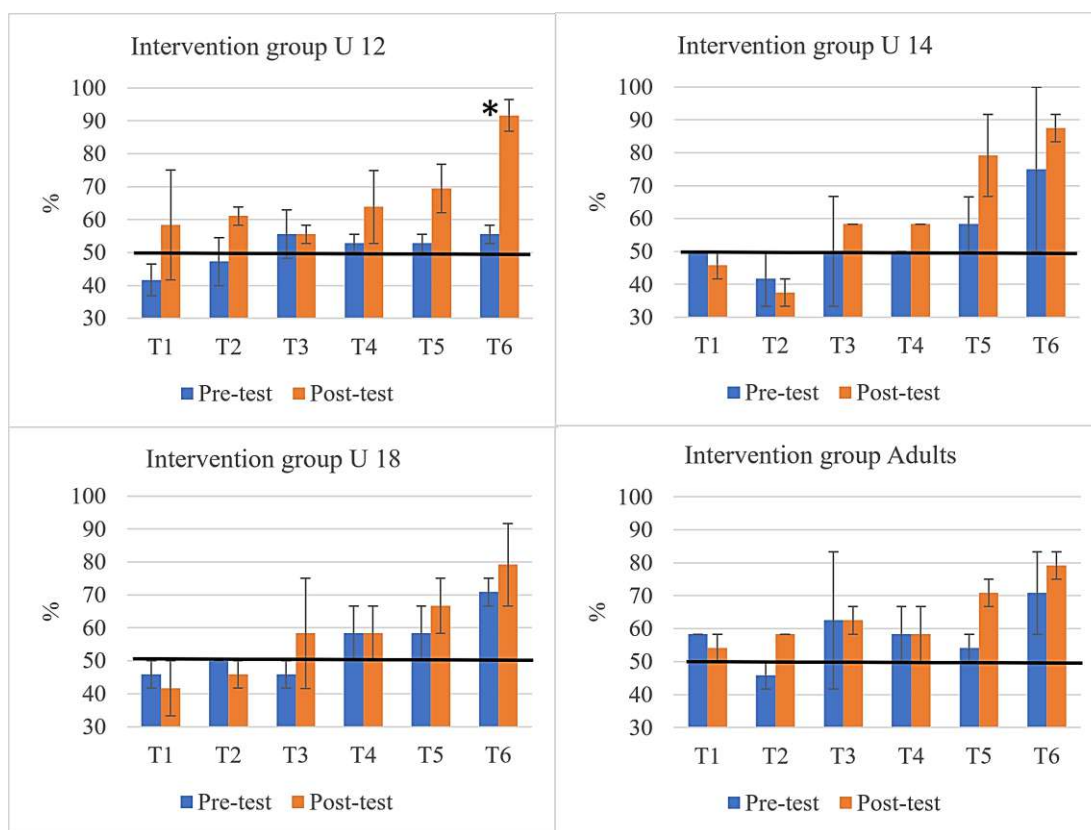
Next, some findings were observed in the pre- and post-test results of the IG (Figure 3) and CG (Figure 4). Using the Mann–Whitney U test to assess the group $\times$ time interaction, non-parametric analyses revealed a

statistically significant effect only in the U12 category under the T6 condition ($U = 0.0$, $p = .048$), indicating greater improvement in the intervention group compared to the control group. No other age categories or occlusion conditions reached statistical significance.



Note. 50 % guess line is highlighted.

Figure 2. Results of all participants performance during pretest.



Note. *Significant group $\times$ time interaction in U12 under T6 ($p < .05$). The 50% guessing level is indicated by the horizontal line. Error bars represent $\pm$ standard error of the mean (SEM).

Figure 3. Intervention group results of pre- and post-test comparisons by age category.

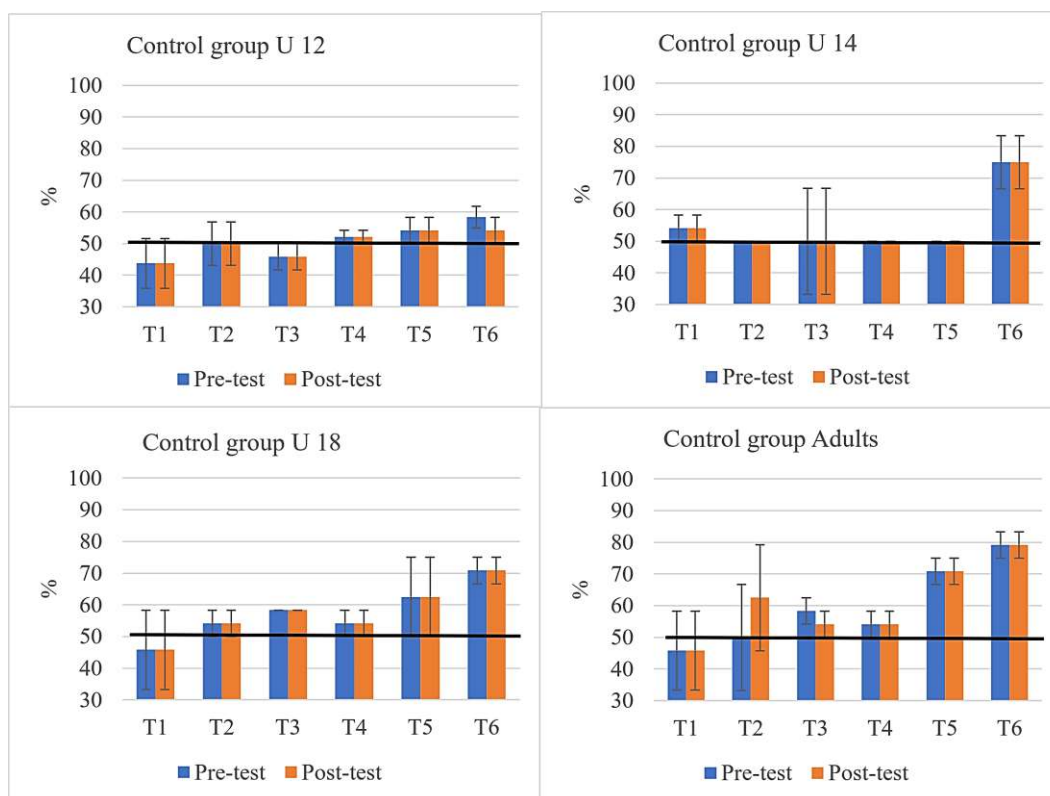
Table 1. Relative percentage values of IG improvement after the intervention.

	T1	T2	T3	T4	T5	T6
U12	16.7	13.9	0	11.1	16.7	36.1
U14	-4.2	-4.2	8.3	8.3	20.8	12.5
U18	-4.2	-4.2	12.5	0	8.3	8.3
Adults	-4.2	12.5	0	0	16.7	8.3

Note. All values are in %. The bold values represent an improvement in performance of over 10% and a success response rate exceeding 60% simultaneously.

The CG reached almost identical results in the pre- and post-test, with U18 and adults had better performance in T5 and T6 occlusion conditions compared to U12 and U14. Within-group pre-post comparisons using the Wilcoxon signed-rank test did not reveal statistically significant changes in either the intervention or control group across any age category or occlusion condition. Interestingly, U12 performance at T6 remained similarly poor (close to 50%) in the IG pretest and CG pre- and post-test. The intervention program showed an effect in IG post-test results.

When evaluating descriptive results based on relative percentages, improvements in correct responses were already observed in the T4 condition in U12; however, the largest improvements occurred in T5 and T6 (for details see Table 1). All age categories improved under T5 and T6, with the greatest relative improvement observed in U12 and U14. In particular, a pronounced improvement was observed in U12 under the T6 condition. Despite this, these results should be interpreted cautiously given the small sample size and should be considered exploratory trends rather than statistically confirmed effects. The present findings should be interpreted as preliminary evidence requiring confirmation in larger controlled investigations.



Note. The 50% guessing level is indicated by the horizontal line. Error bars represent ± standard error of the mean (SEM).

Figure 4. Control group results of pre- and post-test comparisons by age category.

DISCUSSION

The aim was to assess the effect of perceptual-cognitive training of tennis serves modified by temporal occlusion on the development of anticipatory skills in expert tennis players of various age categories. Given the pilot nature of this investigation, we observed descriptive indications that older and more experienced players demonstrated higher initial anticipatory performance. The perceptual-cognitive training was associated with improvements in anticipatory performance across age categories; however, statistically supported effects were primarily observed in the youngest players under late occlusion conditions. In particular, relative improvements were most apparent in the previously less-developed anticipatory performance of the U12 and U14 categories.

Several noteworthy findings emerged from the present results. Firstly, the IG pretest, CG pretest, and CG post-test demonstrated almost identical performance across all occlusion conditions, with participants showing comparable improvements in response accuracy as occlusion timing progressed. This pattern suggests that, in the absence of perceptual-cognitive training, performance remained relatively stable within comparable age categories. However, the IG demonstrated improved performance in the post-test. These changes may be associated with the perceptual-cognitive training intervention and are consistent with previous findings reported in the literature (Farrow & Abernethy, 2002; Maman et al., 2011).

Next, one of the most noteworthy findings was the apparent effect of the training in the U12 participants. They improved towards a level comparable to adults, particularly in the T4, T5, and especially T6 conditions. The hypothesis was only partially supported, as statistically supported group $\times$ time effects were observed primarily in the youngest category under late occlusion conditions. The T6 occlusion performance in U12 during the pretest and in the CG remained at a relatively low response accuracy compared to other age groups, suggesting that participants may have had difficulty extracting serve-direction information after ball impact. These lower results may be related to temporal constraints not being sufficiently present in U12 due to relatively lower serve speeds. Consequently, younger players may experience less pressure to rely on anticipatory cues, as they potentially have more time during serve delivery. Under such conditions, they may rely more on ball-flight information and reactive responses rather than advance perceptual cues.

However, after the intervention program, pronounced improvements were observed not only in T6 but also in the T5 racket-ball impact occlusion and the T4 pre-racket-ball impact occlusion conditions. This pattern may suggest an increased use of advance kinematic information from the server's actions, such as cues originating from the racket-shoulder region, movement patterns, and the ball toss (Carboch et al., 2018; Vernon et al., 2018), which can vary across serve types and serving locations (Abrams et al., 2014; Reid et al., 2011). Nevertheless, due to the exploratory design and limited statistical power, these interpretations should be understood as hypothesis-generating rather than confirmatory evidence of anticipatory learning.

The U12 category was not the only group affected by the intervention. Descriptive results suggested improvements across the remaining age categories as well. Performance gains were particularly visible from T5 to T6 across all groups and from T4 in the U12 and U14 categories. In these younger categories, response accuracy in the T4–T6 occlusion conditions approached levels comparable to older players. Such changes may reflect adaptations in perceptual processing strategies, potentially involving modifications in visual search behaviour, such as directing gaze toward task-relevant locations for longer durations to extract advance information (Abernethy et al., 1999; Murgia et al., 2014). However, these mechanisms were not directly measured in the present study and therefore remain interpretative. Visual search strategies may also vary substantially across individual players (Murray & Hunfalvy, 2017). The T4–T6 IG post-test results,

particularly the improvement observed in U12 and U14, may indicate that anticipatory performance can respond to relatively short perceptual-cognitive interventions even in younger players, thereby extending previous observations reported by Weissensteiner et al. (2008).

However, it should also be considered that the older categories entered the study with greater playing experience and therefore demonstrated improvements as well. With respect to the results, response accuracy from the T4 occlusion onward did not drop below the 50% guessing level across age categories, and in the IG post-test a similar pattern was already observable from the T3 condition compared to earlier occlusions (T1–T3). Even though the overall magnitude of improvement was modest, the absence of performance decline below the 50% level may indicate that participants were occasionally able to utilize limited advance information, preventing performance from falling to chance level. In general, the IG results suggest improved performance in serve anticipation tasks. In some cases, players may have relied on earlier available kinematic cues, potentially allowing responses to be initiated earlier within the occlusion sequence, which could represent a meaningful temporal advantage during serve return situations. However, such interpretations remain speculative, as the timing of information acquisition was not directly measured in the present study.

Video-based perceptual-cognitive training may support the development of anticipatory performance in young tennis players and represents an accessible method allowing independent practice. Such training may enhance anticipatory performance and has previously been associated with implicit perceptual learning processes (Farrow & Abernethy, 2003; Jackson & Farrow, 2005), and can be applied beyond the tennis court, including home environments or travel situations, thereby improving training efficiency. The authors acknowledge that the findings are based on a small pilot sample; however, consistent with previous pilot investigations (see Müller et al., 2015), the results provide preliminary, hypothesis-generating insights suggesting that anticipatory performance may respond to perceptual-cognitive training even in young athletes.

CONCLUSIONS

After the three-week perceptual-cognitive training application, descriptive improvements in anticipatory performance were observed across age categories. Notably, after the intervention, the U12 group showed pronounced relative improvement, with both the U12 and U14 categories approaching levels of anticipatory performance comparable to the U18 and adult participants. However, these findings should be interpreted cautiously given the small pilot sample and cannot be generalized. The results suggest that perceptual-cognitive training may influence anticipatory performance, with preliminary indications that younger players may improve their use of advance anticipatory information. Given the growing interest in anticipation and perception among professional athletes, the present findings support further investigation and application of such training approaches in future controlled studies. Video-based perceptual training may represent a promising approach to enhancing perceptual and anticipatory skills in junior tennis 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: Jan Carboch, John Brenton, Tomas Kocib. Methodology: Jan Carboch, John Brenton. Formal analysis: Kristina Mrazova. Investigation: Kristina Mrazova. Data curation: Kristina Mrazova, Vendula Redlichova, Jan

Carboch. Writing – original draft: Jan Carboch, John Brenton. Writing – review & editing: Jan Carboch, Vendula Redlichova. Supervision: John Brenton, Jan Carboch.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Sprint performance adaptations through different warm up stretching approaches

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ABSTRACT

Background and Aim. Stretching is a crucial component of athletic warm-up routines, influencing flexibility and performance. Static stretching (SS) is commonly used to improve range of motion, whereas dynamic stretching (DS) is often preferred for enhancing explosive movements. The comparative effects of these stretching techniques on sprint performance across multiple distances remain a subject of interest. **Materials and Methods.** Forty male football players (18–23 years) from SRM Institute of Science and Technology were randomly assigned to a Static Stretching Group (SSG) or a Dynamic Stretching Group (DSG) ($n = 20$ each). Both groups completed a six-week stretching routine performed before sprint training, five days per week. Sprint times over 10 m, 20 m, 30 m, 40 m, and 50 m were recorded before and after the intervention. A mixed-design ANOVA was used to assess group $\times$ time interaction effects, supported by effect sizes and 95% confidence intervals. **Results.** Both groups showed statistically significant improvements in sprint times after six weeks. However, the DSG demonstrated comparatively greater gains, particularly in the mid-to-long sprint distances (30–50 m), where moderate to strong interaction effects were observed (partial $\eta^2 = 0.21$ – 0.33). Improvements in the SSG were smaller in magnitude, reflecting modest but meaningful performance changes. Correlation analyses indicated strong relationships among sprint distances, while anthropometric variables showed minimal association with sprint outcomes. **Conclusions.** Dynamic stretching appeared to provide greater short-term benefits for sprint performance compared to static stretching, especially during mid-sprint and longer sprint phases. Although the findings are encouraging, they should be interpreted cautiously due to study limitations such as sample size and intervention duration. Incorporating dynamic stretching into warm-up routines may be a practical strategy for athletes, but further research with larger and more diverse samples is recommended.

Keywords: Performance analysis, Sprinting, Static stretching, Dynamic stretching, Warm-up, Football players.

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INTRODUCTION

Football requires repeated high-intensity sprinting, acceleration, and rapid changes of direction, making sprint performance a key determinant of successful play (Lago et al., 2024; Kalinowski et al., 2021; Maciel et al., 2024). Acceleration and maintaining a high velocity at short distances depend on such components as elasticity of muscles, proper coordination, and neuromuscular conditioning (Nowak et al., 2025). In general, athletes engage in different stretching exercises during warm-ups to increase their flexibility, decrease muscular stiffness, and prepare for an intense activity (Samson et al., 2012; McMillian et al., 2006). Among different types of stretching exercises used in a warm-up routine, static stretching involves holding the muscles in elongated positions for a certain period, while dynamic stretching implies sport-specific movements aimed at activating muscles and increasing the core body temperature. There is some evidence that DS exercises may lead to better performance gains in sprints compared to SS exercises, mainly because of increased preparedness for movement execution (Takeuchi et al., 2024; Hsu et al., 2021). At the same time, extended SS exercises conducted right before starting a sprint exercise can negatively affect the athlete's ability to produce strength in sprinting (Stankovic et al., 2023; Freitas et al., 2023). Moreover, dynamic stretching is known to be positively associated with improved acceleration, coordination, and movement efficiency, while static stretching can be beneficial for achieving flexibility and preventing injuries in the long run (Loughran et al., 2017; Ferger & Moritz, 2017; Takeuchi et al., 2022). However, the effects of dynamic stretching and static stretching on the effectiveness of sprint exercises have not been sufficiently clear yet. In particular, the findings have been controversial, especially as regards the effect on performance at various sprint distances and in football conditions (Alkabi et al., 2020; Alizadeh Ebadi & Çetin, 2018). Anthropometric characteristics such as height, weight, body mass index (BMI), and muscle composition may also influence sprint performance (Woodhouse et al., 2021; Hammami et al., 2023). While DS has been suggested to positively influence movement coordination and sprint-related mechanics (Avloniti et al., 2016), limited research has examined the interaction between stretching protocols and sprint performance specifically among collegiate football players.

Aim of the study

The current study aimed to determine the effects of six weeks of static and dynamic stretching exercises on sprint performance over 10 m, 20 m, 30 m, 40 m, and 50 m distances in male collegiate football players. It was hypothesized that dynamic stretching would produce greater improvements in sprint performance compared to static stretching.

MATERIAL AND METHODS

Study participants

Forty male collegiate football players (aged 18–23 years) from SRM Institute of Science and Technology voluntarily participated in this study. All participants had a minimum of two years of structured football training. Using a computer-generated randomization process, the players were assigned to either the Static Stretching Group (SSG; $n = 20$) or the Dynamic Stretching Group (DSG; $n = 20$). Allocation was performed by an independent investigator using sealed group assignments to minimize selection bias. All participants were clearly briefed on the aims and procedures of the study, and written informed consent was obtained from each individual prior to the commencement of data collection.

Study design

A pre-test/post-test experimental design was used to examine the effects of static and dynamic stretching on sprint performance and body composition. During the pre-test, sprint times were recorded over 10m, 20m,

30m, 40m, and 50m distances. Body weight and BMI were also assessed. The training intervention spanned six weeks. Both groups performed their respective stretching routines before sprint training sessions, conducted five days per week.

Static Stretching Group (SSG)

Engaged in static stretching exercises, holding muscle elongation positions for fixed durations.

Dynamic Stretching Group (DSG)

Performed dynamic movements such as leg swings, lunges, and high knees to activate major muscle groups.

Each stretching session lasted approximately 15 minutes, followed by sprint drills based on weekly progression. Post-testing was conducted at the end of six weeks using the same parameters to identify improvements in sprint performance and body composition. To minimize the variations, tests were performed during similar hours of the day and under identical environmental conditions. Subjects were informed to avoid any rigorous exercises before the test sessions. However, certain factors that could influence the outcome such as sleep patterns, nutrition, fatigue level, recovery process, psychological preparedness, and any other physical exercise aside from the interventions were not considered during this experiment.

Table 1. Weekly training schedule for SSG and DSG.

Week	Day	SSG (Static Stretching)	DSG (Dynamic Stretching)	Sprint training	Repetitions & intensity
1–6	Monday	Quadriceps Stretch, Hamstring Stretch, Calf Stretch, Hip Flexor Stretch, Groin Stretch	Leg Swings (Front & Side), Walking Lunges, High Knees, Butt Kicks	10m	Week 1–2: 4 reps (80%) Week 3–4: 6 reps (85%) Week 5–6: 8 reps (90%)
	Tuesday	Hamstring Stretch, Glute Stretch, Shoulder Stretch, Triceps Stretch	Side Lunges, Arm Swings, Skipping, Knee Hugs	20m	Week 1–2: 4 reps (80%) Week 3–4: 6 reps (85%) Week 5–6: 8 reps (90%)
	Wednesday	Seated Hamstring Stretch, Butterfly Stretch, Arm Across Chest, Neck Stretch	Carioca Drill, High Skips, Bounding, Torso Twists	30m	Week 1–2: 4 reps (80%) Week 3–4: 6 reps (85%) Week 5–6: 8 reps (90%)
	Thursday	Hip Adductor Stretch, Lat Stretch, Shoulder Stretch, Ankle Stretch	Toy Soldiers, Quick Feet, Hip Circles, Knee Drives	40m	Week 1–2: 4 reps (80%) Week 3–4: 6 reps (85%) Week 5–6: 8 reps (90%)
	Friday	Calf Stretch, Cobra Stretch, Wrist Stretch, Groin Stretch	Lateral Shuffles, A-Skips, Backward Runs, Arm Circles	50m	Week 1–2: 4 reps (80%) Week 3–4: 6 reps (85%) Week 5–6: 8 reps (90%)

Statistical analysis

Data were analysed using a mixed-design ANOVA to examine the group $\times$ time interaction effect between the Static Stretching Group and Dynamic Stretching Group across pre- and post-test assessments. Where baseline differences were detected, ANOVA was applied with pre-test values as covariates. Assumptions of normality, homogeneity of variance, and sphericity were verified prior to analysis. To control the risk of Type I error arising from multiple comparisons, appropriate multiplicity adjustments were applied. Effect sizes were reported using Hedges' g for pairwise comparisons and partial η^2 for interaction effects. Additionally, 95% confidence intervals (CIs) were provided for all primary outcome measures to improve the precision and interpretability of the findings. Statistical significance was set at $p < .05$. Post hoc power analysis showed adequate power to identify medium and large interaction effects. Nonetheless, the small sample size may have reduced precision and led to biased overestimation of effect sizes.

RESULTS

The study examined the impact of static and dynamic stretching on sprint performance over different distances. Both stretching methods led to significant improvements, with dynamic stretching showing greater benefits. Statistical analyses, including paired and independent t-tests, confirmed meaningful reductions in sprint times.

Table 2. Within-Group Changes (Pre–Post) – Static Stretching Group (SSG).

Distance (m)	Pre-test (s)	Post-test (s)	Mean Δ (95% CI)	Hedges' g	p-Value (time)
10 m	1.92 $\pm$ 0.33	1.78 $\pm$ 0.42	–0.14 (–0.20 to –0.07)	0.34	.021*
20 m	3.36 $\pm$ 0.34	3.22 $\pm$ 0.39	–0.14 (–0.21 to –0.08)	0.39	.017*
30 m	4.61 $\pm$ 0.34	4.48 $\pm$ 0.38	–0.13 (–0.19 to –0.07)	0.35	.012*
40 m	5.86 $\pm$ 0.38	5.72 $\pm$ 0.40	–0.14 (–0.22 to –0.06)	0.40	.008*
50 m	7.05 $\pm$ 0.48	6.90 $\pm$ 0.50	–0.15 (–0.24 to –0.07)	0.43	.005*

The static stretching group demonstrated small but statistically significant improvements across all sprint distances (10–50 m), with mean reductions ranging from –0.13 to –0.15 seconds. The effect sizes (Hedges' g = 0.34–0.43) indicate small improvements, suggesting that static stretching had a measurable but modest influence on sprint performance. The 95% confidence intervals consistently show negative values, confirming that the improvements were real and not due to chance. Overall, while static stretching produced beneficial changes, the magnitude of improvement remained limited compared to dynamic stretching.

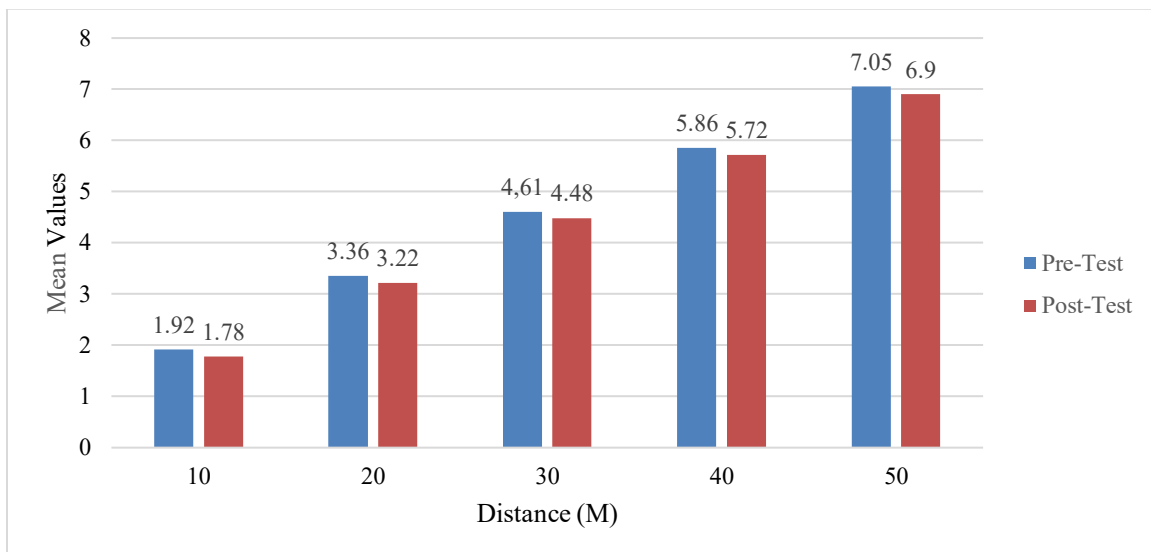


Figure 1. Mean Sprint Times for Static Stretching Group (SSG).

Table 3. Within-Group Changes (Pre–Post) – Dynamic Stretching Group (DSG)

Distance (m)	Pre-test (s)	Post-test (s)	Mean Δ (95% CI)	Hedges' g	p-Value (time)
10 m	1.98 $\pm$ 0.34	1.86 $\pm$ 0.36	–0.12 (–0.18 to –0.06)	0.33	.004*
20 m	3.39 $\pm$ 0.34	3.21 $\pm$ 0.31	–0.18 (–0.25 to –0.11)	0.51	.002*
30 m	4.65 $\pm$ 0.35	4.39 $\pm$ 0.32	–0.26 (–0.33 to –0.19)	0.71	<.001*
40 m	5.96 $\pm$ 0.42	5.68 $\pm$ 0.38	–0.28 (–0.37 to –0.18)	0.65	<.001*
50 m	7.21 $\pm$ 0.49	6.98 $\pm$ 0.44	–0.23 (–0.32 to –0.15)	0.48	<.001*

The dynamic stretching group showed greater and more consistent improvements in sprint times across all distances. Reductions ranged from -0.12 to -0.28 seconds, with the largest decreases observed in the 30 m and 40 m distances (-0.26 and -0.28 seconds). Effect sizes ranged from 0.33 to 0.71, indicating small to large effects, reflecting a stronger training impact than static stretching. The very narrow and negative 95% CI ranges, along with highly significant p -values ($p < .001$ for 30–50 m), confirm that dynamic stretching produced substantial and reliable enhancements in sprint performance.

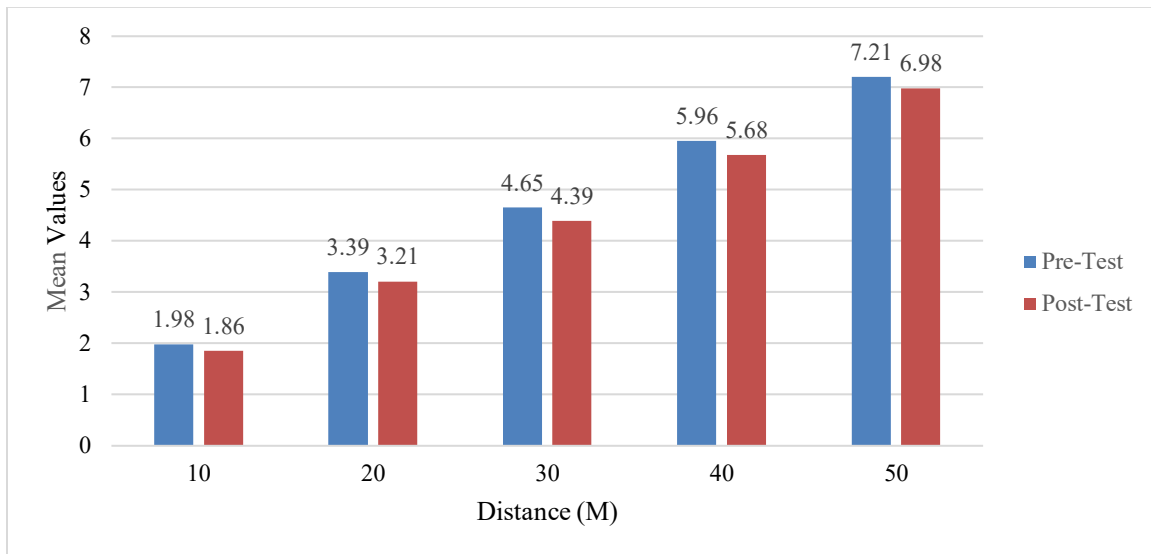


Figure 2. Mean Sprint Times for Dynamic Stretching Group (DSG).

Table 4. Between-group comparison (Mixed ANOVA – Group $\times$ Time interaction).

Distance (m)	F-value	p-Value	Partial η^2	95% CI (η^2)	Interpretation
10 m	4.82	<.05*	0.12	0.02 to 0.24	DSG improved significantly more
20 m	7.96	<.01*	0.19	0.08 to 0.32	Moderate interaction
30 m	15.42	<.001*	0.33	0.18 to 0.46	Strong advantage for DSG
40 m	13.87	<.001*	0.30	0.15 to 0.44	Strong interaction
50 m	8.61	<.01*	0.21	0.09 to 0.34	DSG superior

The mixed ANOVA results presented in Table 4 suggest progressive group $\times$ time interaction effects across all sprint distances, favouring the Dynamic Stretching Group (DSG). At 10 m, a significant interaction ($F = 4.82$, $p < .05$, partial $\eta^2 = 0.12$) shows that DSG achieved greater early-acceleration improvements than SSG. The interaction strengthened at 20 m ($F = 7.96$, $p < .01$, partial $\eta^2 = 0.19$), suggesting that dynamic stretching provided a more meaningful enhancement during the transition phase of sprinting. The most pronounced effect occurred at 30 m, where the interaction reached its peak ($F = 15.42$, $p < .001$, partial $\eta^2 = 0.33$), indicating a substantial performance advantage for DSG during mid-sprint velocity development. Similarly, strong interactions were observed at 40 m ($F = 13.87$, $p < .001$, partial $\eta^2 = 0.30$), reinforcing the superiority of dynamic stretching in sustaining speed over longer distances. Lastly, at 50 m, the interaction remained significant ($F = 8.61$, $p < .01$, partial $\eta^2 = 0.21$), confirming that DSG consistently outperformed SSG across the complete sprint profile.

It was observed that there were highly positive correlations between sprint distances in both groups, showing consistency in sprinting performance during acceleration and maximal sprinting phases. However,

anthropometric factors such as height, weight, and body mass index showed poor correlations with sprint performances (Table 5 & 6), suggesting that they have little bearing on the sprinting ability of athletes at the current level. Due to the expected high degree of correlation between different sprint distances, correlation findings could be considered as additional information to the study objective.

Table 5. Pearson correlation coefficients among study variables static stretching group.

Variables	Age	Weight	Height	BMI	10M	20M	30M	40M	50M
Age	1	.107	.503*	.428	-.246	-.292	-.324	-.310	-.274
Weight	.107	1	.499*	-.127	-.092	-.203	-.209	-.042	-.108
Height	.503*	.499*	1	.773*	-.027	-.084	-.105	-.015	-.045
BMI	.428	-.127	.773*	1	.019	.041	.025	.017	.024
10M	-.246	-.092	-.027	.019	1	.977*	.958*	.952*	.924*
20M	-.292	-.203	-.084	.041	.977*	1	.978*	.963*	.922*
30M	-.324	-.209	-.105	.025	.958*	.978*	1	.970*	.943*
40M	-.310	-.042	-.015	.017	.952*	.963*	.970*	1	.963*
50M	-.274	-.108	-.045	.024	.924*	.922*	.943*	.963*	1

Note. *Correlation is significant at the .05 level (2-tailed).

Table 6. Pearson correlation coefficients between variables dynamic stretching.

Variables	Age	Weight	Height	BMI	10M	20M	30M	40M	50M
Age	1	.025	.534*	.560*	-.273	-.275	-.283	-.315	-.278
Weight	.025	1	.428	-.167	-.177	-.222	-.279	-.198	-.144
Height	.534*	.428	1	.818*	-.072	-.112	-.202	-.116	-.016
BMI	.560*	-.167	.818*	1	.029	.020	-.050	.007	.077
10M	-.273	-.177	-.072	.029	1	.963*	.880*	.922*	.912*
20M	-.275	-.222	-.112	.020	.963*	1	.889*	.957*	.908*
30M	-.283	-.279	-.202	-.050	.880*	.889*	1	.913*	.901*
40M	-.315	-.198	-.116	.007	.922*	.957*	.913*	1	.938*
50M	-.278	-.144	-.016	.077	.912*	.908*	.901*	.938*	1

Note. *Correlation is significant at the .05 level (2-tailed).

DISCUSSIONS

The findings of this study suggest that both static and dynamic stretching may contribute to short-term improvements in sprint performance among male college-level football players, with dynamic stretching showing comparatively greater benefits, particularly over longer distances. While the results generally align with earlier research indicating that dynamic stretching can enhance muscle activation, neuromuscular readiness, and overall sprint mechanics (Behm et al., 2016; McMillian et al., 2006), these interpretations should be made cautiously. The stronger improvements observed in the dynamic stretching group, especially in the 30–50 m distances, are consistent with previous studies reporting enhanced explosive power and stride efficiency following dynamic warm-up routines (Fletcher & Jones, 2004; Yamaguchi & Ishii, 2005). However, despite the lack of examination on any physiologically or biomechanically related variables in this experiment, it is highly possible that the better results following dynamic stretching may have been facilitated by factors such as movement preparation, increased muscle temperature, improved coordination, and other neuromuscular-related factors. All of which can be considered mere possibilities as the inclusion of electromyographic testing and biomechanics was not included in the experiment. Static stretching also produced performance gains; however, the smaller effect sizes support literature noting possible short-term

reductions in muscle stiffness and force output following prolonged static stretching (Kay & Blazevich, 2012). Firstly, it should be emphasized that these findings should not be taken to mean that dynamic stretching is better for everyone in every athletic situation. Instead, these findings can help confirm the potential usefulness of dynamic stretching for short-term warm-ups before football games under certain circumstances described in this study. The correlation results indicated that anthropometric characteristics such as height, weight, and BMI were not strongly associated with sprint times in either group, suggesting that flexibility and neuromuscular preparedness may play a more prominent role in influencing sprint performance in this context. Nevertheless, these observations should be interpreted with some caution due to the design constraints of the study.

A number of limitations have to be pointed out when considering the results of the present study. First of all, it can be assumed that a smaller sample size negatively affected the statistical significance of the estimates. Furthermore, the length of the experiment (6 weeks) is rather short in terms of studying the long-term adaptation processes to physical training. Several potentially influential variables were not controlled, such as sleep quality, nutrition, fatigue, psychological readiness to participate in the program, and others that were known to influence sprint performance outcomes. In addition, the experiment included only male college football players that seriously limits its application for females, professional athletes, younger individuals, or athletes involved in other types of sports activities. Also, there were no direct physiological, biomechanical, or neuromuscular measurements which could shed light on the exact nature of the results obtained (Sanjaykumar et al., 2024; Panasci et al., 2025). Future studies would benefit from more rigorous designs, including larger and more diverse samples, randomized controlled trials, and the inclusion of psychological, nutritional, biomechanical, and hormonal variables to provide a more comprehensive understanding. Investigating differences across genders, training levels, and sport-specific demands may also enhance the practical applicability of the findings (Yevhen Mykhaliuk et al., 2024; Sanjaykumar et al., 2023; Kozina et al., 2024; Ikhsan et al., 2023).

CONCLUSIONS

This study provides preliminary evidence that both static and dynamic stretching may enhance sprint performance in male college football players, with dynamic stretching showing comparatively greater improvements, especially over longer sprint distances. Nonetheless, considering factors like the small number of participants, short intervention period, lack of measurement of mechanism, and narrow population range, these results must be viewed in an exploratory perspective and cannot be taken as conclusive. While dynamic stretching could be a useful aspect in football warming up sessions, many more studies are needed before any concrete practical applications can be made.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Ashokan Praveen: conceptualization, methodology, investigation, resources, writing-review & editing, supervision, writing-original draft and final approval the manuscript. Chandrababu Suresh: methodology, formal analysis, data curation and collection, supervision and final approval the manuscript. Sergio Sebastia-Amat: methodology, formal analysis, writing-review & editing and final approval the manuscript. Mert Kurnaz: methodology, formal analysis, writing-review & editing and final approval the manuscript. Grygus Igor: writing-review & editing, formal analysis, and final approval the manuscript. Yuliya Kalmykova: writing-review & editing, formal analysis, and final approval the manuscript. Swamynathan Sanjaykumar: conceptualization, methodology, investigation, writing-review & editing, writing-original draft and final approval the manuscript.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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) ChatGPT was utilized to support language editing and enhance clarity during the preparation of this manuscript. All content was carefully reviewed, revised, and approved by the authors, who accept full responsibility for the accuracy and integrity of the work. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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Correlation between body composition and gold-standard basal metabolic rate in healthy young adults: A pilot study

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ABSTRACT

Introduction: This pilot study aimed to investigate the correlation between body composition parameters and gold-standard measured Basal Metabolic Rate (BMR) in healthy young adults. **Methods:** Fifteen healthy participants aged 20-34 years were recruited. BMR was measured using indirect calorimetry, and body composition (including body fat percentage, fat-free mass, skeletal muscle mass, visceral fat area, etc.) was assessed using a medical-grade body composition analyser. Pearson correlation analysis was performed to examine the relationships between body composition variables and BMR. **Results:** The participants had a mean body mass index of 24.0 ± 1.6 kg/m² and a mean BMR of 1566.3 ± 228.5 kcal/day. Fat-free mass showed the strongest positive correlation with BMR ($r = .891, p < .001$), followed by total muscle mass ($r = .885, p < .001$) and skeletal muscle mass ($r = .879, p < .001$). All segmental muscle mass indices were strongly positively correlated with BMR (all $p < .001$), with lower limb muscle mass (right: $r = .875$; left: $r = .878$) showing slightly stronger correlations than upper limb muscle mass (right: $r = .852$; left: $r = .846$). In contrast, body fat percentage ($r = -.324, p = .198$) and visceral fat area ($r = -.064, p = .812$) showed no significant correlations with BMR. **Conclusion:** Fat-free mass and skeletal muscle mass (including segmental muscle mass) show the strongest positive associations with BMR in this sample of healthy young adults. Lower limb muscle mass exhibits a marginally stronger association with BMR than upper limb muscle mass, which may be attributed to the larger muscle volume of the lower limbs. These findings highlight the importance of assessing body composition strategies. This is a pilot study with a small sample; results are preliminary and require validation in larger cohorts.

Keywords: Body composition, Basal metabolic rate, Indirect calorimetry, Healthy young adults.

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INTRODUCTION

Basal Metabolic Rate (BMR) refers to the minimum energy expenditure required to maintain basic physiological functions at rest, accounting for 60% – 70% of the total daily energy expenditure in healthy adults (Shetty,2005;Ravussin&Bogardus,1989). Accurate assessment of BMR is of great significance for formulating personalized weight management plans, exercise nutrition programs and clinical metabolic health evaluations. Currently, the methods for assessing BMR include direct calorimetry, indirect calorimetry and formula-based prediction. Among them, direct and indirect calorimetry are the gold standards for measuring human BMR (Levine,2005), which estimate the type, rate of substrate utilization and energy metabolism in the body through gas exchange measurements (Ferrannini,1988). Due to the cumbersome process, long duration and high cost of measuring BMR by indirect or direct calorimetry, predictive equations are now mostly used to estimate individual BMR. Although predictive formulas such as the Mifflin-St Jeor equation, Harris-Benedict equation and Schofield formula are widely used in clinical and scientific research (Harris&Benedict,1918;Mifflin et al.,1990;Nobre et al.,2019), these formulas mostly rely on basic anthropometric indices such as age, body weight, height and Body Mass Index (BMI), and fail to fully consider individual differences in body composition, which may lead to deviations in the estimation of the actual metabolic rate.

Body composition, especially fat-free mass (FFM) and skeletal muscle mass (SMM), is an important determinant of resting energy metabolism (Schofield et al.,2019). Researchers have investigated the associations of BMR with fat-free mass, fat mass and body weight (Johnstone et al.,2005), with fat mass showing the weakest relationship with Resting Metabolic Rate (RMR) (Sokolov et al.,2012). Metabolically active lean tissue in the BMR system consumes significantly more energy at rest than adipose tissue. Previous studies have confirmed a strong positive correlation between FFM, SMM and RMR/BMR (Kajale et al.,2022), but most of them used predictive equations rather than the gold-standard indirect calorimetry to measure metabolic rate. In addition, these studies selected a limited range of body composition indices and rarely explored the segmental differences in muscle mass (e.g., upper vs. lower limbs) and their relative contributions to BMR.

Against this background, the present pilot study aimed to: (1) investigate the correlations between comprehensive body composition parameters (including total FFM, SMM, segmental muscle mass, body fat percentage and visceral fat area) and gold-standard measured BMR in healthy young adults; (2) compare the relative strength of associations between upper and lower limb muscle mass and BMR; (3) preliminarily explore gender differences in the above relationships. We hypothesized that FFM and SMM (especially lower limb muscle mass) would exhibit the strongest positive correlations with BMR, while body fat percentage and visceral fat area would show no significant associations with BMR.

METHODS

Study subjects

A convenient sampling method was adopted in this study, and 15 healthy young subjects were recruited in Tianjin, China, from October 2025 to January 2026, including 12 males and 3 females, aged 21 – 35 years (mean: 23.9 ± 3.2 years), with a height range of 154.0 – 188.0 cm and a body weight range of 56.2 – 92.0 kg.

Inclusion criteria: (1) Aged 20 – 35 years; (2) No history of metabolic-related diseases such as definite cardiovascular disease, diabetes and thyroid dysfunction; (3) No special physiological states such as

pregnancy and lactation; (4) No allergy to mask-type equipment; (5) Voluntarily participate in and cooperate with the study and sign the informed consent form.

Exclusion criteria

(1) Implantation of electronic or metal implants such as metal stents and cardiac pacemakers in the body; (2) Presence of physical defects, muscular atrophy and other conditions that affect body composition measurement; (3) Taking drugs that affect metabolism (e.g., hormonal drugs, weight-loss drugs) within the last month; (4) Alcohol consumption, strenuous exercise or abnormal eating (e.g., overeating, fasting) within 24 h before the test.

Testing instruments and methods

Anthropometric indices

A calibrated height and weight scale was used to measure height (accurate to 0.1 cm) and body weight (accurate to 0.1 kg). Body Mass Index (BMI) was calculated according to the formula: $BMI = \text{body weight (kg)} / \text{height}^2 (\text{m}^2)$.

Body composition measurement

A medical-grade bioelectrical impedance analyser (Yueqi BIA-100) was used to assess body composition parameters. The testing procedure was as follows: the subjects removed metal ornaments and heavy clothes, stood barefoot on the electrode plates of the instrument, held the upper limb electrodes naturally with both hands, kept the body upright and muscles relaxed, and avoided contact between limbs and other objects. After the correct posture was maintained, the device automatically collected indices including total body water (TBW), fat-free mass (FFM), total muscle mass, skeletal muscle mass (SMM), body fat percentage (BF%), body fat (BF), visceral fat area (VFA) and segmental muscle mass (right upper limb, left upper limb, trunk, right lower limb, left lower limb muscle mass). Each subject was measured twice, and the average value was taken as the final data.

BMR measurement

Indirect calorimetry is widely recognized as the gold standard for BMR measurement, and recent studies have verified its high validity in healthy young adults, with significantly lower error than the Mifflin-St Jeor or Harris-Benedict equations (Van Dessel et al., 2024). Indirect calorimetry (the gold standard) was used to measure BMR with a medical-grade indirect calorimeter (Schiller HS-MetaX). Strict control conditions were implemented before the test: (1) The subjects fasted for more than 3 h (only a small amount of boiled water was allowed); (2) Strenuous exercise, alcohol consumption, smoking and caffeine intake were avoided within 24 h before the test; (3) No physical discomfort such as colds in the recent period.

Test implementation

The test was conducted in a quiet and comfortable indoor environment (temperature: 22 – 25°C, humidity: 50%-60%). The subjects rested at the test site for at least 15 min. Professional staff fitted the subjects with a breathing mask, connected the mask to the instrument and ensured no air leakage. After the preparation work was completed, the subjects maintained a supine resting position to start the test, breathing through the mouth throughout the process. The test duration was 20 min. The instrument automatically recorded oxygen consumption (VO_2) and carbon dioxide production (VCO_2), and calculated BMR (kcal/day).

Statistical analysis

SPSS 26.0 statistical software was used for data analysis. Measurement data were expressed as mean $\pm$ standard deviation ($\bar{X} \pm s$). Pearson correlation analysis was performed to examine bivariate associations.

No multivariable adjustments for gender, body size or confounders were performed; thus, observed associations may be affected by overall body morphology. The criteria for judging the strength of correlation were as follows: $|r| \geq .8$ for extremely strong correlation, $.6 \leq |r| < .8$ for strong correlation, $.4 \leq |r| < .6$ for moderate correlation, $.2 \leq |r| < .4$ for weak correlation, and $|r| < .2$ for extremely weak correlation. The statistical significance level was set at $\alpha = .05$ (two-tailed test).

RESULTS

General Characteristics of Subjects, and Overall Status of Body Composition and BMR: A total of 15 healthy young subjects were enrolled in this study, including 12 males and 3 females. The descriptive statistical results of the subjects' general characteristics, body composition and Basal Metabolic Rate (BMR) are shown in Table 1.

Table 1. General characteristics of subjects, and overall status of body composition and BMR ($\bar{X} \pm s$).

Index	Total (n = 15)	Male (n = 12)	Female (n = 3)
Age (years)	23.9 $\pm$ 3.2	23.3 $\pm$ 2.7	26.3 $\pm$ 4.2
Height (cm)	171.2 $\pm$ 9.8	174.5 $\pm$ 8.9	161.2 $\pm$ 7.5
Body weight (kg)	71.4 $\pm$ 10.5	73.8 $\pm$ 9.6	61.7 $\pm$ 8.3
BMI (kg/m ²)	24.0 $\pm$ 1.6	24.2 $\pm$ 1.5	23.6 $\pm$ 1.8
Body fat percentage (%)	23.1 $\pm$ 7.8	20.5 $\pm$ 6.2	32.9 $\pm$ 5.1
Fat-free mass (kg)	53.9 $\pm$ 10.2	58.0 $\pm$ 8.7	40.5 $\pm$ 4.6
Total muscle mass (kg)	50.7 $\pm$ 9.8	54.5 $\pm$ 8.3	39.2 $\pm$ 4.3
Skeletal muscle mass (kg)	31.5 $\pm$ 7.6	33.9 $\pm$ 6.5	23.4 $\pm$ 3.2
Right upper limb muscle mass (kg)	3.0 $\pm$ 0.8	3.3 $\pm$ 0.7	2.1 $\pm$ 0.3
Left upper limb muscle mass (kg)	2.9 $\pm$ 0.8	3.2 $\pm$ 0.7	2.1 $\pm$ 0.3
Trunk muscle mass (kg)	24.1 $\pm$ 4.9	25.9 $\pm$ 4.2	19.1 $\pm$ 2.8
Right lower limb muscle mass (kg)	8.3 $\pm$ 1.8	8.9 $\pm$ 1.5	6.8 $\pm$ 0.7
Left lower limb muscle mass (kg)	8.3 $\pm$ 1.8	8.9 $\pm$ 1.5	6.8 $\pm$ 0.6
Visceral fat area (cm ²)	70.1 $\pm$ 26.5	65.8 $\pm$ 25.1	87.2 $\pm$ 24.3
BMR (kcal/day)	1566.3 $\pm$ 228.5	1632.5 $\pm$ 201.8	1321.7 $\pm$ 189.6

Correlation analysis between body composition indices and BMR

Pearson correlation analysis showed that most body composition indices in the total sample were significantly correlated with BMR (Table 2). Among them, fat-free mass had the strongest positive correlation with BMR ($r = .891$, $p < .001$), followed by total muscle mass ($r = .885$, $p < .001$) and skeletal muscle mass ($r = .879$, $p < .001$), all of which were extremely strong positive correlations.

Table 2. Pearson correlation analysis results between body composition indices and BMR in the total sample.

Index	Correlation coefficient (r)	p-Value	Correlation strength
Body fat percentage (%)	-.324	.198	Weak negative correlation
Fat-free mass (kg)	.891	<.001	Extremely strong positive correlation
Total muscle mass (kg)	.885	<.001	Extremely strong positive correlation
Skeletal muscle mass (kg)	.879	<.001	Extremely strong positive correlation
Right upper limb muscle mass (kg)	.852	<.001	Extremely strong positive correlation
Left upper limb muscle mass (kg)	.846	<.001	Extremely strong positive correlation
Trunk muscle mass (kg)	.863	<.001	Extremely strong positive correlation

In terms of segmental muscle mass, all regional muscle mass indices were extremely strongly positively correlated with BMR (all $p < .001$), and lower limb muscle mass had a slightly stronger correlation with BMR than upper limb muscle mass: right lower limb muscle mass ($r = .875$), left lower limb muscle mass ($r = .878$); right upper limb muscle mass ($r = .852$), left upper limb muscle mass ($r = .846$).

In contrast, body fat percentage ($r = -.324$, $p = .198$) and visceral fat area ($r = -.064$, $p = .812$) had no significant correlations with BMR.

DISCUSSION

We studied 15 healthy young adults in this research. We measured their BMR using indirect calorimetry, which is the gold standard for this kind of test. We also used bioelectrical impedance analysis to assess various body composition indicators in detail. Then we systematically looked into how body composition relates to BMR. We found that fat-free mass and skeletal muscle mass are the key factors that determine BMR in healthy young adults. We also noticed that lower limb muscle mass has a slightly closer connection with BMR than upper limb muscle mass. These findings provide experimental evidence for accurately assessing BMR by looking at body composition.

The results of this study showed that fat-free mass had the strongest positive correlation with BMR ($r = .891$, $p < .001$) in the total sample, and total muscle mass and skeletal muscle mass also had extremely strong positive correlations with BMR (all $p < .001$), which was consistent with the conclusions of most previous studies. The reason is that skeletal muscle, which accounts for the largest proportion of fat-free mass, is a metabolically active tissue (Kuzne), and its energy consumption at rest is much higher than that of adipose tissue (Wang et al., 2010; Zurlo et al., 2010). In contrast, body fat percentage ($r = -.324$, $p = .198$) and visceral fat area ($r = -.064$, $p = .812$) had no significant correlations with BMR. This result suggests that in healthy young adults, the total amount of adipose tissue and the distribution of visceral fat have a much lower impact on basal metabolism than lean tissue (Maleki et al., 2026), which also indirectly confirms the limitations of traditional BMR predictive formulas based only on body weight and BMI—such indices cannot distinguish the proportion of fat and lean tissue in body weight, and are prone to cause deviations in BMR estimation for people with high muscle mass or high body fat percentage.

This study further found that all segmental muscle mass indices were extremely strongly positively correlated with BMR, and lower limb muscle mass had a slightly stronger association with BMR than upper limb muscle mass (lower limbs: $r = .875 \sim .878$; upper limbs: $r = .846 \sim .852$). The core reason for this phenomenon is the difference in limb muscle volume: the total skeletal muscle mass of the lower limbs in healthy young adults accounts for more than 50% of the whole-body skeletal muscle mass, while the upper limbs only account for about 20%. The difference in muscle volume directly leads to more energy consumption contributed by lower limb muscle to basal metabolism. At the same time, lower limb muscle is mainly composed of slow-twitch muscle fibres, which may have higher mitochondrial density and relatively higher energy consumption at rest. This is a theoretical explanation rather than a directly measured mechanism in this study. This result supplements the research data on the association between segmental muscle distribution and BMR, suggesting that in personalized BMR assessment, the detection of lower limb muscle mass can be focused on to further improve the estimation accuracy, and future interventional studies may explore whether lower limb training could contribute to changes in BMR.

This study has some strengths. First, we used indirect calorimetry (the gold standard) to measure BMR. This way, we avoided measurement errors that come from using predictive equations. Second, we tested

many body composition indicators, including segmental muscle mass. We also analysed how muscle distribution relates to BMR in detail. These steps made our research results more objective and targeted. But this study has some limitations too. First, the sample size is small ($n = 15$) with an extremely unbalanced gender distribution (12 males, 3 females), which limits the generalizability of the results and does not allow reliable gender-stratified analysis. Correlation coefficients in small pilot samples may be unstable and potentially overestimated. Second, all participants are healthy young adults. We didn't include middle-aged people, elderly people, obese people, or those with metabolic diseases. So we can't show how body composition and BMR relate differently in these groups. Third, this is a cross-sectional pilot study without intervention. Causal relationships cannot be established; only associations can be reported. For future studies, researchers can increase the number of participants and balance the number of males and females. They can also include people of different ages and metabolic statuses. Besides, doing long-term intervention experiments (like exercises to build muscle) can help further confirm how body composition and BMR are related. This will provide more complete evidence for managing metabolic health.

Based on the results of this study, the following practical implications can be drawn: in the formulation of personalized weight management and exercise nutrition programs, the traditional model of only referring to body weight and BMI should be abandoned, and focus should be placed on body composition assessment, especially the detection of fat-free mass and skeletal muscle mass; for people who need to increase BMR, lower limb muscle strength training can be taken as the focus to increase BMR by increasing lower limb muscle mass; at the same time, in clinical BMR assessment, predictive formulas should be optimized by including body composition indices such as fat-free mass and skeletal muscle mass to reduce estimation deviations.

In summary, fat-free mass and skeletal muscle mass are the main correlates associated with BMR in this sample of BMR in healthy young adults, and lower limb muscle mass has a slightly stronger association with BMR than upper limb muscle mass, while body fat percentage and visceral fat area have no significant correlations with BMR. The overall BMR of males is higher than that of females, and the correlation patterns between body composition and BMR are generally consistent between males and females, Mainly attributed to its higher lean body mass compared to women (Verma et al., 2023). Assessing body composition indices is of great significance for the accurate estimation of BMR and the formulation of personalized metabolic health management programs.

CONCLUSION

From this study's results, we can see that fat-free mass and skeletal muscle mass are the main factors that affect BMR in healthy young adults. Both of these have a very strong positive correlation with BMR, and fat-free mass has the strongest connection. All segmental muscle mass indicators also have a significant and extremely strong positive correlation with BMR. Lower limb muscle mass is a little more closely related to BMR than upper limb muscle mass. This is because the lower limbs have larger muscle volume and higher metabolic activity—these are their normal physiological traits. On the other hand, body fat percentage and visceral fat area do not have a significant correlation with BMR in healthy young adults. This shows that adipose tissue is not a key factor affecting basal metabolism in this group of people.

This study confirms that body composition assessment has high value for the accurate estimation of BMR in healthy young adults and provides experimental evidence for the formulation of personalized weight management and exercise nutrition programs. Limited by the small sample size, the extrapolation of the research results is restricted. Future studies should expand the sample size and balance the gender

ratio, include populations of different ages and metabolic statuses to carry out longitudinal intervention research, further verify the causal relationship between body composition and BMR, and provide more comprehensive theoretical and practical support for metabolic health management.

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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.

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Circadian biorhythms in athletes through rapid sleep induction: A quasi-experimental study using the military 2-minute method

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ABSTRACT

The aim of this study was to determine the effects of the military rapid sleep induction method on circadian adaptation, sleep quality, and physiological variables in high-performance athletes who travel internationally. A longitudinal quasi-experimental design with pre-test/post-test measurements and a non-equivalent control group was used, involving a sample of 72 athletes from Honduras, Moldova, and Cuba, divided into an experimental group ($n = 36$) and a control group ($n = 36$). The intervention consisted of applying the military sleep induction method for four weeks, based on muscle relaxation techniques, breathing control, and cognitive visualization. Objective and subjective instruments were used, such as actigraphy, the Pittsburgh Sleep Quality Index (PSQI), the Epworth Sleepiness Scale (ESS), and heart rate variability (RMSSD). The results showed significant improvements in the experimental group compared to the control group, including reduced sleep latency ($d = 0.82$), improved sleep quality ($d = 0.85$), increased heart rate variability (HRV), longer sleep duration, reduced daytime sleepiness, and a shorter circadian adaptation time. Repeated measures analysis of variance confirmed significant effects ($p < .05$). It is concluded that the military method of rapid sleep induction is an effective non-pharmacological strategy for improving recovery and circadian adaptation in high-performance athletes.

Keywords: Sport medicine, Sleep, Circadian rhythms, Jet lag, Heart rate, Recovery.

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INTRODUCTION

High-level athletic performance depends on the complex interaction of physiological, psychological, and behavioural factors, among which sleep has emerged as a key component for recovery, adaptation to training, and performance optimization (Fullagar et al., 2015). In this regard, scientific evidence indicates that adequate quantity and quality of sleep promote fundamental processes, such as protein synthesis, hormonal regulation, and the consolidation of motor memory, which are essential for athletic development (Walker, 2017).

However, in the context of contemporary sport, characterized by frequent international competitions, athletes are repeatedly exposed to transmeridian travel, which disrupts their circadian rhythms. This desynchronization, commonly known as jet lag, disrupts the sleep-wake cycle, causes fatigue, reduces cognitive performance, and impairs physical capacity (Fullagar et al., 2015). Recent studies have indicated that elite athletes, even under normal conditions, experience difficulties maintaining adequate sleep quality, a challenge exacerbated by factors such as competitive stress, irregular schedules, and international travel (Estivill-Domènech et al., 2018).

From a physiological perspective, the circadian system regulates essential bodily functions, such as melatonin secretion, body temperature, and metabolic processes (Czeisler and Gooley, 2007). Disruption of these rhythms affects not only sleep but also muscle recovery and endocrine balance. In this context, heart rate variability (HRV), particularly the RMSSD index, has been widely used as a valid indicator of the state of the autonomic nervous system and the level of recovery in athletes (Task Force, 1996).

In response to these challenges, various strategies have been proposed to optimize sleep in athletes, including behavioural interventions, sleep hygiene, and psychological techniques. Evidence suggests that self-regulation-based interventions, such as psychological skills training, can significantly improve athletic performance (Birrer & Morgan, 2010). In this regard, recent reviews have highlighted the positive impact of sleep-related interventions on athletes' physical and cognitive performance (Cunha et al., 2023).

Among these strategies, the military method of rapid sleep induction has gained relevance as a practical technique for facilitating sleep onset in high-pressure situations. This method combines muscle relaxation, breathing control, and cognitive visualization, elements that have been shown to reduce physiological arousal and improve sleep (Good et al., 2020). Furthermore, studies in military contexts have demonstrated that sleep pattern training can improve sleep effectiveness even under adverse conditions (Miller et al., 2010).

Despite these advances, there is a gap in the scientific literature regarding the experimental evaluation of these types of interventions in high-performance athletes, especially in intercultural contexts. Recent research has highlighted the importance of circadian rhythms in performance, immune function, and injury prevention, reinforcing the need to develop strategies to optimize them (Nobari et al., 2023).

In this context, this study aims to determine the effect of the military-grade rapid sleep induction method on sleep latency, sleep quality, heart rate variability, and circadian adaptation in high-performance athletes. The hypothesis is that the systematic application of this method will result in significant improvements in the assessed indicators compared to a control group.

MATERIALS AND METHODS

This study was designed to evaluate, from an applied experimental perspective, the effectiveness of the military rapid sleep induction method as a non-pharmacological strategy to optimize circadian rhythm adaptation in high-performance athletes undergoing international travel. In accordance with this objective, a quantitative methodological approach was adopted, based on a longitudinal quasi-experimental design with repeated measures (pre-test-post-test) and the inclusion of a non-equivalent control group, which allowed for the analysis of both intraindividual changes and intergroup differences resulting from the intervention.

The choice of a quasi-experimental design reflects the specific characteristics of the high-performance sports context, where strict random assignment of participants can be limited by logistical, ethical, and organizational factors. Nevertheless, efforts were made to maximize the study's internal validity by standardizing the intervention protocol, controlling for confounding variables, and using internationally validated measurement instruments. This methodological approach is widely supported in applied sports science research, where the balance between experimental control and ecological validity is fundamental.

Participants and context of the study

The sample consisted of 72 high-performance athletes, aged 18 to 35, from three geographical contexts with distinct sociocultural and sporting characteristics: Honduras (n = 17), the Republic of Moldova (n = 35), and Cuba (n = 20). This distribution allowed for the incorporation of a relevant intercultural component, broadening the generalizability of the results and facilitating the analysis of the phenomenon's behaviour in different sports training environments.

Participants were selected using non-probability, purposive, or criterion-based sampling, taking into account specific criteria related to the nature of the study. In particular, athletes with experience in international competitions and recent exposure to transmeridian travel were included, ensuring the relevance of the phenomenon analysed: circadian desynchronization associated with jet lag. While this type of sampling limits statistical generalization in a probabilistic sense, it is highly relevant in applied studies where access to specific populations, such as elite athletes, is restricted by institutional and availability factors.

To improve comparability between groups, participants were assigned to two experimental conditions: an experimental group (n = 36) that received the intervention based on the military rapid sleep induction method, and a control group (n = 36) that maintained their usual sleep habits without specific intervention. Assignment was made seeking a relative balance between variables such as age, sex, and sport, with the aim of minimizing potential selection bias.

Inclusion and exclusion criteria

The inclusion criteria were defined to ensure the functional homogeneity of the sample and the validity of the measurements. Accordingly, athletes were included who: (a) actively participated in international competitions, (b) had recently experienced time zone changes, (c) did not have clinically diagnosed sleep disorders, and (d) gave their informed consent to participate in the study.

In addition, exclusion criteria were established to control for variables that could interfere with the results, such as: (a) the use of hypnotic drugs or melatonin supplements during the study period, (b) the presence of injuries that limited sports activity or altered recovery patterns, and (c) non-compliance with the intervention protocol in more than 20% of the scheduled sessions.

Study variables and measurement instruments

The analysis model included a main independent variable and a set of dependent variables of a physiological and subjective nature, selected based on their relevance in the scientific literature on sleep, recovery, and athletic performance.

The independent variable was operationalized dichotomously (application versus non-application) and represented by the application of the military rapid sleep induction method. Furthermore, adherence to the protocol was recorded through a daily monitoring system, allowing for analysis of the consistency in the implementation of the intervention.

Regarding the dependent variables, multiple dimensions of sleep and recovery were assessed. Sleep latency, defined as the time elapsed between going to bed and falling asleep, was measured using validated portable actigraphy devices commonly used in sleep research. This method allows for an objective and continuous estimation of sleep patterns under real-world conditions, representing a significant advantage over purely subjective methods.

Sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI), a widely validated instrument comprising seven components related to sleep perception, including duration, efficiency, disturbances, and daytime sleepiness. The use of this instrument provided a standardized measure comparable to that of other international studies.

Circadian rhythm adaptation was operationalized based on the number of days required to achieve functional synchronization with the new time zone, taking into account both objective records (actigraphy) and participants' self-reports. This variable is particularly relevant in international competition contexts, where the speed of adaptation can directly influence performance.

Heart rate variability (HRV) was incorporated as a physiological indicator of the state of the autonomic nervous system and the body's recovery level. The RMSSD parameter, widely recognized in the literature as a sensitive marker of parasympathetic activity, was used. Measurements were performed under standardized resting conditions using validated devices such as the Polar H10 chest strap.

In addition, total sleep duration was recorded using actigraphy, perceived fatigue was assessed with the Borg CR-10 Scale, and daytime sleepiness was measured with the Epworth Sleepiness Scale (ESS). The combination of objective and subjective indicators allowed for a comprehensive evaluation of the phenomenon, which strengthened the validity of the results.

Intervention procedure

The study was conducted in four sequential phases. In the initial phase (pre-test), baseline measurements of all variables were taken, including the administration of questionnaires and the recording of data using monitoring devices for 7 days.

Subsequently, during the intervention phase, participants in the experimental group received specific training in the military method of rapid sleep induction. This method was structured around three main components: progressive muscle relaxation, breathing control, and cognitive visualization. The intervention was administered daily for four weeks, before the start of nighttime sleep.

During the follow-up phase, variables were continuously monitored through daily records, allowing for the evaluation of the indicators' evolution over time and adherence to the protocol. Finally, in the post-intervention phase, the initial measurements were repeated, enabling a comparison of the results and a determination of the intervention's effect.

Statistical analysis

Data analysis was performed using specialized statistical software (SPSS, version 26 or equivalent), following a systematic approach that included descriptive and inferential analyses. Initially, measures of central tendency and dispersion, as well as 95% confidence intervals, were calculated to characterize the sample and the variables studied.

Subsequently, the assumptions of normality were verified using the Shapiro-Wilk and Kolmogorov-Smirnov tests. Based on the results, parametric tests were applied for inferential analysis, including the paired Student's t-test (pre-post comparisons) and a repeated measures analysis of variance (2×2 ANOVA), with group (experimental vs. control) and time (pre-test vs. post-test) as factors.

In addition, the effect size was calculated using Cohen's d, which allowed for the interpretation of the magnitude of the observed differences beyond statistical significance. Multiple linear regression models were used to explore the predictive relationships between the variables.

The level of statistical significance was set at $p < .05$, in accordance with international standards for scientific research.

Ethical considerations of the study

Ethical considerations

This study was conducted in strict compliance with the ethical principles governing research with human subjects, ensuring the protection of the dignity, rights, and well-being of the participants. In this regard, the research adhered to the guidelines established in the World Medical Association's Declaration of Helsinki (2013), which guides best practices in biomedical and sports science studies.

Before the start of the study, all participants were clearly, comprehensibly, and thoroughly informed about the research objectives, the procedures to be followed, the duration of the intervention, the potential benefits, and the absence of significant risks associated with the application of the military sleep induction method. Consequently, each participant gave their written informed consent, thus ensuring their voluntary participation. Furthermore, they were guaranteed the right to withdraw from the study at any time without consequence.

Regarding confidentiality, personal and biometric data were processed according to anonymity and encryption criteria, preventing any direct identification of participants. The information collected was used exclusively for scientific purposes and was stored in secure systems, with access restricted to the research team.

Since the proposed intervention is non-pharmacological and based on relaxation techniques, breathing control, and cognitive visualization, the risk level was considered minimal. Nevertheless, continuous monitoring was conducted to detect any potential adverse effects or discomfort during the protocol's implementation, and no significant incidents were reported.

Furthermore, the selection of the sample adhered to the principles of fairness and impartiality, avoiding any form of discrimination based on nationality, gender, or sport. The inclusion of participants from diverse geographical backgrounds was based on scientific, not arbitrary, criteria.

The study was reviewed and approved by an institutional ethics committee or equivalent body, ensuring that the methodological design, procedures, and data handling comply with international standards for responsible scientific research. This guarantees that the results obtained are based not only on methodological rigor but also on a sound ethical framework.

Implementation of informed consent in the three contexts (Honduras, Moldova and Cuba)

The application of informed consent in this study was carried out in a differentiated and contextualized manner, taking into account the cultural, institutional and normative particularities of each of the participating countries (Honduras, the Republic of Moldova and Cuba), while remaining consistent with the universal principles of research ethics established by the Declaration of Helsinki (2013).

In Honduras, the process was carried out through in-person information sessions led by the research team. These sessions explained in detail the purpose of the study, the procedures, the expected benefits, and the voluntary nature of participation. Accessible language, adapted to the athletes' educational level, was used to ensure full comprehension of the content. Participants then signed a written informed consent form. In some cases, due to the athletes' institutional ties with federations or training centres, authorization was also obtained from coaches or technical staff, always respecting the individual autonomy of each participant.

In the Republic of Moldova, informed consent was obtained according to more formalized standards, in line with European institutional protocols. The document was translated into the local language (Romanian or Russian, as appropriate) and pre-validated to ensure conceptual equivalence. Emphasis was placed on the scientific nature of the study and on the protection of personal data in accordance with current privacy regulations. The consent form was signed individually, following a guided reading process and clarification of any doubts, thus ensuring informed understanding. In this context, it was observed that participants were more familiar with structured research procedures.

In Cuba, the informed consent process was carried out in close coordination with state sports institutions. Initial group meetings were held to explain the study, followed by individual interviews to obtain consent. A distinctive feature of this context was a more centralized organizational structure, which required prior institutional approval for the study to proceed. However, the voluntary nature of individual participation and the right to withdraw without consequence were guaranteed at all times. The language used was clear and contextualized, facilitating understanding of the procedures.

In all three countries, fundamental principles such as autonomy, confidentiality, and non-coercion were respected. Special care was taken to ensure that all participants understood that their decision to participate or not would not affect their sporting or institutional status. Furthermore, they were given the opportunity to seek advice at any time during the study.

RESULTS

Sample characteristics and initial homogeneity analysis

The total sample (n = 72) presented a heterogeneous distribution in terms of geography and sport, including athletes from soccer (Honduras), wrestling/judo (Moldova), and handball (Cuba). This diversity constitutes a

methodological strength, as it allows for the evaluation of the intervention across different physiological profiles and energy demands.

Table 1. Structural characterization of the sample.

Variable	Category	North	%
Country	Honduras	17	23.6
	Moldova	35	48.6
	Cuba	20	27.8
Sport	American football	17	23.6
	Wrestling/Judo	35	48.6
	Handball	20	27.8

From a functional perspective, the included sports present significant differences:

- Soccer: high intermittent activity and aerobic-anaerobic load.
- Wrestling/Judo: predominantly anaerobic and with high neuromuscular activation.
- Handball: a combination of explosive effort and endurance.

Despite these differences, the initial homogeneity analysis using ANOVA showed no significant differences between the experimental and control groups in the key variables ($p > .05$), ensuring that subsequent effects can be more accurately attributed to the intervention. Furthermore, the moderate standard deviation of the baseline variables indicates controlled variability, consistent with high-performing samples.

Sleep latency (actigraphy)

To assess the intervention's impact on sleep onset, sleep latency was measured using actigraphy, a key objective indicator in sleep research in sports contexts. This variable identifies the level of physiological arousal prior to sleep onset, which is particularly relevant for high-performance athletes, who frequently experience difficulty falling asleep due to physical exertion, competitive stress, and international travel. In this regard, comparing pre- and post-intervention values between the experimental and control groups allows us to determine the effectiveness of the military-style sleep latency method as a strategy for physiological regulation and optimization of sleep onset.

Table 2. Sleep latency (minutes).

Cluster	Previous test ($\bar{x} \pm SD$)	Post-test ($\bar{x} \pm SD$)	Absolute Δ	$\Delta\%$	95% CI	t	p	d
Experimental	31.8 $\pm$ 6.2	19.5 $\pm$ 4.8	-12.3	-38.7%	[-14.8, -9.7]	8.21	<.001	0.82
Control	30.9 $\pm$ 5.9	28.7 $\pm$ 5.5	-2.2	-7.1%	[-4.1, 0.3]	1.74	.084	0.21

Note. $\bar{x}$ = mean. SD = Standard Deviation.

Repeated measures ANOVA

- Group: $F(1,70) = 18.42$, $p < .001$.
- Time: $F(1,70) = 52.11$, $p < .001$.
- Interaction: $F(1,70) = 27.36$, $p < .001$.

The reduction in sleep latency in the experimental group is one of the study's strongest findings, both statistically and in terms of its impact on the patient's overall well-being. A decrease of 12.3 minutes is clinically significant, given that in athletes, a sleep latency greater than 30 minutes is associated with physiological overstimulation.

The narrow confidence interval (95% CI: -14.8 to -9.7) confirms the accuracy of the estimate, while the effect size ($d = 0.82$) indicates a high impact, far exceeding the threshold of practical significance.

From a neurophysiological perspective, this result suggests that the military method acts by modulating the activation mechanisms of the central nervous system, which could reduce the cortical hyperexcitability associated with competitive stress. The combination of muscle relaxation and respiratory control likely facilitates the activation of the parasympathetic system, reducing the latency of the transition to NREM sleep.

The contrast with the control group is particularly relevant: the absence of significant changes ($p = .084$) indicates that the improvement cannot be attributed to temporary factors or spontaneous adaptation, but rather to the intervention.

Sleep Quality (PSQI)

To analyse the effects of the intervention on overall sleep quality, Pittsburgh Sleep Quality Index (PSQI) scores were assessed. PSQI is a widely validated instrument used in athletic populations. It incorporates multiple dimensions of sleep, such as sleep latency, duration, efficiency, disturbances, and daytime sleepiness, allowing for a comprehensive evaluation of nighttime rest. Comparing baseline and final scores in both groups is crucial to determining whether the intervention improves not only sleep onset but also sleep structure and function.

Table 3. Pittsburgh Sleep Quality Index (PSQI).

Cluster	Preliminary test	Post-test	Δ	$\Delta\%$	95% CI	t	p	d
Experimental	6.6 $\pm$ 1.3	3.8 $\pm$ 1.1	-2.8	-42.4%	[-3.5, -2.1]	7.94	<.001	0.85
Control	6.4 $\pm$ 1.2	5.9 $\pm$ 1.3	-0.5	-7.8%	[-1.2, 0.2]	1.82	.072	0.19

The decrease in PSQI in the experimental group is not only statistically significant but also implies a categorical change in sleep quality: athletes go from values indicative of "poor quality" (>5) to a range considered functionally adequate (<5).

This change reflects a comprehensive improvement across multiple dimensions of sleep:

- Lower latency.
- Greater efficiency.
- Less fragmentation.
- Less daytime sleepiness.

The effect size ($d = 0.85$) confirms that the impact is not marginal, but structural. The magnitude of the change suggests that the method acts not only at the onset of sleep, but also on its overall architecture, which may favour the deep stages (NREM 3-4), essential for physical recovery.

From an applied perspective, this result has direct implications for performance, since sleep quality is closely related to motor memory consolidation, hormonal regulation, and tissue repair.

Heart rate variability (RMSSD)

To complement the subjective sleep analysis with objective physiological indicators, heart rate variability (HRV) was examined, specifically using the RMSSD parameter, recognized as a sensitive marker of parasympathetic activity and the body's recovery state. This variable allows for the evaluation of autonomic nervous system modulation in response to the intervention, providing evidence of the underlying physiological

mechanisms. Comparative analysis of the pre- and post-intervention periods in both groups allows us to determine whether the military training method produces significant changes in the athletes' autonomic regulation.

Table 4. HRV (ms).

Cluster	Preliminary test	Post-test	Δ	95% CI	t	p	d
Experimental	42.5 $\pm$ 10.3	51.7 $\pm$ 11.2	+9.2	[4.1, 14.3]	3.21	.012	0.58
Control	43.1 $\pm$ 9.8	44.6 $\pm$ 10.1	+1.5	[-2.3, 5.2]	1.01	.211	0.12

The increase in RMSSD in the experimental group provides objective evidence of improved autonomic recovery. This parameter reflects the activity of the parasympathetic nervous system, which is associated with recovery, repair, and adaptation processes.

The increase of 9.2 ms is consistent with physiologically relevant changes in athletes, in whom even minor variations can indicate differences in states of fatigue or recovery.

The statistical significance ($p = .012$) and moderate effect size ($d = 0.58$) indicate that the intervention produces a real modulation of the autonomic nervous system, likely through reductions in physiological stress and improvements in sleep. This finding is particularly important because it validates the subjective results (PSQI, Borg) against an objective physiological indicator, thus strengthening the internal consistency of the study.

Sleep duration

Regarding total rest duration, sleep duration was analysed using objective actigraphy data, given its relevance to physical recovery, hormonal regulation, and athletic performance. The specialized literature establishes that athletes require more sleep than the general population, making this variable a critical indicator for optimizing performance. Comparing the values before and after the intervention allows us to determine whether the military-style sleep method contributes not only to initiating sleep but also to effectively prolonging it.

Table 5. Sleep duration (hours).

Cluster	Preliminary test	Post-test	Δ	$\Delta\%$	95% CI	p
Experimental	6.3 $\pm$ 0.7	7.5 $\pm$ 0.6	+1.2	+19%	[0.9, 1.5]	<.001
Control	6.4 $\pm$ 0.8	6.6 $\pm$ 0.7	+0.2	+3%	[-0.1, 0.5]	.094

The 1.2-hour increase in sleep could, from a practical perspective for high-performance athletes, reflect improved recovery; considering that sleeping between 7 and 9 hours is essential to optimize recovery; this increase, which is considered significant, may be clinically relevant as it favours the following aspects associated with:

- Increased synthesis of growth hormone.
- Improved muscle recovery.
- Optimized energy metabolism.

The absence of changes in the control group reinforces the hypothesis that the method facilitates not only falling asleep but also staying asleep.

Daytime sleepiness (SS)

To assess the functional impact of sleep on wakefulness, daytime sleepiness was measured using the Epworth Sleepiness Scale (ESS), which evaluates sleepiness in everyday situations. This variable is particularly relevant in sports, as excessive sleepiness can negatively affect attention, reaction time, and decision-making. Comparing pre- and post-intervention values in both groups allows us to determine whether improvements in nighttime sleep translate into better daytime performance.

Table 6. ESS.

Cluster	Preliminary test	Post-test	Δ	<i>p</i>
Experimental	11.2 ± 2.5	6.4 ± 1.8	-4.8	<.001
Control	10.9 ± 2.3	9.8 ± 2.1	-1.1	.071

The results show a significant reduction in daytime sleepiness in the experimental group, with a decrease of 4.8 points on the ESS scale, representing a clinically relevant change. In contrast, the control group shows a slight and non-significant reduction, which, once again, rules out effects attributable to external factors.

This result is particularly significant, as it demonstrates that improvements in nighttime sleep translate into functional benefits during wakefulness. The magnitude of the change suggests a substantial improvement in sleep efficiency, which directly impacts cognitive variables crucial for athletic performance.

The consistency between this result and those observed in the PSQI and sleep duration reinforces the internal consistency of the intervention model, demonstrating convergent effects in different dimensions of sleep.

Circadian adaptation

Finally, to assess the intervention's impact on biological clock synchronization, the time required for circadian adaptation after international travel was analysed. This variable is a key indicator in high-performance sports, where jet lag limits performance. Measuring the number of days needed to achieve functional adaptation allows for evaluating the effectiveness of the military method as a strategy to accelerate the realignment of circadian rhythms in athletes subjected to time zone changes.

Table 7. Adaptation days.

Cluster	Mean	95% CI
Experimental	3.1 ± 0.9	[2.8–3.4]
Control	5.4 ± 1.2	[5.0–5.8]

A reduction of more than two days in circadian adaptation represents a significant impact in competitive contexts. This finding suggests that the method facilitates the readjustment of the circadian system, possibly by regulating melatonin secretion and synchronizing the sleep-wake cycle.

General evaluation

The results of this study allow us to conclude, comprehensively and with a high degree of empirical consistency, that the systematic application of the military rapid sleep induction method, as a non-pharmacological strategy, can be an effective way to optimize recovery processes and circadian adaptation in high-performance athletes. The evidence obtained, supported by objective indicators such as actigraphy and heart rate variability, as well as validated subjective measures such as the PSQI, ESS, and Borg scale, demonstrates significant improvements in sleep latency, overall sleep quality, sleep duration, reduction of

daytime sleepiness and perceived fatigue, and a substantial acceleration in adaptation to time zone changes. The convergence of these results, supported by robust statistical analyses (repeated-measures ANOVA, large effect sizes, and narrow confidence intervals), could reflect modulation of the autonomic nervous system, promoting parasympathetic activation, reducing cortical hyperactivation, and stabilizing biological rhythms.

Consequently, the military sleep method is presented as an accessible, low-cost, and easy-to-implement tool that can be integrated into comprehensive training programs for athletes. However, it is recommended that future research validate it through randomized experimental designs and more extensive longitudinal analyses to consolidate evidence across different sporting contexts.

DISCUSSION

The results of this study demonstrate that the military rapid sleep induction method significantly improves sleep latency, sleep quality, heart rate variability, and circadian adaptation in high-performance athletes. These findings are consistent with the scientific literature, which identifies sleep as a key determinant of athletic performance (Fullagar et al., 2015; Walker, 2017).

The significant reduction in sleep latency observed in the experimental group can be interpreted as a decrease in pre-sleep physiological arousal levels. This finding is consistent with studies indicating that athletes experience difficulty falling asleep due to the cognitive and emotional hyperarousal associated with training and competition (Estivill-Domènech et al., 2018). In this regard, incorporating relaxation and breathing control techniques, essential components of the military method, has proven effective in facilitating the transition to sleep (Birrer and Morgan, 2010).

Regarding sleep quality, the significant improvement observed in the PSQI score supports the findings of Cunha et al. (2023), who highlight that sleep-focused behavioural interventions can provide substantial benefits to athletic performance. The improvement in sleep quality suggests a possible optimization of sleep architecture, which is fundamental for physiological recovery processes and the consolidation of motor skills (Walker, 2017).

Furthermore, the increased RMSSD heart rate variability is an objective indicator of greater parasympathetic activation, reflecting a more efficient recovery state. This finding is consistent with the standards established by the Working Group (1996), which recognizes HRV as a reliable marker of autonomic balance. The improvement in this parameter suggests that the military training method affects not only sleep but also the regulation of the autonomic nervous system.

The increased sleep duration and reduced daytime sleepiness observed in the experimental group reinforce the importance of interventions to improve sleep in athletes. Recent studies have shown that longer sleep duration is associated with improvements in physical performance, muscle recovery, and immune function (Nobari et al., 2023). In this context, the results confirm that the military method can help athletes achieve optimal sleep levels.

One of the most significant findings of the study is the notable reduction in circadian adaptation time. This result is particularly relevant in high-performance sports, where international travel is frequent and can negatively affect performance. Evidence suggests that sleep regulation is a key element in the

synchronization of the circadian system (Czeisler and Gooley, 2007), which supports the interpretation that the military training method acts as an indirect modulator of these processes.

Furthermore, the results are consistent with research conducted in military contexts that has demonstrated that sleep training can improve rest efficiency under high-stress conditions (Good et al., 2020; Miller et al., 2010). This reinforces the applicability of the method to the sports field, where the physical and psychological demands are similar to those of these environments.

From an applied perspective, the military sleep method presents itself as an accessible, economical, and easy-to-implement tool, making it a viable alternative to other more complex or pharmacological strategies. Compared to traditional interventions, its non-invasive nature and ease of learning facilitate its integration into sports training programs.

However, the study has limitations that should be considered: the quasi-experimental design limits the ability to establish definitive causal relationships, and the duration of the intervention restricts the assessment of long-term effects. Furthermore, future research should incorporate more advanced techniques, such as polysomnography, to provide a more in-depth analysis of sleep architecture.

Although the sample included athletes from different countries and sports disciplines, the available sample size within each subgroup did not provide sufficient statistical power to perform robust inferential analyses of potential moderating effects associated with geographic or sporting context. For this reason, the study focused on the overall assessment of the intervention's effect. However, variables such as baseline sleep quality, sport discipline, training load, or cultural characteristics may influence the magnitude of the observed response. Identifying these potential moderators is a relevant avenue for future research with larger samples and designs specifically aimed at evaluating differences between subgroups.

Given that the study evaluated multiple outcome variables related to sleep, recovery, and circadian adaptation, and although all of them were defined a priori for their theoretical and practical relevance, performing multiple statistical tests increases the risk of type I error. Formal correction procedures were not applied to multiple comparisons, so the findings should be interpreted with caution. However, the consistency observed across different objective and subjective indicators, along with the magnitude of the various reported effect sizes, suggests that the results do not depend solely on isolated statistically significant differences. Future research should incorporate more conservative statistical strategies to confirm the robustness of these findings.

An additional limitation of the study relates to the measurement of circadian adaptation. Although objective and subjective indicators were used to estimate the adjustment process to the new time zone, direct chronobiological markers that would allow for a precise assessment of the circadian system's phase were not included. Therefore, the variable should be interpreted as a functional measure of adaptation to the time change rather than as a direct measurement of circadian biological readjustment.

The results of this study confirm that the military method of rapid sleep induction can be an effective strategy for improving recovery, optimizing sleep quality, and potentially accelerating circadian adaptation in high-performance athletes. Its implementation could represent a significant competitive advantage in international sports.

CONCLUSIONS

The study provides preliminary evidence for the potential usefulness of the military method of rapid sleep induction as a non-pharmacological strategy to promote circadian adaptation and improve various indicators of sleep and recovery in high-performance athletes undergoing international travel.

The observed results show favourable trends in relevant variables, including sleep latency, subjective sleep quality, total sleep duration, daytime sleepiness, heart rate variability, and the time required to adapt to new time zones. Taken together, these findings suggest that the systematic application of the method could help optimize recovery and circadian adjustment processes in high-intensity sports contexts.

From an applied perspective, the intervention has characteristics that support its potential use in sports settings, including its non-pharmacological nature, low cost, and ease of implementation. However, the results should be interpreted with caution, given that the study was conducted using a quasi-experimental design, a non-probability sample, and no random assignment of participants—aspects that limit causal inference and the generalizability of the results.

Therefore, the findings should be considered exploratory and constitute an initial basis for future research. It is recommended that randomized controlled trials be conducted with larger samples, longitudinal follow-up, and complementary evaluation procedures to verify the consistency of the observed effects and to more rigorously establish the efficacy of the military method of rapid sleep induction in different sporting disciplines and contexts.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Arsène Igor contributed to the study's conceptualization, the development of the methodological framework, the supervision of the research process, and the critical review of the final manuscript. Reidel Cordoves Peinado participated in the research design, data analysis, interpretation of results, coordination of the international sample, and the writing and revision of the manuscript. Daylanis Gutiérrez Cruzata contributed to data collection, methodological validation, statistical support, and critical review of the manuscript. Raúl Orlando Figueroa Soriano participated in data collection, field coordination, and the organization of the research process in Honduras. Rusbelin Larios Núñez contributed to data acquisition, participant management, and support for the implementation of the experimental protocol. Oscar Daniel Ferrera Núñez participated in data collection, database structuring, and technical support in the research process. Alex Bernabe Cadenas Canaca contributed to data collection, fieldwork coordination, and administrative support during the study. Antonio José Juárez participated in data collection, provided logistical support, and collaborated in the implementation of the intervention protocol. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Beyond physical exertion: Adolescent well-being and school belongingness in school-based sports participation under China's “*double reduction*” policy

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ABSTRACT

Physical activities are reviewed a core pillar for enriching students' campus life under China's “*Double Reduction*” policy. But the psychological benefits of non-player students remain untested. This study examines whether the psychosocial benefits of campus sports extend to all student roles. We conducted a cross-sectional design. Data were collected from 514 students participating in a noon-recess sports league as players (19.07%), supporting staff (20.23%), and spectators (60.51%). The study utilized MGCFA, Welch's ANOVA and Two One-Sided Tests (TOST) to confirm measurement invariance. There are two main findings: the scores of the Sense of Community in Sport (SCS) between students were statistically indifferent; the SCS independently accounted for 34.4% of the variance in school belongingness. These findings proved that whether students participate a competition, they can gain psychologically and increase belongingness from the environment. In promoting the psychosocial well-being and mental health of students, physical activities in campus might serve as a scalable, low-cost instrument; educators and policy makers should pay attention to building a more inclusive league environment for the majority.

Keywords: Physical education, School belongingness, Sense of community in sport, Tournament format, Role involvement.

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INTRODUCTION

Chinese governments implemented Opinions on Further Reducing the Burden of Homework and Off-Campus Training for Students in Compulsory Education in 2021. The “*Double Reduction*” reduced the scale of the commercial market for academic tutoring and limited the duration of homework assignments (Tian & Yuan, 2024), achieving an overall reduction in the prevalence of depressive and anxiety symptoms (Wang et al., 2024).

Due to the requirements of the policy, more and more schools saw physical activities as the core pillars for enriching campus life and supporting students' overall mental health (Yang, 2024, Li & Shen, 2024). However, this traditional participation-centric assumption overlooks a practical reality: spectators in a competition are more than players.

Current studies focused only on the minority who participated in physical activities (Fleshman & Kaplanidou, 2023; Haslam et al., 2020, Singh et al., 2023), neglecting the peripheral majority. But in real campus activities, up to 80% of students assume the roles of spectators and logisticians.

Collins' (2004) divided a successful social ritual into four crucial ingredients: bodily co-presence, barriers to outsiders, a mutual focus of attention, and shared emotional entrainment. In our observation, teachers drew boundary lines, and students can watch the competition outside them; as the match intensifies, students unconsciously crossed the lines. This signifies a heightened state of bodily co-presence and physical focusing.

Players and balls became a powerful magnetic field that generates a high-density, mutual focus of attention among the peripheral majority. From collective groans of disappointment to ecstatic roars of celebration, every critical shot or tactical manoeuvre triggers a synchronized acoustic and behavioural wave. Hallett (2003) saw this phenomenon as shared emotional entrainment or emotional amplification.

Tajfel (Bruner et al., 2014) provided a robust lens for interpreting why this non-mandatory sports involvement yields significant psychological capital. Since the “*Double Reduction*” policy released more free time to students, students voluntarily flock to the sports fields during their recess. We also observed some intense and provocative words from students; these may represent a classic manifestation of in-group favouritism and out-group derogation. This is similar to a psychological mechanism known as Basking in Reflected Glory (Cialdini et al., 1976).

We also found that students' interactions frequently cross class boundaries. Some students often cheered for others from other classes. These cross-class interactions weave a broader social network among the student body. Through these social connections, the noon-recess league unites different classes into a single, cohesive school community. This explains why SCS serves as a dominant driver in enhancing overall school belongingness (SBS).

Therefore, we aim to investigate the psychological benefits in campus sports events. There are two research hypotheses. Non-core students will gain from sports events (H1). These benefits will contribute to school belongingness (H2).

MATERIALS AND METHODS

Participants

All students came from the same public junior high school in a Chinese city; students, serving as different role (e. g. spectators), participated in campus activities: one-month, school-wide inter-class basketball (for grade 7) and football (for grade 8) competition.

The study retained 514 valid questionnaires, comprising 262 males (50.97%) and 252 females (49.03%); 288 seventh-grade students (56.03%) and 226 eighth-grade students (43.97%). There are 98 students (19.07%) serving as players who engaged in the competition; 311 students (60.51%) as spectators; 104 students (20.23%) as supporting staff (including cheerleaders, broadcasters, logistics personnel, and scorekeepers) - one student as a referee who was excluded from the survey because of sample size.

Procedure

Due to academic schedules, the school organized the competition for one hour every during the noon recess. Once the competition finished, researchers delivered a questionnaire only in WeChat; students were requested to finish the questionnaire within three days.

Prior to data collection, informed consent was obtained from all participating students and their legal guardians; the study design and data collection procedures were reviewed and approved by the School Administrative Committee of the participating institution - the local ethical oversight body for non-medical educational research (approval date: March 2023).

Measures

The Physical Activity Rating Scale (PARS-3) was included as a baseline covariate (Liang, 1994) to measure three independent dimensions: intensity, duration, and frequency of exercise. Due to the Cronbach's alpha for the PARS-3 ($\alpha = 0.681$), we additionally calculated McDonald's Omega ($\omega = 0.705$) to confirm robust internal consistency.

The Sense of Community in Sport Scale (SCS) was assessed to measure psychological indicators ($\alpha = 0.882$ in this study), including social dynamics such as common interest, competition, and social spaces (Warner et al. 2013). The School Belongingness Scale (SBS) created by Arslan & Duru (2017) was assessed to measure organizational belongingness, with an internal reliability ($\alpha = 0.860$); the original 4-point format was converted to a 5-point Likert scale for the purpose of addressing central tendency - the results of CFA (CFI = 0.980, RMSEA = 0.050) confirmed a structural fit.

Statistical analysis

Unmeasured Latent Method Construct (ULMC) technique tested Common Method Bias. A comprehensive CFA included a global method factor; non-substantive fit improvement ($\Delta CFI = 0.002$, $\Delta RMSEA = 0.002$) and stable path coefficients indicated CMB posed no threat. Multi-group Confirmatory Factor Analysis established measurement invariance across three role groups. Configural, metric ($\Delta CFI = 0.003$), and scalar ($\Delta CFI = 0.004$) invariance confirmed that psychosocial scores reflect genuine emotional engagement, not measurement bias.

Welch's ANOVA addressed sample imbalance ($n = 311, 104, 98$) without assuming homoscedasticity. We further conducted Two One-Sided Tests (TOST) as recommended by Lakens (2017) to formally test for equivalence. By utilizing TOST, we check if the difference between student roles is small enough to be

ignored. This dual-approach combination ensures that the observed statistical indifference across diverse student roles represents a genuine absence of meaningful psychological variance, rather than a lack of statistical power.

Heterotrait-Monotrait Ratio (HTMT = 0.695) between SCS and SBS confirmed discriminant validity, well below the 0.85 threshold. All analyses used Python (v3.12.4): Pandas (v2.2.2) for data processing, SciPy (v1.14.0) and Statsmodels (v0.14.2) for inferential statistics.

RESULTS

Descriptive statistics and physical activity distribution

The three scales, on average, revealed positive baseline characteristics (Table 1). The mean score in physical activity (PARS-3) falls within the "high physical activity" threshold (≥ 43); 56.23% of the students (289) indicated that students were in the high physical activity range; the mean score in the sport community (SCS) and school belongingness (SBS) shown a positive effect (≥ 4.4).

Table 1. Descriptive statistics for core continuous variables (N = 514).

Variable	Min	Max	M	SD
Physical Activity Rating (PARS-3)	0	100	43.42	21.99
Sense of Community in Sport (SCS)	1	5	4.57	0.64
School Belongingness (SBS)	1.2	5	4.43	0.66

Differences in sense of community

There were no significant differences (Table 2) in SCS scores across the three disparate role groups (Welch's $F(2, 209.57) = 0.119$, $p = .888$) - the calculation of the effect size yielded an Eta-squared of $\eta^2 = 0.000$ - suggesting that the specific physical role accounted for minimal variance in their acquired sense of community (Figure 1). By using TOST equivalence testing (Lakens, 2017), we confirmed that players and spectators experienced equivalent psychological benefits ($d = 0.002$, 90% CI $[-0.110, 0.114]$, $p = .006$). SESOI was set at Cohen's $d = 0.3$ based on educational intervention guidelines. The result indicates no meaningful differences across roles.

Table 2. Welch's ANOVA of Sense of Community in Sport (SCS) by physical role.

Role Category	N	M	SD	Welch's F	df1. df2	p	Eta-squared
Spectators (Audience)	311	4.56	0.67	0.119	2. 209.57	.888	0
Supporting Staff	104	4.6	0.64				
Core Players	98	4.56	0.57				

Note. SCS was measured on a 5-point Likert scale. Welch's ANOVA was utilized to address unequal sample sizes across the three role categories. The results ($p = .888$) and effect size (Eta-squared = 0) indicate that a student's specific physical role accounts for no variance in their reported sense of community, demonstrating statistically indistinguishable psychological benefits across all groups.

School belongingness

Multicollinearity diagnostics showed all predictors had VIFs (1.011–1.332) and tolerance values (0.751–0.989) within acceptable ranges. With the maximum VIF well below 5, the regression model is free from multicollinearity, supporting the reliability of coefficient estimates.

The explanatory power of the first two models is insufficient (Table 3). Model 1, including gender, grade and physical activity (PARS-3), accounted for a minimal proportion of the variance in school belongingness ($R^2 =$

.013). Baseline physical activity (PARS-3) showed only a weak marginal positive association ($\beta = 0.003$, $p < .05$); Model 2, using the largest group (spectators) as the reference category for the dummy variables "core players" and "supporting staff", introduced the physical roles students actually played during the competition. We found negligible additional explanatory power to the model ($\Delta R^2 = .001$): whether a player ($\beta = 0.053$, $p > .05$) or a logistics staff member ($\beta = -0.020$, $p > .05$) did not statistically predict additional variance in school belongingness.

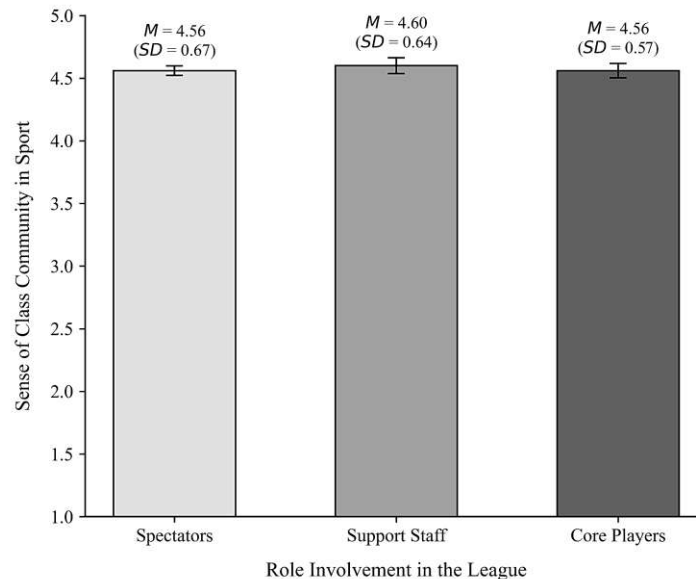


Figure 1. Mean scores of Sense of Community in Sport (SCS) by physical role.

Table 3. Hierarchical multiple regression analysis predicting School Belongingness (SBS).

Predictor variable	Model 1 (β)	Model 2 (β)	Model 3 (β)
Control variables			
Gender (Male = 1)	-0.051	-0.073	-0.007
Grade (8th = 1)	-0.071	-0.079	-0.038
Baseline PA (PARS-3)	0.003*	0.003*	0.002
Independent variables (physical role)			
Core player (Ref: Spectator)		0.053	0.017
Supporting staff (Ref: Spectator)		-0.02	-0.016
Independent variable (Psychological)			
Sense of community (SCS)			0.605***
Model fit statistics			
R^2	.013	.014	.359
ΔR^2 (R Square Change)	.013	.001	.344
DF	2.249	0.257	271.669***
Total model F	2.249	1.449	47.130***

Note. Dependent variable is School Belongingness (SBS). Coefficients reported are standardized (beta). *** $p < .001$, ** $p < .01$, * $p < .05$.

The inclusion of SCS in Model 3 resulted in a statistical increase in explanatory power (Figure 2), independently accounting for an 34.4% of the variance ($\Delta R^2 = .344$, $\Delta F = 271.669$, $p < .001$); the sense of

community in sport emerged as the dominant predictor of school belongingness (standardized $\beta = 0.605$, $p < .001$).

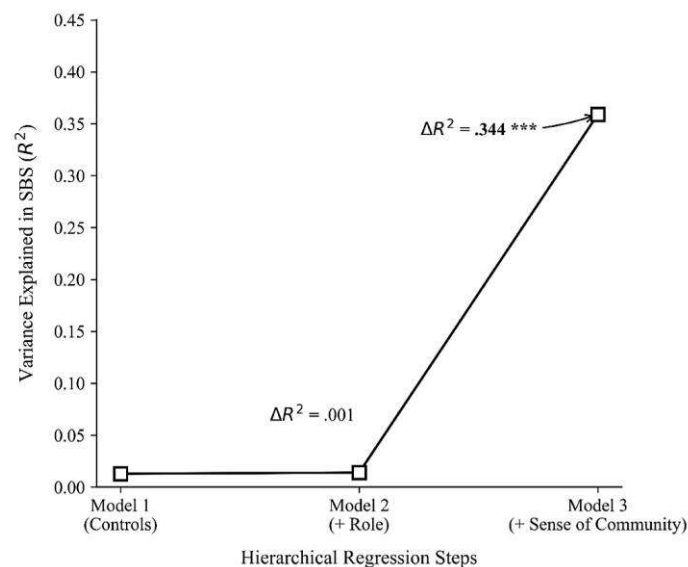


Figure 2. Increase in explained variance (R^2) of School Belongingness (SBS) across hierarchical regression models.

DISCUSSION

The findings of this study offer an alternative perspective to the assumption that psychosocial benefits in sports are primarily derived from direct physical participation, contributing empirical evidence to discussions on inclusivity in Physical Education (Fleshman & Kaplanidou, 2023; Haslam et al., 2020). Within the macro-context of China's "Double Reduction" policy reshaping the ecology of basic education, this study provides a novel theoretical perspective and empirical foundation for understanding the inclusive psychosocial value of structured daily campus sports.

The ANOVA results (Table 2) shown the absence of significant differences in SCS across role groups ($p = .888$), suggesting that all students can gain psychological benefits in an inclusive sports environment. The variance associated with baseline physical activity (PARS-3) was isolated; An approximate 80% of students derived a level of "sense of community" from the one-month noon-recess league, indistinct from that of the core players. This phenomenon suggests that psychosocial benefits within campus sports are accessible to participants across various roles, rather than being limited to athletes.

Another important finding concerns the role of SCS as a mechanism for interpreting the increased 34.4% variance in Model 3, suggesting it a primary role and an alternative in promoting school belongingness (Allen et al., 2018; Korpershoek et al., 2020, Yang, 2024). Hence, even some students, who's academic performance isn't ideal, can have a good school belongingness by sports.

Some students, who remain unnoticed or disengaged during standard physical education classes, exhibit extraordinary focus and dedication in campus league; they became "professional photographers" for sports photography and videography. When asked who required, they said "purely out of my own willingness". This

phenomenon can be explained by Self-Determination Theory (Deci & Ryan, 2000): when marginalized students utilize their distinct talents to capture collective moments and support their class honour, their psychological needs for autonomy, competence, and relatedness are fully satisfied.

With students' daily routines becoming more diverse, they have more time to interact with other students and receive frequent feedback from peers rather than just from exams. This aligns with empirical evidence that youth sport interventions frequently function as crucial mechanisms to foster a greater sense of community and social cohesion among adolescents (Legg et al., 2015). Finally, these connections will be converted into school belongingness.

This study challenges the traditional "*player-oriented*" model, providing feasible suggestion for administrators to implement the "*Double Reduction*" policy. For teachers, who are suffering administrative burnout (Chen & Lin, 2024), especially for physical education teachers, their role is evolving from a direct instructor to an inclusive environmental creator; by empowering student committees to manage everything from officiating to media broadcasting, students have more opportunities to serve as different roles, forming emotional sympathy.

While this study highlights the inclusive benefits of campus sports, a few practical limitations remain. We did not track the marks of each class. It is natural for spectators to feel highly connected when their class is winning, and depressed when their class is losing. Hence, the high sense of community we observed might not be a lasting bond. We conduct the research in a single school and treated student roles as fixed categories, but real campus life, students might serve as different roles from game to game. Future studies should include diverse schools and explore how experiencing multiple roles shapes a student's psychological growth.

Data collection occurred at a single point in time. This might confuse cause and effect. It is possible that students who already felt a strong sense of school belonging simply chose to engage in the sporting events, rather than the events alone creating that belongingness. Future research needs to track students' multiple times over the course of a semester or school year; by doing this, researchers can more confidently show how inclusive sports environments build psychosocial capital.

CONCLUSIONS

The study indicates that the psychological benefits in the scores of SCS are equal, regardless of the role assumed by the students, and SCS is the key mechanism for predicting school belongingness. These findings provide empirical basis for schools to utilized physical activities in promoting students' mental health and well-being.

The educational value of campus sports extends beyond the physical development. Educators and policy maker should realize the point and consider how to build a more inclusive environment, a kind valuable psychological capital. By fostering a structured and inclusive sporting environment, schools can create a supportive psychosocial setting that enhances security, collective honour, and a sense of belonging for the broader student body.

We also note that this study has limitations such as single time-point measurement; future research could further verify the causal mechanism through longitudinal designs and examine the long-term impact of factors like winning or losing on psychological benefits.

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: Tiansuo Chang, Meng Cao. Methodology: Tiansuo Chang. Formal analysis: Hongxin Ma, Huan Chen. Investigation: Tiansuo Chang, Hongxin Ma, Huan Chen, Zejun Yan. Data curation: Tiansuo Chang, Hongxin Ma. Writing – original draft: Tiansuo Chang, Zejun Yan. Writing – review & editing: Tiansuo Chang, Meng Cao. Supervision: Meng Cao. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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

Polishing this essay is the core purpose of using AI. We used Mita to translate Chinese version into English, and improved language and readability by Gemini. After using these tools, the authors reviewed and edited the content. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

INSTITUTIONAL REVIEW BOARD STATEMENT

The study was conducted in accordance with the Declaration of Helsinki and approved by the School Administrative Committee of Beijing No.12 High School (Protocol code: BJSZ-2026-001, approved March 2026).

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study and their legal guardians.

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Sustainability knowledge, attitudes and behaviors: Psychometric properties and perceptions among sport science students in higher education

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ABSTRACT

Sustainable development is a widely used concept today, making education for sustainable development one of the pillars of the 2030 Agenda. Recent research highlights persistent disparities between students' cognitive understanding of sustainability and their actual sustainable actions. In this context, this research aims to analyse the psychometric properties of the Sustainability Consciousness Questionnaire in a sample of 201 undergraduate students enrolled in the Bachelor's Degree in Physical Activity and Sport Sciences program. Secondly, it assesses perceptions of sustainability awareness segmented by gender and academic year. The results reveal adequate psychometric properties in a factor structure that differs slightly from the original. Student assessments show higher scores among women, with significant differences compared to men in 17 of the 27 items. Regarding academic year, first-year students (1st and 2nd year) showed higher scores overall, although the differences were significant in only 2 items. These findings confirm the existence of a cognitive-behavioural gap that limits the effective integration of sustainability in higher education. The study underscores the need to strengthen experiential and transformative learning approaches that promote not only awareness but also real behavioural change in university settings.

Keywords: Sustainability consciousness, Sustainability knowingness, Sustainability attitudes, Sustainable development goals, Higher education, University students.

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INTRODUCTION

Sustainable development (SD) currently represents a dynamic concept with multiple interpretations, with the most widely accepted definition established by the World Commission on Environment and Development (1987, p. 41), which describes it as development that “*meets the needs of the present generation without compromising the ability of future generations to meet their own needs*”. In this sense, the current societal challenges regarding sustainability issues generated by human–environment interaction (Voulvoulis et al., 2019) require addressing behaviour, lifestyle, and undertaking a collaborative effort to meet this challenge where education plays a fundamental role as an agent of change.

Within this framework, Education for Sustainable Development (ESD) constitutes one of the fundamental pillars of the 2030 Agenda, which is structured around the 17 Sustainable Development Goals (SDGs). Specifically, SDG 4 includes Target 4.7, which calls for ensuring that all learners acquire the knowledge and skills necessary to promote sustainable development (UNESCO, 2015, 2017). According to Berglund et al. (2014), ESD represents a teaching and learning approach aimed at developing skills through active and participatory citizenship. In this context, universities play a crucial role in training future professionals capable of integrating sustainability both into their professional fields and daily lives. Nevertheless, several studies have shown that the presence of sustainability in higher education remains uneven, often limited to declarative approaches with little translation into real behaviour (Gericke et al., 2019; Marcos-Merino et al., 2020; Mohamed et al., 2024).

To assess the effectiveness of ESD strategies, the concept of sustainability consciousness (SC) has been consolidated. It is understood as the combination of knowledge, attitudes, and sustainable behaviours (KAB) across three dimensions: environmental, social, and economic (Gericke et al., 2019). This is a concept developed to measure the effect of the implementation of EDS on students in Swedish schools (Nousheen & Kalsoom, 2022) and is defined as the experience or understanding of sustainability phenomena (Gericke et al., 2019). It therefore integrates the environmental, social, and economic dimensions of SD, emphasizing the importance of knowledge, attitudes, and behaviours across these dimensions (Olsson, 2014). This perspective connects knowing, feeling, and acting in relation to sustainability, enabling a holistic assessment of the educational impact on the formation of committed citizens and a genuine disposition toward transformation.

To understand why knowledge and attitudes do not always translate into behaviour, it is useful to situate SC within theoretical models of behavioural change. In the literature on pro-environmental behaviour and education, the Theory of Planned Behaviour (Ajzen, 1991) remains widely used and validated in recent contexts, including meta-analyses highlighting its predictors and mechanisms of action (Hagger & Hamilton, 2025). Likewise, transformative learning theory (Mezirow, 1991) has been applied to explain the mediation of attitudes, social norms, and perceived behavioural control in the transition from knowing to doing. Applied to the university context, these approaches suggest that educational interventions should go beyond information transmission and address motivational, contextual, and self-efficacy factors that facilitate the adoption of sustainable practices.

Research on SC in the educational field has grown significantly in recent years, with studies analysing SC across different educational levels and contexts—for example, in secondary education in Canada (Michalos et al., 2011; Michalos et al., 2015) and in higher education in countries such as Sweden, Spain, Egypt, and Indonesia (Berglund et al., 2014; Gericke et al., 2019; Marcos-Merino et al., 2020; Mohamed et al., 2024; Suwanto et al., 2021). Despite heterogeneity in samples (ranging from 27 to over 1,500 students) and

disciplines (sciences, social sciences, teacher education, or nursing), findings show consistent patterns: in general, students present relatively high levels of knowledge and positive attitudes toward sustainability but lower engagement in sustainable behaviours, particularly in the environmental dimension (Berglund et al., 2014; Gericke et al., 2019; Michalos et al., 2011; Marcos-Merino et al., 2020). This pattern highlights a discrepancy between knowledge, attitudes, and behaviours, evidencing that formal education contributes to awareness-raising but does not always lead to concrete actions (Olsson et al., 2016). Moreover, several studies point out that specific training in sustainability and active or contextualized learning experiences (such as service-learning or interdisciplinary projects) are associated with a more integrated and coherent awareness across the three dimensions of SC (Evans, 2019; Lozano et al., 2017).

Methodologically, several studies have employed the Sustainability Consciousness Questionnaire (SCQ), in either its long (SCQ-L) or short (SCQ-S) versions, as a validated instrument with adaptations to different educational contexts. This instrument assesses the three dimensions of SD through the three components of SC: knowledge, attitudes, and behaviours (KAB). In this sense, as Gericke et al. (2019) indicates, including the three psychological constructs of knowledge, attitudes and behaviour implies adopting a holistic approach to researching people's cognitive and affective perspectives on sustainable development, where section K covers what people recognize as necessary characteristics of SD, section A reflects attitudes towards SD problems, and section B indicates what people do in relation to SD problems (Figure 1). Validation results have demonstrated adequate psychometric properties, confirming internal consistency and cross-cultural applicability (Berglund et al., 2014; Gericke et al., 2019; Michalos et al., 2015; Marcos-Merino et al., 2020).

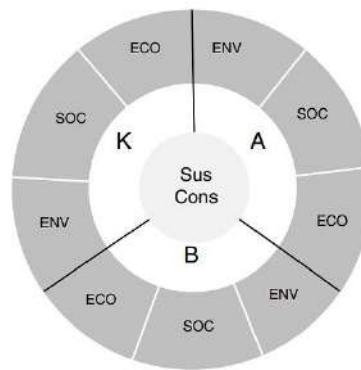


Figure 1. Conceptual representation of sustainability consciousness (Gericke et al., 2019).

The Bachelor's Degree in Physical Activity and Sport Sciences (GCCAFD) presents specific educational and professional characteristics that may influence sustainability consciousness: a high practical orientation, an emphasis on the management of sports facilities and events, and a direct connection with the areas of health, leisure, and consumption (Baena-Morales et al., 2023). These authors also point out that Physical Education possesses unique features that can mobilize competencies essential to enhancing sustainability consciousness, reinforcing the relevance of addressing these specificities in university education. In fact, these characteristics may influence how students perceive and prioritize the environmental, social, and economic dimensions of sustainability; therefore, it is particularly relevant to assess SC in this population to design educational strategies adapted to their professional profile and to promote training aligned with the 2030 Agenda.

Despite the growing number of studies, the literature on sustainability consciousness among Spanish university students remains limited and fragmented, particularly in degrees related to GCCAFD, leaving a

gap in the literature. Therefore, it would be appropriate to analyse the levels of sustainable knowledge, attitudes, and behaviours among these students, contributing to a better understanding of the effectiveness of ESD in specific educational contexts and its potential to promote sustainability through professional practice (Fuentes-Camacho et al., 2019), who point out that integrating sustainability into university curricula is essential for future professionals to understand how their activity relates to society and the environment and to develop competencies that foster real change toward a sustainable culture in higher education.

This research has a dual objective. The first is to validate the Sustainability Consciousness Questionnaire (SCQ) in the context of university students in Spain, verifying the psychometric properties of the tool in a sample of GCCAFD students. The second objective is to evaluate and analyse students' perceptions of sustainability awareness (knowledge, attitudes, and behaviours) (KAB), segmenting the results according to gender and academic year.

MATERIAL AND METHODS

Participants

A non-probabilistic convenience sampling method was used, resulting in the participation of 201 students after cleaning the database and excluding 12 cases due to incomplete questionnaire responses (missing data detection). Participation was entirely voluntary and anonymous, and students provided informed consent before beginning, being reminded that they could withdraw at any time without the need for justification. All participants are studying for the GCCAFD degree at different universities (both public and private) in the city of Seville (Spain), having in common that they were taking sports management courses. The gender distribution revealed a predominantly male sample ($N = 160$; 79.6%), mainly aged between 18 and 21 years, distributed fairly evenly across the first three years of study, with a slightly higher representation of fourth-year students. Table 1 displays the complete sociodemographic information.

Table 1. Sociodemographic characteristics.

Variable / Category	N	%
Gender		
Female	40	19.9
Male	160	79.6
Lost	1	0.5
Age		
18	41	20.4
19	30	14.9
20	43	21.4
21	45	22.4
22	21	10.4
23	11	5.5
24 or more	10	5.0
Academic year		
1º	49	24.4
2º	43	21.4
3º	44	21.9
4º	65	32.3

Instruments

Data collection was carried out using the Sustainability Consciousness Questionnaire (SCQ; Gericke et al., 2019), an instrument that encompasses the three dimensions of sustainable development (SD)—namely, sustainability knowledge, sustainability attitudes, and sustainable behaviour—as established within the

UNESCO framework (2006; 2009; 2014). This allows the measurement of the integrated and holistic concept of sustainability (Gericke et al., 2019). The questionnaire consists of 27 items, organized into three blocks of nine items corresponding to each dimension. Within each dimension, there are three factors (environment, society, and economy) with three items each. Responses are recorded on a five-point Likert scale, ranging from “strongly disagree” (1) to “strongly agree” (5).

This instrument was originally applied in a sample of Swedish students aged 18–19 years (Gericke et al., 2019) and has since been used with pre-service primary teachers sample in Spain (Marcos-Merino et al., 2020), as well as with the long version (SCQ-L, 49 items) among nursing students from three Egyptian public universities, all demonstrating adequate psychometric properties.

Data analysis

Data were analysed using SPSS and AMOS (v.21.0). SPSS was used for the descriptive analysis of sociodemographic variables, exploratory factor analysis (EFA), reliability testing, item analysis, and group comparisons (U Mann–Whitney test for gender differences and Kruskal–Wallis H test for academic year differences). AMOS was used for the confirmatory factor analysis (CFA).

The EFA was conducted using maximum likelihood estimation and oblique Oblimin rotation, with factor loadings used to assess item adequacy, alongside the Kaiser–Meyer–Olkin (KMO) index and explained variance. Reliability was assessed using Cronbach’s alpha coefficient. The CFA used on a combination of fit indices, including the χ^2/df ratio, Comparative Fit Index (CFI), Incremental Fit Index (IFI), Tucker–Lewis Index (TLI), Parsimony Comparative Fit Index (PCFI), and Root Mean Square Error of Approximation (RMSEA). Additionally, Composite Reliability (CR), Average Variance Extracted (AVE) for convergent validity, and discriminant validity were examined.

Procedure

Data were collected through an online questionnaire distributed via the Microsoft 365 Forms platform. The data collection took place during the first semester of the 2025–2026 academic year, between September 8 and 23. Prior to participation, students were informed about the study objectives, the voluntary nature of participation, and guarantees of anonymity and confidentiality. Participants were also reminded that they could withdraw at any time and that no incentives or compensation were provided. This study received ethical approval from the Ethics Committee of the local University (ID: 2024/130). Additionally, informed consent was obtained from all participants. The inclusion criteria were: (i) being enrolled in the GCCAFD program, and (ii) studying sports management courses at the time of participation. The exclusion criteria were: (i) not having completed 100% of the questionnaire, or (ii) providing inconsistent responses. The questionnaire was self-administered and took approximately 10–15 minutes to complete. It was available both during class time (with teachers’ consent and supervision) and remotely through an online link.

Regarding the instrument used, content validity was determined despite its previous application in a Spanish university context. For this purpose, an expert panel of seven university lecturers specializing in sport management (each with over five years of experience) was convened. Experts remained anonymous to avoid mutual influence. They were contacted individually via email and provided with an evaluation template containing four criteria: adequacy, clarity, coherence, and relevance. Each item was rated on a four-point scale: (1) does not meet the criterion, (2) low level, (3) moderate level, and (4) high level. Only minor recommendations for slight modifications were received for a few items, and no changes were implemented as fewer than three experts suggested them.

RESULTS

Descriptive analysis of the items

The descriptive analysis of the items showed skewness and kurtosis values within the acceptable normality criteria (-3 to 3 for skewness and -7 to 7 for kurtosis) (Finney & DiStefano, 2006). Overall, participants' evaluations of the items exceeded the value of 4 in the sustainability knowingness and sustainability attitudes dimensions (except for item A5). However, the sustainability behaviours dimension obtained the lowest mean scores, although all of them were above the midpoint of the scale.

Exploratory factor analysis

The results confirmed the suitability of conducting a factor analysis. Both the KMO measure and Bartlett's test of sphericity revealed that the items presented adequate common variance for the factor analysis (KMO = 0.87; $\chi^2 = 2311.59$, $df = 351$, $p < .001$), resulting in a factorial solution explaining 57.34% of the variance. Factor loadings exceeded the 0.60 cutoff point (Hair et al., 2009), except for item A5 ($\lambda = 0.37$). The reliability of the dimensions, assessed using Cronbach's alpha coefficient, was above 0.70 (Table 2).

Table 2. Descriptive items related to mean (M) and standard deviation (SD), internal consistency (α), factor loadings (λ) in exploratory and confirmatory factor analyses, composite reliability (CR), and average variance extracted (AVE).

Dimension / Factor / Item		M (SD)	λ EFA	λ CFA	CR	AVE
Sustainability knowingness ($\alpha = 0.83$)						
Env	K3	4.28 (0.84)	0.62	0.73	0.78	0.54
	K14	4.59 (0.60)	0.66	0.72		
	K21	4.36 (0.76)	0.61	0.74		
Soc	K5	4.45 (0.67)	0.67	0.73	0.76	0.52
	K10	4.56 (0.62)	0.71	0.77		
	K11	4.45 (0.70)	0.69	0.64		
Eco	K12	4.44 (0.63)	0.64	0.76	0.74	0.49
	K16	4.21 (0.78)	0.67	0.69		
	K17	4.10 (0.85)	0.62	0.64		
Sustainability attitudes ($\alpha = 0.77$)						
Env	A5	2.42 (1.34)	0.66	0.39*	0.76	0.61
	A6	4.15 (0.84)	0.76	0.73		
	A10	4.32 (0.77)	0.76	0.83		
Soc	A1	4.47 (0.64)	0.76	0.80	0.79	0.55
	A2	4.52 (0.63)	0.65	0.68		
	A18	4.56 (0.62)	0.63	0.73		
Eco	A3	4.30 (0.75)	0.74	0.73	0.75	0.50
	A7	4.39 (0.72)	0.69	0.69		
	A8	4.00 (0.92)	0.68	0.68		
Sustainability behaviours ($\alpha = 0.80$)						
Env	B3	3.94 (0.91)	0.68	0.78	0.81	0.59
	B10	3.73 (1.06)	0.73	0.80		
	B12	3.76 (1.02)	0.69	0.73		
Soc	B4	4.45 (0.67)	0.62	0.67	0.65	0.49
	B15	3.13 (1.27)	0.75	0.41*		
	B17	4.74 (0.51)	0.60	0.71		
Eco	B6	3.69 (0.92)	0.65	0.70	0.76	.051
	B9	3.47 (1.13)	0.65	0.69		
	B11	3.40 (1.07)	0.69	0.73		

Note. * = Items removed during the refinement of the confirmatory factor analysis.

Confirmatory factor analysis

The second phase of the psychometric evaluation included a confirmatory factor analysis (CFA) based on the original structure. However, the initial results did not show satisfactory goodness-of-fit indices, as they were below the minimum recommended thresholds [χ^2 (288) = 580.25; χ^2/df = 2.01; CFI = 0.86; TLI = 0.83; IFI = 0.86; PCFI = 0.75; RMSEA = 0.07]. Although the χ^2/df (≤ 3.0 ; Kline, 2005) and RMSEA (≤ 0.08 ; Hu & Bentler, 1999) indices were adequate, the others did not meet the minimum acceptable values.

Modification indices were examined, but no substantial values were found that would suggest incorporating covariances between pairs of errors. However, when reviewing the factor loadings, items A5 (sustainability attitudes dimension) and B15 (sustainability behaviours dimension) showed values below 0.5 (λ = 0.39 and λ = 0.41, respectively) (Table 2). These items were therefore removed from the model, resulting in a satisfactory model fit in the confirmatory factor analysis [χ^2 (239) = 381.38; χ^2/df = 1.59; CFI = 0.92; TLI = 0.91; IFI = 0.93; PCFI = 0.81; RMSEA = 0.05]. The complementary measures of composite reliability (CR) and average variance extracted (AVE) were also satisfactory, although the economic factor of the sustainability knowingness dimension and the social factor of the sustainability behaviours dimension were slightly below the recommended cutoff point of 0.50 (Bagozzi & Yi, 1988) (Table 2).

Table 3. Perception of sustainability knowingness, sustainability attitudes, and sustainability behaviours according to gender.

Dimension / Factor / Item		M (SD)		U-Mann Whitney (sig.)
Sustainability knowingness		Women	Men	
Env	K3	4.53 (0.71)	4.21 (0.86)	0.030*
	K14	4.68 (0.57)	4.56 (0.61)	0.240
	K21	4.52 (0.64)	4.31 (0.78)	0.144
Soc	K5	4.60 (0.70)	4.41 (0.65)	0.038*
	K10	4.68 (0.52)	4.52 (0.64)	0.205
	K11	4.65 (0.53)	4.40 (0.73)	0.058
Eco	K12	4.68 (0.52)	4.38 (0.64)	0.005**
	K16	4.43 (0.71)	4.16 (0.79)	0.047*
	K17	4.38 (0.74)	4.03 (0.87)	0.022*
Sustainability attitudes				
Env	A5	2.03 (1.27)	2.50 (1.33)	0.025*
	A6	4.50 (0.71)	4.06 (0.85)	0.001***
	A10	4.63 (0.66)	4.24 (0.78)	0.002**
Soc	A1	4.83 (0.38)	4.37 (0.66)	0.000***
	A2	4.80 (0.46)	4.45 (0.65)	0.001***
	A18	4.88 (0.33)	4.48 (0.65)	0.000***
Eco	A3	4.48 (0.81)	4.26 (0.72)	0.024*
	A7	4.62 (0.62)	4.32 (0.74)	0.012*
	A8	4.15 (0.92)	3.94 (0.92)	0.183
Sustainability behaviours				
Env	B3	4.20 (0.88)	3.87 (0.90)	0.019*
	B10	4.00 (1.06)	3.65 (1.05)	0.038*
	B12	3.95 (1.01)	3.71 (1.02)	0.158
Soc	B4	4.62 (0.58)	4.41 (0.68)	0.053*
	B15	3.23 (1.31)	3.10 (1.26)	0.632
	B17	4.90 (0.30)	4.69 (0.54)	0.026*
Eco	B6	3.90 (1.05)	3.63 (0.88)	0.104
	B9	3.40 (1.21)	3.48 (1.11)	0.730
	B11	3.33 (1.20)	3.41 (1.04)	0.735

Note: * = $p < .05$; ** $p < .01$; *** $p < .001$.

Subsequently, students' perceptions were analysed considering segmentation by gender and academic year. In the first case, the results are presented in Table 3, showing that mean scores were generally higher among female students, with the exception of three items (A5, B9, and B11). Significant differences were found using the Mann-Whitney U test in 17 of the 27 items, with highly significant differences observed in the three items corresponding to the society factor within the sustainability attitudes dimension.

Regarding students' perceptions according to academic year, those enrolled in the 1st and 2nd years generally obtained higher mean scores, with only five items showing higher scores among students in the 4th or 5th years. In this case, only two items displayed significant differences, both within the sustainability attitudes dimension (A6 from the environment factor and A1 from the society factor) (Table 4).

Table 4. Perception of sustainability knowingness, sustainability attitudes, and sustainability behaviours according to academic year.

Dimension / Factor / Item		M (SD)				H Krustal-Wallis (sig.)
Sustainability knowingness		1º	2º	3º	4º	
Env	K3	4.18 (0.80)	4.21 (0.91)	4.45 (0.76)	4.28 (0.87)	0.342
	K14	4.59 (0.61)	4.49 (0.63)	4.59 (0.54)	4.65 (0.62)	0.472
	K21	4.43 (0.57)	4.53 (0.70)	4.16 (0.86)	4.32 (0.83)	0.152
Soc	K5	4.43 (0.81)	4.49 (0.63)	4.45 (0.50)	4.45 (0.68)	0.914
	K10	4.59 (0.61)	4.58 (0.54)	4.48 (0.62)	4.57 (0.68)	0.700
	K11	4.55 (0.64)	4.49 (0.70)	4.41 (0.75)	4.38 (0.72)	0.580
Eco	K12	4.59 (0.61)	4.40 (0.62)	4.50 (0.55)	4.31 (0.68)	0.090
	K16	4.35 (0.72)	4.14 (0.74)	4.20 (0.82)	4.17 (0.84)	0.553
	K17	4.02 (0.92)	4.19 (0.79)	4.09 (0.83)	4.12 (0.87)	0.876
Sustainability attitudes						
Env	A5	2.43 (1.51)	2.53 (1.29)	2.27 (1.33)	2.43 (1.26)	0.657
	A6	4.45 (0.61)	4.09 (0.84)	4.16 (0.86)	3.95 (0.94)	0.033*
	A10	4.43 (0.67)	4.37 (0.87)	4.36 (0.68)	4.18 (0.82)	0.364
Soc	A1	4.69 (0.46)	4.49 (0.59)	4.43 (0.66)	4.31 (0.72)	0.030*
	A2	4.69 (0.50)	4.60 (0.54)	4.48 (0.62)	4.37 (0.74)	0.074
	A18	4.71 (0.45)	4.47 (0.70)	4.55 (0.58)	4.52 (0.68)	0.369
Eco	A3	4.43 (0.67)	4.33 (0.83)	4.30 (0.66)	4.20 (0.79)	0.426
	A7	4.41 (0.73)	4.33 (0.77)	4.27 (0.75)	4.49 (0.66)	0.434
	A8	4.10 (0.84)	4.05 (0.92)	3.89 (0.89)	3.94 (1.01)	0.674
Sustainability behaviours						
Env	B3	3.98 (0.98)	3.95 (0.92)	3.95 (0.83)	3.89 (0.90)	0.902
	B10	3.86 (1.22)	3.84 (1.02)	3.57 (0.97)	3.66 (1.03)	0.301
	B12	3.65 (1.14)	3.79 (1.03)	3.86 (0.90)	3.75 (1.01)	0.888
Soc	B4	4.59 (0.53)	4.42 (0.69)	4.27 (0.75)	4.49 (0.66)	0.181
	B15	3.33 (1.36)	3.26 (1.27)	3.11 (1.29)	2.92 (1.17)	0.217
	B17	4.86 (0.35)	4.60 (0.62)	4.70 (0.50)	4.75 (0.53)	0.148
Eco	B6	3.82 (0.92)	3.70 (0.98)	3.70 (0.90)	3.57 (0.90)	0.414
	B9	3.43 (1.25)	3.60 (1.21)	3.64 (0.99)	3.29 (1.07)	0.264
	B11	3.41 (1.15)	3.51 (1.07)	3.45 (1.02)	3.29 (1.07)	0.550

Note: * = $p < .05$; ** $p < .01$; *** $p < .001$.

DISCUSSION

The present study was designed with the objective of examining the psychometric properties of the Sustainability Consciousness Questionnaire (SCQ; Gericke et al., 2019) in a sample of university students from different academic years within the GCCAFD, as well as a secondary objective of evaluating and

analysing participants' perceptions of sustainability consciousness, segmenting the analysis by gender and academic year.

The results of the factor analyses indicate that the scale is valid and reliable, displaying adequate psychometric properties. The exploratory factor analysis revealed a slight weakness in the evaluation of factor loadings (item A5 with $\lambda < 0.6$), although overall suitability tests were adequate. However, in the confirmatory factor analysis, the scale required adjustment due to poor initial fit resulting from low factor loadings in two items (A5 and B15), whose removal produced satisfactory model fit. This outcome, however, provides a structure that differs from the study conducted by Gericke et al. (2019) on a sample of upper secondary students in Sweden (equivalent to Spanish *bachillerato*), as well as from the study by Marcos-Merino et al. (2020) with university students in the Primary Education degree, both of which maintained the original 27-item structure without reporting any factorial modification.

These findings are particularly relevant considering the recent decline in job satisfaction and employment conditions among graduates in Sport Sciences in Spain, reflecting challenges to the social sustainability of the sector (Grimaldi-Puyana et al., 2025). Hence, the results of the present study confirm trends observed in the international literature: university students generally present high levels of knowledge and attitudes toward sustainability, but significantly lower sustainable behaviours (Berglund et al., 2014; Marcos-Merino et al., 2020; Michalos et al., 2011; Michalos et al., 2015; Mohamed et al., 2024). This cognitive-behavioural gap indicates that awareness generated through formal education does not always translate into sustainable practices, particularly in the environmental domain. Consistent with previous studies, the social dimension was rated highest, while the economic dimension showed weaker scores, which may be linked to a more limited understanding of this aspect within the GCCAFD educational context.

Previous research, such as studies conducted in Canada, has shown that knowledge and attitudes explain approximately 25% of the variance in sustainable behaviour, with knowledge exerting a slightly stronger influence (Michalos et al., 2011; Michalos et al., 2015). This pattern appears partially reproduced in the present sample, where high scores in knowledge are not accompanied by equivalent behaviours, suggesting that increasing sustainability information does not necessarily guarantee real behavioural change. This finding aligns with the notion that knowledge acquisition represents only a first step toward the internalization of sustainable values and practices, requiring transformative learning experiences to consolidate into everyday action.

Moreover, the results highlight the importance of the educational context in developing sustainability consciousness. In Indonesia, the implementation of structured EDS programs, such as the *Adiwiyata* model, significantly enhances the environmental dimension, while in Egypt, universities that are institutionally more committed to sustainability obtain higher overall SC scores (Mohamed et al., 2024; Suwanto et al., 2021). Similarly, in Canada, the explicit inclusion of sustainability content in university courses has been shown to improve all three dimensions of the construct (Michalos et al., 2015). In this regard, the results obtained from GCCAFD students confirm the need to integrate sustainability in a transversal and practical manner within sport-related degrees, fostering learning experiences that connect knowledge with transformative action and the social responsibility of future professionals.

Overall, the findings indicate that university education in the field of sport and physical activity contributes partially to the development of balanced sustainability consciousness. Although high levels of knowledge and attitudes are achieved, the persistence of moderate sustainable behaviours underscores the need to rethink current pedagogical strategies. These results highlight the importance of promoting more experiential,

reflective, and contextualized learning experiences that facilitate the transfer of learning to students' every day and professional actions. Furthermore, the validation of the SCQ in this specific population provides a robust tool for diagnosing and monitoring sustainability consciousness in sport-related degrees, opening new avenues of research aimed at evaluating the impact of active methodologies and institutional programs on the transformation of sustainable behaviours.

Limitations

This study presents several limitations that should be considered when interpreting the results, providing a deeper understanding of their scope. The use of a non-probabilistic convenience sample, composed of university students from the Autonomous Community of Andalusia, restricts the generalizability of the findings to other geographical, cultural, or academic contexts. Therefore, it would be advisable to expand the study to other degree programs and universities in different geographical areas to obtain a more representative view of Spanish university students. On the other hand, the sample size limits the results obtained from segmentation by gender and academic year. In addition, the uneven gender distribution (predominantly male) could introduce bias into the results, although it should be noted that this situation is quite common in studies involving sport sciences students in the Spanish context (Escamilla-Fajardo et al., 2021). Therefore, future studies across other degree programs and geographical contexts would enable more in-depth comparative analyses, allowing better identification of the profile of university students.

Practical implications

The findings of this study have important implications for the design and implementation of educational strategies aimed at strengthening sustainability consciousness in the university context. First, the observed gap between knowledge and sustainable behaviours suggests that universities should reconsider their pedagogical approaches, shifting from information-transmission models toward active, participatory, and transformative methodologies. Strategies such as service-learning, project-based learning, or community immersion experiences enable students to apply the principles of sustainable development in real contexts, thereby facilitating the internalization of sustainable values and behaviours.

Second, the results highlight the need to integrate sustainability transversally across curricula, particularly within the GCCAFD. Beyond including specific courses, it is recommended that all subjects, from biomechanics to sport management, incorporate content, activities, and assessments that promote ethical reflection, social responsibility, and understanding of the three dimensions of sustainable development: environmental, social, and economic. Such integration would support education that is more coherent with the Agenda 2030 goals and with the demands of employers who value sustainability competencies.

Third, the data encourage institutions to reinforce their institutional commitment to sustainability, generating university environments aligned with the values being taught. This involves promoting sustainable practices in resource management, mobility, food, and energy, as well as fostering student participation in sustainability projects and initiatives both on and off campus.

Finally, the results support the use of the SCQ as a valuable tool for diagnosing and monitoring sustainability consciousness in higher education. Its periodic application could facilitate the evaluation of the impact of educational programs and institutional policies, providing valuable information for decision-making and the continuous improvement of sustainability training strategies.

CONCLUSIONS

The present study analysed the sustainability consciousness of GCCAFD university students, examining the relationship between sustainability knowingness, sustainability attitudes, and sustainability behaviours. The results confirmed the reliability and validity of the Spanish version of the SCQ in the university student context, showing adequate psychometric properties with a factor structure that differs slightly from that obtained in other studies. Regarding the participants' perceptions, students demonstrated high levels of knowledge and positive attitudes toward sustainability, but lower levels of sustainable behaviours, highlighting the existence of a cognitive-behavioural gap. This pattern aligns with previous international studies and underscores the difficulty of translating consciousness and attitudes into concrete and lasting actions in the university context.

These results suggest that current ESD strategies in higher education are effective in generating awareness and favourable attitudes but insufficient to promote real behavioural changes, suggesting the need for active methodologies such as project-based learning or service-learning (Marcos-Merino et al., 2020; Suwanto et al., 2021). Therefore, universities should move beyond declarative approaches and implement active, participatory, and transformative methodologies, such as project-based learning or service-learning (Marcos-Merino et al., 2020; Suwanto et al., 2021), which strengthen the connection between knowing and doing. In conclusion, consolidating sustainability in the university context requires the balanced integration of the three dimensions of sustainable development (environmental, social, and economic) through learning experiences that enable students not only to understand sustainability but also to live it and apply it in their everyday lives and future professional practice.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. PCLD – conceptualization of the study, data collection, writing - original draft, review and editing; PGR – study design, data curation, analysis and interpretation of the data, writing of the article; JMLG – conceptualization of the study, writing of the article; MGP – study design, development of the theoretical bases, data collection, review and editing. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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.

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Effect of psychological skills intervention on exercise adherence among university staffers in Nigeria

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ABSTRACT

This study examined the effect of psychological skills interventions (PSIs) (goal setting, positive self-talk and a combined intervention) on exercise adherence among university staffers in South-west, Nigeria. This study employed the post-test-control group experimental design. 107 participants were recruited and randomly assigned to four different groups: goal setting ($n = 26$), positive self-talk ($n = 26$), combined goal setting and positive self-talk ($n = 27$), and control ($n = 28$), age ranged between 23 and 64 years. All groups engaged in a 13-week structured exercise programme, but only the experimental groups received psychological skills training. Exercise programme prescriptions of the American College of Sports Medicine and Adapted Educational talk on PSIs were used. The participants completed Goal Orientation in Exercise Measure (GOEM), Self-Talk Use Questionnaire (STUQ) and Combined Goal Setting/Positive Self-Talk Questionnaire (CGSPSQ), and attendance logbooks were completed by the participants. The data were analysed using T-test, Analysis of Variance (ANOVA) and Scheffe Post-hoc test. The study indicated significant differences in exercise adherence between each experimental group and the control group ($p < .05$). The combined PSI demonstrated the highest exercise adherence rate (67.33%), followed by goal setting (60.26%) and positive self-talk (52.56%), while the control group recorded the lowest (37.09%). PSI positively influenced exercise adherence, with combined goal setting and positive self-talk indicating most effective. The study emphasized the importance of integrating PSI into workplace health and wellness programmes to enhance long-term physical activity participation. Recommendations are made.

Keywords: Exercise adherence, Goal setting, Psychological skills intervention, Positive self-talk, University staffers.

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INTRODUCTION

Physical inactivity remains one of the global public health concerns of the 21st century, as it contributes heavily to the burden of non-communicable diseases (NCDs) such as cardiovascular disease, type 2 diabetes and cancer (Gao et al., 2025). The benefits of regular physical exercise are well-documented (Cabo et al., 2025; Caparrós Pons et al., 2023; Oguntuase et al., 2021). Despite several pieces of evidences, there exists a strong persistent gap between knowledge of these benefits and continuous participation in physical exercise, a situation referred to as “*intention-behaviour gap*” (Rhodes & de Bruijn, 2013). This gap is prevalent especially among adult working populations, who often associate primary barriers to regular participation in exercise to lack of time, work-related fatigue, demotivation and lack of space to exercise (Souza et al., 2022; Odunaiya et al., 2021; Jaiyeoba & Oguntuase, 2019).

These challenges alongside rising rates of NCDs is common in most societies around the world without the exemption of middle and lower income countries like Nigeria (Olamide et al., 2023; Oguntuase et al., 2021). The Nigerian working adult populations, including university staffers face unique diverse sociocultural and infrastructural challenges, which involve demanding workloads, economic stressors, limited access to recreational facilities and lack of essential equipment (Odunaiya et al., 2021). Consequently, exercise adherence - defined as the degree at which an individual's behaviour meets with agreed recommendations for exercise programme in terms of frequency, duration and intensity (Rivera-Torres, Fahey & Rivera, 2019), remains critically low. Bridging the intention-behaviour gap in this specific population requires innovative, evidence-based and cost-effective strategies.

Two fundamental psychological skills that have received substantial empirical support are goal setting and positive self-talk. These mental resources can substantially help participants to engage in regular participation of physical activity and enhance sustained participation. Goal setting is a mental tool that specifies what an individual aims to accomplish, and it can immensely enhance performance (Mellalieu et al., 2006). Goal-setting should be specific, measurable, challenging, attainable, exciting, and time-bound. Effective goal setting has been shown to increase physical activity participation, enhance self-efficacy and sense of accomplishment, and presents a framework for self-monitoring (Swann et al., 2023; Howlett et al., 2019; Meade et al., 2019). Positive self-talk involves verbalization directed toward oneself (Hall et al., 2014). It is the use of optimistic, instructional, or motivational self-statements to override negative ones (e.g., “*I am too tired*”) that often lead to exercise avoidance (Hardy et al., 2009). Research indicates that self-talk is a trainable skill that can be developed and applied to achieve desired goals (Hall et al., 2014). As a self-regulation skill, self-talk can be used to change one's thoughts, behaviours, increase competence and emotional responses, making it particularly relevant for examining exercise-related challenging behaviours (Puddister et al., 2021; Conley, 2019; Ives, 2011; Hardy et al., 2009).

Studies have shown significant effectiveness of PSIs when implemented independently (Meade et al., 2019; Hardy et al., 2009). Combining PSIs like goal setting and positive self-talk can yield synergistic result by concurrently addressing multiple factors affecting exercise adherence. Specifically, goal setting functions as a structural behavioural roadmap, while positive self-talk functions as a spontaneous motivational resource required for facilitating persistence in the face of challenges (Jones & Mattie, 2024; Papaioannou et al., 2004). This combined approach agrees with Multi-Process Action Control (M-PAC) framework (Rhodes, 2017), which accentuates three layers of connected progressive processes (reflective, regulatory, reflexive). This denotes that behaviour change toward exercise adherence is a progressive process that emerges from intention formation to sustained efforts and habit maintenance which is driven by the dynamic interaction of reflective, regulatory and reflexive processes.

Goal setting and self-talk establishes the structured planning for action and strengthened by automated drive, which effectively bridges intention-behaviour gap, thereby enhancing long-term consistency required for adherence (Rebar & Rhodes, 2020). The university remains a strategic and ideal setting for the implementation of health-promotion interventions. As institutions committed to the generation and dissemination of knowledge, universities have a keen interest in safeguarding and promoting the well-being of staff, whose health directly has significant impacts on innovation, productivity and institutional reputation (Proper & van Oostrom, 2019). Workplace wellness programmes that integrate psychological skill-building transcend the common provision of physical facilities (e.g., gymnasiums) to address the underlying psychological determinants of exercise adherence.

Psychological skills interventions (PSIs) have been recognized as catalyst that equips individuals with cognitive tools to self-regulate their behaviour, manage internal barriers and sustain motivation over time (Lange-Smith et al., 2023; Tod et al., 2011; Zhang et al., 2025). Though a handful of PSIs have been employed for enhancement of sport skills and performance such as goal setting, positive self-talk, concentration, imagery, mindfulness among others (Weinberg & Gould, 2024; Oguntuase & Sun, 2022; Adegbesan, 2009); it has not been sufficiently utilized among Nigerian exercisers for exercise adherence especially in areas of fitness and wellness.

Against this backdrop, this present study examined the effect of psychological skills interventions (PSIs) (goal setting, positive self-talk and a combined intervention) on exercise adherence among staff of a university in South-west, Nigeria. Accordingly, this study hypothesizes that: (i) there would be a significant difference in exercise adherence between goal setting and control group. (ii) There would be a significant difference in exercise adherence between positive self-talk and control group (iii) there would be a significant difference in exercise adherence between combined psychological skills of goal setting and positive self-talk and control group.

METHODS

Participants

This study employed randomised post-test control group experimental design. The participants were one hundred and seven ($n = 107$) university staff [Academic, $n = 52$ (48.6%); Non-Academic, $n = 51.4\%$], male ($n = 48$) 45%, female ($n = 59$, 55%). The participants were assigned into four groups (Group 1 (Goal setting), $n = 26$; Group 2 (Positive Self-talk), $n = 26$; Group 3 (Combined Goal setting and Positive self-talk), $n = 27$; Group 4 (Control), $n = 28$). The first three groups served as experimental which received PSIs intervention of goal setting, positive self-talk and combined goal setting and positive self-talk respectively, while the fourth group served as control, which received no intervention. All the four groups participated in the same exercise programmes for a period of thirteen (13) weeks. All the participants were active staff members of a university in South-west, Nigeria. They were cooperated and fully participated in the course of the programme voluntarily.

Measures

Goal Orientation in Exercise Measure (GOEM)

Goal Orientation in Exercise Measure developed by Petherick and Markland (2008) was used to assess the participants' goal orientation in exercise contexts. GOEM contains 10 items scale with two subscales dimension: Task Orientation and Ego Orientation. Each subscale has 5 items. For instance, Task Orientation items include "I feel successful in exercise when I learn a new skill", and "I feel successful in exercise when I try my hardest". Ego Orientation items include "I feel successful in exercise when others don't do as well as

me" and "I feel successful in exercise when I am the best". GOEM is rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Higher scores on task orientation indicate stronger motivation driven by personal improvement, mastery and effort. Similarly, higher scores on ego orientation indicates stronger primary motivation driven by social comparison and demonstrating superior norm-based ability. The Cronbach's alpha coefficient was measured as .82 in this present study.

Self-Talk Use Questionnaire (STUQ)

The Self-Talk Use Questionnaire which was developed by Hardy et al. (2005) was used to assess the frequency at which participants used different types of positive self-talk during exercise. STUQ is a 21-item questionnaire with four subscales which include cognitive mastery (6 items, e.g., "How often do you use self-talk to improve your concentration?"), cognitive efficiency (5 items, e.g., "How often do you use self-talk to psych yourself up after something bad happens?"), emotion control (5 items, e.g., "How often do you use self-talk to increase your effort?") and motivation (5 items, e.g., "How often do you use self-talk to motivate yourself to work hard?"). STUQ is rated on a 5-point Likert scale based on frequency of 1 = Never to 5 = Very Often. A high rating on STUQ indicates a greater reported frequency of using self-talk. The internal consistency reliability of STUQ in this present study was .79.

Combined Goal Setting/Positive Self-Talk Questionnaire (CGSPSQ)

Self-report Combined Goal Setting/Positive Self-Talk Questionnaire (CGSPSQ) was specifically developed to assess combined goal setting and positive self-talk of university staff in response to structured exercise programme. It consists of 7 items (e.g., "writing down my exercise goals and writing positive statement against my self-doubt increase my commitment", "the use of positive statement reminds me of my goals whenever I get discouraged making me to concentrate better"). CGSPSQ is rated on a 5-point Likert scale ranging from 1 = Never to 5 = Always. Cronbach alpha reliability value of CGSPSQ was found to be .76.

Interventions

Goal setting protocols

Goal setting guidelines "SMART" by Cox (2002) and goal setting acronym "SMARTS" by Weinberg and Gould (2011) were adopted for this study. The acronym "SMARTER" was coined out to give educational talk on goal setting to the participants in the goal setting group 1. The outline of SMARTER guideline includes;

"S" - Setting specific goals: to attend an exercise programme 3 times in a week for 3 months. It is important to note that participation will bring about a whole lot of fun and enjoyment and positively impact on their well-being.

"M" - Measurable: Having personal exercise logbook to record progress using dates and the number of days per week. This sort of recording system will help to sustain progress towards achieving attendance goals.

"A" - Action-oriented: Action-oriented goal is not one that is thought about and then forgotten. Pursue your spark by using fitted fitness outfit. Wear the clothes and shoes. Make a mental shift on how good you look in a fitted fitness colourful outfits. Think about "playing out" and not "work out" and natural exhilaration that comes from meeting and making friends. Take a step today and stop procrastination. Journey of one thousand miles starts with a step. The best time to start exercise is when one is young while the second best time is now. Take a step to complete the first one month programme and subsequent months will be easier.

"R" - Reward Self: For the first month.

"T" - Time Frame: Set out to exercise for an hour, between 7am and 8am for at least 12 times in a month and at least, 36 times in 3 months.

“E” - Evaluation: At the end of the first month, exercisers should evaluate the number of times they attended the programme. That is, whether they have achieved the 12x target of attendance they set for themselves or not. Adherence needs to be achieved first before all other intending motives can be attained. Trainers should give feedback of attendance record to exercisers individually at the end of each month.

“R” - Reinforcement: Do not relent on the gains and strive to maintain or achieve more. If you have not achieved anything, adjust your personal programme, carry along your significant other and seek for more support from him or her.

Positive self-talk protocols

Positive self-talk guideline and principles of Cox (2002), Hardy and Hall (2005) were modified by the research team. The outlines of the modified positive self-talk guideline include;

1. A plain paper and a pen were given to every participant and were told to think about the meaning of the phrase “self-talk”.
2. They were asked to think of a time when they made a huge mistake such as not keeping timing for important meeting (s), or when they ceased participation in an exercise programme and give examples in situations.
3. Exercisers were asked to remember what they said to themselves in that situation.
4. They were asked to write it down briefly.
5. Exercisers were instructed to get a partner and read out what they wrote loud to their partner, similar to the way they would say it to themselves.
6. It was explained to the exercisers that they would probably never say the things that they say to themselves when they make mistakes or cease participation to another person. Why do they treat themselves this way? Emphasis was put on the fact that negative self-talk is detrimental to their participation, performances and is unproductive.
7. The exercisers were asked to rephrase their original self-talk into a more positive manner and let them read it out to their partner for some feedback.
8. The exercisers were asked to create a long term positive self-talk and commit it to training logs. The participants were helped to monitor their own self-talk in changing their self-talk behaviours. Examples were given thus:

Table 1. Positive self-talk protocols.

Negative self-talk	Positive self-talk
<i>“My condition remains the same even if I exercise”.</i>	<i>“I see myself a fitter person as I exercise”</i>
<i>“I doubt if I can stick to this exercise programme”.</i>	<i>“Just hang in there a little longer”.</i>
<i>“My condition remains the same even if I exercise”</i>	<i>“I see myself a fitter person as I exercise”.</i>
<i>“I doubt if I can stick to this exercise programme”.</i>	<i>“Just hang in there a little longer”</i>
<i>“Don’t let me start what I can’t finish”</i>	<i>“It’s time for a change or if I don’t effect a change, there won’t be a change”</i>
<i>“I have never been timing conscious” or “African-time is in my blood.”</i>	<i>“I am a responsible and time conscious exerciser (person).”</i>
<i>“Let me rest today, I’ll go next tomorrow”.</i>	<i>“Just take one day at a time and make exercise fun.”</i>

Note: Do this at home and internalize before going for the exercise.

The combined psychological intervention of goal setting and positive self-talk

This followed the principles of Cox (2002) in the teaching of confidence and positive self-talk; as well as the principles outlined by Weinberg and Gould (2011) in the teaching of goal setting and positive self-talk to

athletes. After modifying these combined skills of goal setting and positive self-talk, an acronym “*REGUSTE*” was coined. That is:

“**R**” Remember; “**E**” Exercise; “**G**” Goals “**U**” Using “**S**” Self “**T**” Talk “**E**” Encourage

“**R**” Remember: Have focus; be dedicated; be passionate. You can’t do what you have always done and not expect to get what you have always got. If you want a different outcome a good physique make different decisions; change from sedentary lifestyle.

“**E**” Exercise that is planned and purposive yields fruitful and desired results.

“**G**” Goals set should be specific realistic, attainable and measurable e.g. setting specific goals: to attend an exercise programme 3 times in a week for 3 months. It is important to note that participation will bring about a whole lot of fun and enjoyment and impact positively on participant’s well-being.

Realistic: Setting out between 6.30am and 6.35am and exercising between 7am and 8am on Tuesday, Thursdays and Saturdays weekly for a month and subsequently for 2 and 3 months is achievable.

Attainable: Goals should be set on short term. It should be programmed from the first week to first month and to 3 months. That is if you must climb a six storey building in a situation where the elevator malfunctions you can start by telling yourself that I can get to the first floor, and take a minute rest, till I reach my goal. Set a goal to attend 3 times programme in the first week; then plan for the second week; third week and continue till you reach your goal(s).

Measurable: Have a personal exercise logbook to record dates and the numbers of days per week as charted under goal setting skill.

“**U**” “**S**” “**T**” **Using Self Talk:** Identify some negative thoughts and draw a chart as contained in the changing of negative self-talk to positive self-talk, and as brief as possible.

“**E**” The exercisers were taught to encourage themselves through reward as contained in reward and reinforcement under goal setting.

Procedure

Ethical clearance was obtained from the first author’s higher institution of learning (FUOYE/FED/KHE-HUK/301-2025-06/IRE). Both academic and non-academic staff of the sampled university participated in the study. Upon securing informed consent from the participants, they were randomly assigned into four groups of three experimental and one control. The education phase of the psychological skills teaching took place on specified dates with the three experimental groups differently. Educational talk was given to each experimental group for a period of 120 minutes. Exercise programme prescriptions of the American College of Sports Medicine (ACSM 2007) was utilized and monitored for a period of thirteen weeks to both experimental and control group. The exercise programme included walking, jogging, stretching and minor games.

The participants in both experimental and control groups were told about the varied exercise programme, and to attend the exercise programme actively three times in a week (Tuesdays, Thursdays and Saturdays) between 7.00am and 8.00am. Four different locations in a university campus were used for the exercise programmes of each group. The psychological skills training designed for each experimental group was reviewed for 10 – 15 minutes once a week from the 2nd week of the exercise programme to the 7th week. Tuesday was for goal setting group; Thursday was for positive self-talk group and Saturday was for the combined goal setting and positive self-talk groups. Post-test was conducted for the participants after the 13-weeks of exercise programmes. Eight (8) research assistants were employed to provide compliance and feedback on attendance of the participants.

Data analysis

Descriptive statistics of mean, range, frequency counts and percentages were employed to analyse the demographic characteristics of the participants, while the main analyses were conducted through inferential statistics of t-test, Analysis of Variance (ANOVA) and Scheffe post-hoc analysis. Analyses were done using SPSS statistical software version 26.0.

RESULTS

Table 2. T-test analysis on the difference between goal setting and control groups.

	Mean	N	SD	Std Error Mean	Df	T- test	Sig.
Goal setting	22.5385	26	8.59875	1.68635			
Control	20.1923	28	29.06134	5.69940	27	3.863	.001

Note. * $p < .05$.

Results on Table 2 show that there was a statistically significant difference in exercise adherence between goal setting and the control group. Goal setting intervention group demonstrated higher scores (mean = 22.54, t -value = 3.863, $p < .05$) than the control group. Thus, goal-setting intervention had a positive effect on exercise adherence of university staff.

Table 3. T-test analysis on the difference between positive self-talk and control groups.

	Mean	N	SD	Std Error Mean	Df	T- test	Sig.
Positive self-talk	20.5000	26	5.84637	1.14657			
Control	20.1923	28	29.06134	5.69940	27	3.335	.003

Note. * $p < .05$.

Results on Table 3 indicate that there was a statistically significant difference in exercise adherence between the positive self-talk and the control groups. Positive self-talk intervention group demonstrated higher scores (mean = 20.50, t -value = 3.335, $p < .05$) than those of the control group. Positive self-talk positively influenced exercise adherence among the sampled staff.

Table 4. T-test analysis on the difference between combined goal setting and positive self-talk and control groups.

	Mean	N	SD	Std Error Mean	Df	T- test	Sig.
Goal setting /Positive self-talk	29.2593	27	6.83088	1.31460			
Control	20.1923	28	20.50841	5.48645	27	9.523	.000

Note. * $p < .05$.

Results on Table 4 showed that there was a highly significant difference between the combined intervention (goal setting and positive self-talk) and the control groups. Combined intervention group demonstrated higher scores (mean = 29.26, t -value = 9.523, $p < .05$) than the control group. The combined intervention had the strongest effect on exercise adherence of the staffers.

Table 5. One way analysis of Variance (ANOVA) of experimental groups one (goal setting), two (positive self-talk) and three (combined goal setting and positive self-talk) as they influence adherence of participation in exercise programme.

	Sum of Squares	Df	Mean Square	F	Sig.
Between groups	3063.936	3	1021.312	20.638	.000
Within groups	5097.111	103	49.187		

Results on Table 5 show that there was a significant overall difference in exercise adherence among the four groups ($F = 20.64, p < .05$). This implies that at least one group differed significantly from the others without performing equally in exercise adherence among these staffers.

Table 6. Post-hoc analysis (Scheffe) to determine the significance of all the differences between all pairs of means in respect of all psychological skills as they influence exercise adherence.

(I) Groups	(J) Groups	Mean difference (I – J)	Std. Error	Significance
1.00	2.00	2.03846	1.95107	.779
	3.00	-6.72080*	1.93292	.009
	4.00	8.07418*	1.91591	.001
2.00	1.00	-2.03846	1.95107	.779
	3.00	-8.75926*	1.93292	.000
	4.00	6.03571*	1.91591	.009
3.00	1.00	6.72080*	1.93292	.009
	2.00	8.75926*	1.93292	.000
	4.00	14.79497*	1.89742	.000
4.00	1.00	-8.07418*	1.91591	.001
	2.00	-6.03571*	1.91591	.023
	3.00	-14.79497*	1.89742	.000

Results on Table 6 revealed Scheffe post-hoc test that identified exactly which groups differed from each other. First, there was no significant difference in goal setting (1) and positive self-talk (2) (Mean difference = 2.03846, $p = .779$). Second, there was significant difference between goal setting group (1) and combined intervention group (3) (Mean difference = 6.72080, $p = .009$). The combined intervention was more effective than goal setting alone. Third, there was significant difference between positive self-talk and combined intervention (Mean difference = 8.75926, $p = .000$). The combined intervention was more effective than positive self-talk alone. Fourth, there was significant difference between each of the three experimental and control groups. Each PSI was effective in exercise adherence compared to the control group.

From the foregoing, all the three PSIs (goal setting, positive self-talk and combined goal setting and positive self-talk) were effective in improving exercise adherence among university staff compared to the control group. The combined goal setting and positive self-talk intervention was the most effective, demonstrating significantly higher exercise adherence than either single intervention of goal setting or positive self-talk. There was no significant difference between goal setting and positive self-talk alone, suggesting they may be similarly effective when used independently.

DISCUSSION

The present study examined the effectiveness of psychological skills interventions (PSIs) - goal setting, positive self-talk and combined goal setting and positive self-talk on exercise adherence among university staffers in Nigeria. The findings provide empirical support for the efficacy of these interventions in promoting sustained physical activity participation. Specifically, all experimental groups demonstrated significantly higher exercise adherence compared to the control group, with the combined goal setting and positive self-talk intervention yielding the most potent effect.

Consistent with previous research, participants exposed to goal setting exhibited significantly greater exercise adherence than those in the control group. The finding aligns with Howlett et al. (2019) study that

posits that goal-setting enhances behavioural demonstration, practice/rehearsal and graded tasks. It was added that action planning and instruction on demonstration and maintenance of behaviour is associated with continuous physical activity participation. Similarly, Meade et al. (2019) review indicate that improved exercise adherence is associated with five behavioural cognitive techniques which include goal setting, instruction of behaviour, demonstration of behaviour, behavioural, practice/rehearsal and social support. Goal setting provides exercisers with clear behavioural targets and temporal benchmarks, translating intention into actionable plans. Within the Multi-Process Action Control (M-PAC) framework (Rhodes, 2017), goal setting operates primarily at the reflective and regulatory levels, supporting deliberate planning and execution of health behaviours. In the present study, the use of the SMARTER protocol provided exercisers with a clear behavioural guidance, which likely contributed to improved attendance and consistency over the 13-week exercise programme.

Furthermore, the present findings showed that the positive self-talk intervention significantly enhanced exercise adherence of university staff compared to the control group. This could be attributed to the positive self-talk training which emphasized restructuring negative self-statements into positive, instructional, or motivational affirmations possibly empowered participants to persist in the face of common barriers such as lack of time or low energy. This is in accordance with Puddister et al. (2021) findings that frequent exercisers utilized self-talk that focus on self-presentational concerns than their counterparts with less frequent exercise. The frequent exercisers reported consistent use of motivational and positive statements. It was added that self-talk provided a mental image of exercisers' behaviour towards exercise via thoughts and attitudes display. Similarly, Conley (2019) found that participants who received structured self-talk training (emphasizing positive, goal-oriented statements) showed improvements in motivation and exercise behaviour compared to control group, emphasizing the efficacy of positive self-talk to enhance commitment and adherence to exercise routines. Ives (2011) indicated that individuals who used positive and motivational self-talk were more likely to engage and maintain regular participation in physical activity compared to those who did not use self-talk.

Notably, the combined intervention of goal setting and positive self-talk demonstrated substantially higher exercise adherence than either strategy alone, indicating a clear synergistic effect. Post-hoc analyses confirmed that the combined PSI was significantly higher than both single intervention groups and control. This finding supports previous research suggesting that integrating multiple psychological skills yields stronger behavioural outcomes than isolated techniques (Papaioannou et al., 2004). From a theoretical perspective, this finding is consistent with the M-PAC model, which posits that sustained physical activity requires the interaction of reflective (intention formation), regulatory (planning and self-monitoring), and reflexive (automatic motivational processes) mechanisms (Rhodes, 2017; Rebar & Rhodes, 2020). In the present study, goal setting facilitated reflective-regulatory control by structuring exercise behaviour, while positive self-talk strengthened reflexive processes by providing immediate motivational reinforcement during moments of fatigue or resistance. Jointly, this combined approach addressed both the planning and persistence components of adherence, effectively bridging the intention-behaviour gap identified in previous literature (Rhodes & de Bruijn, 2013).

The higher influence of the combined intervention on adherence could be attributed to higher attendance rates of the participants in the intervention group compared to their control group counterparts. These findings strengthened the efficacy of multifaceted psychological interventions in workplace wellness programmes, specifically in a Nigerian university population impeded with cumbersome workloads, limited recreational facilities, and economic stressors which constrain physical activity participation (Odunaiya et al., 2021; Jaiyeoba & Oguntuase, 2019).

The lack of significant difference between goal setting and positive self-talk separately suggests that, while both are effective, neither is substantially higher than the other when applied independently. This may imply that different individuals may benefit from different psychological strategies based on personal cognitive preferences or perceived barriers to behavioural change (Tod et al., 2011). However, the combined approach offers a more generalizable potent intervention that concurrently targets both the structural (behavioural planning and regulation) and affective (motivation) dimensions of exercise adherence.

Limitations

There are some limitations in the present study. First, the study relied on self-reported scale and attendance logs, which may have been subjected to social desirability bias. Future studies could incorporate objective measures such as wearable activity trackers. Second, the sample was drawn from a single university in South-west, Nigeria, which may limit generalisability to other regions or occupational groups. Third, the 13-week exercise programme, while sufficient to detect short- to medium-term effects, does not confirm long-term maintenance of exercise behaviour. Longitudinal follow-ups should be considered. Future studies could examine the integration of other psychological skills such as imagery or mindfulness, examine moderating factors such as age or baseline fitness and test digital delivery formats (e.g., mHealth apps) to enhance scalability.

CONCLUSION

This present study provides convincing evidence that psychological skills interventions (PSIs) specifically goal setting, positive self-talk and combined approach are effective in enhancing exercise adherence among Nigerian university staff. All the intervention groups demonstrated higher exercise adherence compared to the control group, with the combined goal setting and positive self-talk intervention yielding the most significant impact. This emphasizes the potential benefits resulting from integrating structured behavioural planning (goal setting) together with motivational self-regulation (positive self-talk) to promote workplace wellness and combat malaise of physical inactivity in resource-limited settings. Organisational health policies should consider integrating structured psychological training into existing employee wellness programmes to promote sustained health behaviour change.

Recommendation

Arising from the findings of this study, it is recommended that psychological Skills Intervention should be adopted by fitness trainers in developing their training programmes so that exercise adherence is enhanced. Psychological Skills Intervention should be adopted by exercisers who desire to solve the nagging problem of drop out in exercise programmes. Psychological Skills Intervention should be adopted by policy makers in the ivory tower in fine tuning policies that relates to recreational activities especially among university staff.

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: Adekoya, A. F., Osiesi, M. P., Ipinmoroti, O. A., and Oguntuase, S. B. Methodology: Adekoya, A. F., Osiesi, M. P., Ipinmoroti, O. A., and Oguntuase, S. B. Formal analysis: Adekoya, A. F., Osiesi, M. P., Ipinmoroti, O. A., and Oguntuase, S. B. Investigation: Aribamikan, C., Ogunbamowo, W., and Ayenigbara, T. Data curation: Adekoya, A. F., and Osiesi, M. P. Writing – original draft: Adekoya, A. F., and Osiesi, M. P. Writing – review & editing: Adekoya, A. F., Osiesi, M. P., Ipinmoroti, O. A., and Oguntuase, S.

B., Aribamikan, C., Ogunbamowo, W., and Ayenigbara, T. Supervision: Adekoya, A. F., Osiesi, M. P., Ipinmoroti, O. A., and Oguntuase, S. B. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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, no Generative AI nor AI assisted Technologies was used during the writing process of this manuscript. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

ETHICS DECLARATION

Ethical Approval was obtained from the Research Ethics Committee of the Faculty of Education, Federal University Oye-Ekiti, Nigeria (FUOYE/FED/KHE-HUK/301-2025-06/IRE).

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