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REVIEW ARTICLE

Exercise-induced neuroplasticity: Molecular mechanisms and implications for cognitive health and disease intervention

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ABSTRACT

This review synthesizes recent advances in elucidating the molecular basis underlying the effects of exercise on neuroplasticity. Specifically, we will focus on how exercise induces changes in neural connectivity at different levels of organization through conserved signalling pathways mediated by brain-derived neurotrophic factor (BDNF), insulin-like growth factor-1 (IGF-1), and dopamine, which differentially modulate region-specific synaptic plasticity, neurogenesis, and large-scale brain network reorganization. Recent technological breakthroughs have enabled the exploration of cellular heterogeneity and circuit-level plasticity in the hippocampus and prefrontal cortex through single-cell sequencing and optogenetics following chronic and acute exercise interventions. Additionally, recent evidence suggests that the gut microbiota-brain axis plays a regulatory role in mediating the effects of exercise on neuroplasticity. Clinically, exercise interventions can mitigate the pathophysiology of neurodegenerative diseases (NDs), psychiatric disorders, and aid recovery after brain injury. In the future, we envision personalized exercise prescriptions based on individual molecular and phenotypic profiles as an emerging concept in the field of precision medicine. From an evolutionary perspective, the co-adaptation of physical activity and cognitive capacity highlights the adaptive significance of exercise-induced neuroplasticity. Through the integration of basic and clinical science, we hope this review will propel the field forward to new, more targeted, efficacious interventions.

Keywords: Exercise-induced neuroplasticity, Molecular mechanisms, Cognitive health, Neurodegenerative diseases, Interdisciplinary research, Gut microbiota-brain axis, Personalized exercise prescription.

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INTRODUCTION

Physical exercise has attracted considerable attention as a powerful non-pharmacological intervention to enhance cognitive function and brain health across populations ranging from healthy individuals to clinical populations with specific neurological or psychiatric conditions. The accumulating evidence base supports exercise's benefits for brain health, including promoting neuroplasticity, enhancing cerebral metabolism, reducing neuroinflammation, and maintaining neurovascular integrity. It has therefore become an essential topic of interest across the fields of public health, neuroscience, and clinical rehabilitation given the increasing burden of cognitive decline and neurodegenerative diseases in modern aging populations.

The mechanisms by which exercise modulates brain health are through exercise's ability to enhance neuroplasticity – the brain's ability to reorganize both structurally and functionally in response to environmental stimuli and experiences. Learning, memory consolidation, and recovery from injury are all dependent on neuroplasticity and the existing evidence supports the idea that exercise exerts its effects on brain health through the modulation of neuroplasticity via a complex set of molecular, cellular, and systemic mechanisms, including upregulation of neurotrophic factors (for example: brain-derived neurotrophic factor, BDNF), modulating neurotransmitter systems, increasing cerebral blood flow and vascular function, and enhancing neurogenesis and synaptogenesis (Barnes et al., 2021; Hashimoto et al., 2021; Oyovwi et al., 2025). Recent studies have demonstrated that exercise-induced neuroplasticity is heterogeneous and region-specific within targeted brain regions involved in cognition, including the hippocampus, prefrontal cortex, and medial temporal lobe.

For example, aerobic exercise has been shown to be associated with greater hippocampal volume and greater functional activation (or connectivity) within memory-related circuits, and these changes were associated with better executive function and memory performance in older adults (Sinha et al., 2021; Szabo-Reed et al., 2022). Critically, both the intensity and modality of exercise can modify both the nature and amount of neuroplastic changes following exercise (Dhahbi et al., 2025; Jiang et al., 2025). Methodological developments—such as multimodal neuroimaging and electrophysiological phenotyping—have allowed us to characterize the induced brain changes in greater detail following exercise. Functional MRI (fMRI) studies have demonstrated that the types and amounts of exercise modify activity and connectivity within multiple brain networks, including the default mode, salience, and central executive networks, which are involved in cognitive control and attention (Bray et al., 2021; Rosso et al., 2025). Electroencephalography and transcranial magnetic stimulation have additionally supported exercise-induced changes in cortical excitability and synaptic plasticity mechanisms by which exercise may influence cognitive speed and inhibitory control (Turco & Nelson, 2021; Wu et al., 2022). Finally, exercise results in the release of signalling molecules called exerkines—such as lactate, myokines, and microRNAs—that give rise to both systemic and central adaptations. Lactate, a metabolic waste product, serves as a signalling molecule that supports neuroplasticity and cerebral metabolism, thus integrating peripheral muscle activity with brain function (Hashimoto et al. 2021; Zhu et al. 2025). Exercise results in increases in BDNF and other neurotrophic factors that induce changes in synaptic remodelling, neurogenesis, and neuronal survival, which are essential for cognitive resilience and recovery after neurodegenerative disease (Abuleil et al. 2022; Oyovwi et al. 2025).

The clinical application of exercise-induced neuroplasticity has value for individuals with or at risk for cognitive impairment and neurodegenerative disease, including mild cognitive impairment, Alzheimer's disease, Parkinson's disease, and stroke. Randomized controlled trials have shown that different forms of structured exercise improve global cognition, executive function, and memory, along with beneficial changes in brain structure and function (Da Silva-Grigoletto et al. 2024; Karamacoska et al. 2023; Klein et al. 2023; Li et al.

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2021). Exercise also reduces neuroinflammation and vascular dysfunction, both of which are critical mediators of cognitive decline and the pathophysiology of dementia (Barnes et al. 2021; Ribarič, 2022). The exciting new frontier in exercise science and clinical practice is the combination of cognitive and physical training modalities that induce neuroplastic and cognitive changes.

Multimodal exercises, including aerobic and resistance exercise combined with cognitive tasks, hold potential for greater brain functional enhancements beyond exercise (Dhahbi et al., 2025; Mantovani et al., 2024). Novel approaches targeting potentiation of exercise-induced plasticity through virtual reality, neurofeedback, and non-invasive brain stimulation are also being developed (Calabrò et al., 2025; Szabo-Reed et al., 2022). However, no clear guidelines exist yet for the exercise components (type, intensity, frequency, and duration) for targeted interventions in clinical use for a broad spectrum of patients. Longitudinal studies with good designs and high quality, including multimodal biomarkers to decode the exercise–neuroplasticity–cognition loop are urgently needed, particularly in vulnerable populations (Dhahbi et al., 2025; Karamacoska et al., 2023; Sinha et al., 2021). In conclusion, physical exercise represents a powerful, accessible, multifactorial modulator of neuroplasticity with clear implications for cognitive health and intervention in neurodegenerative diseases. It triggers a cascade of molecular, cellular, and network changes that add up to provide better brain function and resilience (Figure 1). The new findings open questions for future interdisciplinary studies connecting neuroscience and exercise physiology with clinical practice to harness exercise-induced neuroplasticity for the sake of cognitive health..

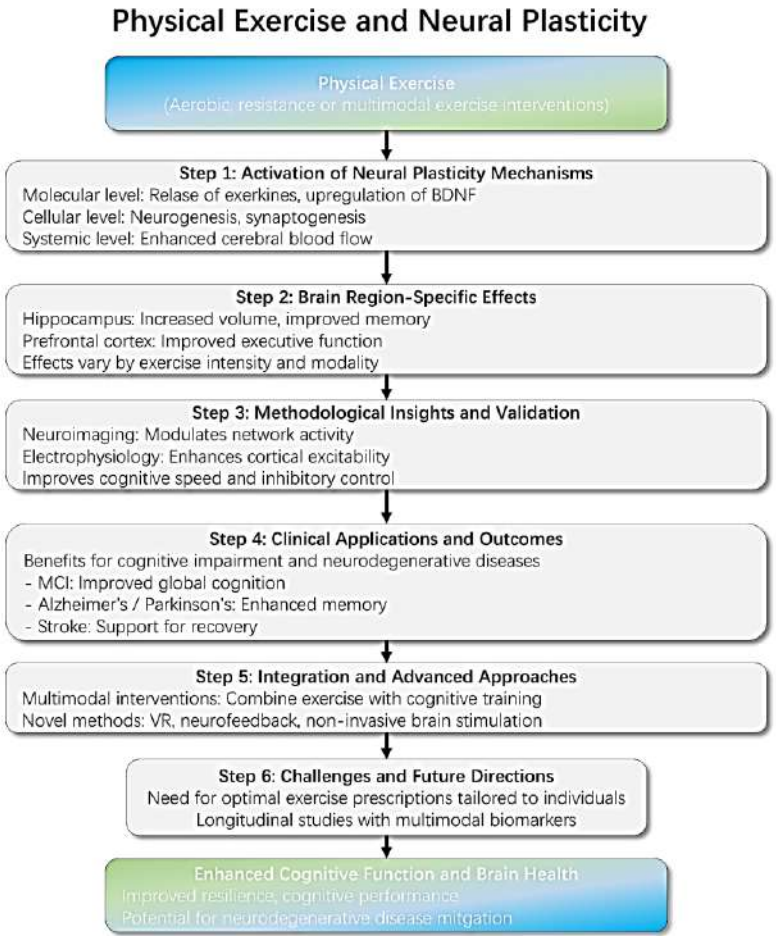


Figure 1. The exercise-neuroplasticity-cognition axis: mechanisms and clinical implications.

MAJOR MECHANISMS OF EXERCISE-INDUCED NEURAL PLASTICITY

Molecular and cellular mechanisms

Key neurotransmitters and growth factor signalling pathways

Physical exercise strongly promotes neuroplasticity at multiple stages by modulating some prototypical neurotransmitters and growth factors that regulate synaptic remodelling, neurogenesis, and cognition. Among them, brain-derived neurotrophic factor (BDNF) is a well-known regulator. Exercise upregulates BDNF expression both peripherally and centrally. Metabolic mediators such as lactate, generated during high-intensity aerobic exercise, promote exercise-induced upregulation of peripheral and brain BDNF expression. This, in turn, provides positive feedback for synaptogenesis, long-term potentiation, and neurogenesis (Müller et al., 2020; Oyovwi et al., 2025; Vints et al., 2022). BDNF exerts its actions through the TrkB receptor and its downstream signalling cascades that promote synaptic plasticity and neuronal survival. Recently, two different BDNF transcript variants, Bdnf I and Bdnf IV, were reported to have different roles in the regulation of dendritic growth and synaptic spine formation, and protein catabolism and fear memory, respectively, suggesting the complexity of BDNF plasticity (Bach et al., 2023, 2024).

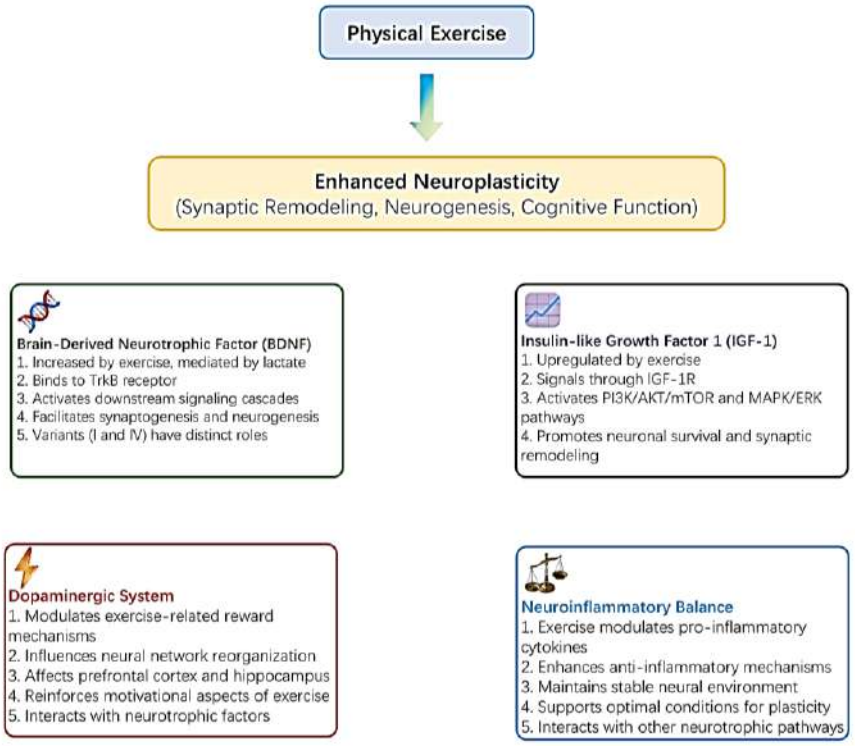


Figure 2. Molecular pathways mediating exercise-induced neuroplasticity.

Insulin-like growth factor 1 (IGF-1) is another important growth factor that is upregulated by exercise. IGF-1 is involved in neuronal survival and synaptic remodelling. IGF-1 signalling through its receptor (IGF-1R) activates downstream intracellular signalling pathways such as PI3K/AKT/mTOR and MAPK/ERK (Hochmuth & Hirrlinger, 2024; Oyovwi et al., 2025; Pike et al., 2020). Exercise also induces upregulation of IGF-1, and IGF-1 signalling pathway interacts with BDNF signalling pathway to mediate exercise-induced enhancements in cognition and neuroprotection (Oyovwi et al., 2025). The dopaminergic system regulates the reward mechanisms elicited by exercise and modulates neural network reorganization in the prefrontal cortex and hippocampus. The dopamine release during exercise not only enhances motivational properties of exercise

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but also interacts with neurotrophic factors to promote plasticity (Turco & Nelson, 2021). In addition, exercise modulates neuroinflammation by regulating the balance between pro- and anti-inflammatory cytokines to maintain a stable neural environment for plasticity (Chen et al., 2025; Zou & Hao, 2024). As illustrated in Figure 2, interacting neurotransmitter and growth-factor pathways collectively mediate exercise-induced changes in brain structure and function.

Epigenetic regulatory mechanisms

Exercise-induced neuroplasticity is also controlled by dynamic epigenetic modifications that affect gene expression without changing the DNA sequence. These modifications include DNA methylation and histone modifications, which affect the accessibility of chromatin and the transcriptional state of genes involved in neuroplasticity (Chen et al., 2020; Shalabi et al., 2024). Exercise can change the methylation state of DNA in promoter and enhancer regions of genes, activating or repressing genes involved in synaptic plasticity and neuronal growth. For example, Pérez et al. showed that the methylation state of blood tissue-specific enhancer elements is associated with functional states in blood during early life, and thus exercise may induce epigenetic remodelling of the methylome in neural tissues (Pérez et al., 2019).

MicroRNAs (miRNAs) are small noncoding RNAs that regulate the expression of target genes at the post-transcriptional level. Many miRNAs are involved in exercise-induced neural adaptations by modulating genes involved in neuroinflammatory pathways, synaptic plasticity, and neuronal survival, which in turn affect cognitive functions ("*MicroRNAs*", 2025; X. Xu, R. Liu, et al., 2024). Exercise can change the expression of several miRNAs, such as miR-21, miR-146a, and miR-155, which are involved in the anti-inflammatory response and neuroprotection. In addition, several miRNAs are involved in feedback regulation of the microRNA machinery itself, which helps to fine-tune the expression of other genes during neuroplastic changes (Liu et al., 2021; Min et al., 2024). RNA methylation may also exert feedback regulation on DNA methylation or vice versa (Xu & Shen, 2022).

In total, epigenetic modifications provide a quick and easily reversible mechanism by which exercise modulates the expression of neural genes to induce long-lasting neuroplasticity. Epigenetic modifications induced by exercise provide potential biomarkers and therapeutic targets for cognitive health and neurological diseases.

Intercellular signal transduction and neural network remodelling

Astrocytes and microglia, the two major glial populations in the central nervous system, contribute to exercise-induced neuroplasticity by supporting neurons and regulating immune responses. Exercise induces region-specific remodelling of astrocyte morphology and reactive gene expression, which is favourable for the enhancement of synaptic support and neurorehabilitation (Li et al., 2021; Lundquist et al., 2019). Astrocytes, microglia, and neurons exhibit crosstalk to promote synapse formation and neurogenesis as well as cerebrovascular remodelling, which leads to the reorganization of neural circuits (Chen et al., 2025; Li et al., 2021). Exercise modulates activation phenotypes of microglia to regulate different states of microglial activation to facilitate neural circuit homeostasis (Cornelison & Fadel, 2022; Sarkar et al., 2020).

Intercellular communication mediated by neurotransmitters, neuropeptides, and growth factors facilitates the dynamic remodelling of neural networks during exercise. For instance, dopamine released during exercise modulates synaptic plasticity and neural circuit function, whereas astrocyte-neuron signalling modulates activity of the mesolimbic dopamine circuit (Corkrum & Araque, 2021). Exercise also induces adjustments in functional connectivity within and between brain regions, which facilitate integration of cognitive networks (Müller et al., 2020; Turco & Nelson, 2021). The interaction between neurons and oligodendroglia facilitates

myelination and neural circuit maturation and repair through regulation of activity-dependent calcium signalling (Thornton & Hughes, 2020). In this way, the intercellular signalling pathways and glial-neuronal interactions generate a plastic and adaptive neural environment. Modulation of these cellular networks by exercise may underlie the improvement in cognitive function and recovery after neurological insults. The involvement of glial cells and the importance of signal transduction in modulating neural networks facilitate our understanding of exercise-induced neuroplasticity.

Advanced technologies and emerging pathways in exercise-induced neuroplasticity

Single-cell sequencing technology to decipher cell type-specific responses

Single-cell RNA sequencing (scRNA-seq) has enabled transcriptomic profiling at the level of single cells and has empowered the investigation of cellular heterogeneity in brain regions involved in cognition and motor skills, such as the hippocampus and prefrontal cortex, by identifying the cell type-specific gene expression changes induced by exercise. For instance, by resolving diverse neuronal subpopulations within these brain regions, scRNA-seq may reveal transcriptional responses to physical activity that are difficult to distinguish in bulk tissue transcriptomes. In other words, the dynamic expression profiles of genes across neuronal and glial populations will be informative of the underlying transcriptional responses driving the modulation of neuronal plasticity, neurogenesis, and metabolic adaptation by exercise. Alternatively, the analysis of cellular heterogeneity in the transcriptomic profiling of neuronal and non-neuronal cells will be informative of how exercise may affect cell fate decisions and functional differentiation, for example promoting neurogenic lineages, or altering the balance between inhibitory versus excitatory neuron development. This will be critical for understanding the cellular mechanisms underlying exercise-induced neuroplasticity, and putative molecular targets that may contribute to cognitive enhancement and neuroprotection. This is possible because we can profile non-neuronal cell types, like astrocytes, microglia, and oligodendrocyte precursor cells, and gain insights into the modulatory and, perhaps, supportive effects these cells may undergo during exercise-induced brain remodelling.

All in all, we suggest that single-cell sequencing provides a means to decode the type-specific molecular adaptations induced by physical exercise on the central nervous system (Crow & Gillis, 2019; Marciante et al., 2024; Thornton & Hughes, 2020).

Optogenetics and neural circuit functional analysis

Optogenetics is an approach that uses light-sensitive opsins to enable spatiotemporal control of specific neuronal populations in targeted brain regions. Here we provide a schematic overview of these applications and mechanisms in Table 1. To understand the plasticity of neural activity induced by exercise, optogenetics has been used to dissect motor-related neural circuits by selectively activating or inhibiting excitatory neurons that participate in motor planning, execution, and learning. It has also been used to dissect discrete neuronal subtypes within motor cortex, basal ganglia, and spinal cord circuits to understand their respective contributions to exercise-induced behavioural improvements and synaptic plasticity. For example, optogenetic activation of motor cortex neurons after stroke enhances motor recovery by promoting synaptic plasticity and circuit reorganization (Berglund et al., 2021; Chowdhury & Yamanaka, 2021; Lu et al., 2019; Vogt, 2020).

By combining optogenetics with approaches such as calcium imaging or functional MRI, researchers can dynamically observe changes in neural network activity induced by exercise or other specific manipulations. This integrated approach characterizes how exercise modulates functional connectivity and neural ensemble dynamics underlying improved motor and cognitive functions. Finally, recent advances in fibreless optogenetics and bioluminescence-driven optogenetics have eliminated many limitations of invasive light

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delivery and enabled chronic and minimally invasive modulation of neural circuits during natural behaviours. These methodological advances open new opportunities to study exercise-induced plasticity in freely moving animals and for translational applications in neurorehabilitation and brain–machine interfaces.

Table 1. Key applications and mechanisms of optogenetics in studying exercise-induced.

Aspect	Description	Key findings/Applications
Core Technology	Enables precise spatiotemporal control of specific neuronal populations using light-sensitive opsins.	Selective activation/inhibition of neurons in motor planning, execution, and learning circuits.
Application in Research	Dissects motor-related neural circuits involved in exercise-induced plasticity.	Identifies neuronal subtypes in motor cortex, basal ganglia, and spinal cord; links their activity to synaptic remodelling.
Therapeutic Example	Optogenetic stimulation post-stroke enhances motor recovery.	Promotes synaptic plasticity and circuit reorganization in motor cortex.
Integrated Methods	Combined with calcium imaging or functional MRI for dynamic monitoring of neural activity.	Elucidates changes in functional connectivity and neural ensemble dynamics induced by exercise.
Recent Advances	Fibreless and bioluminescence-driven optogenetics enable less invasive and chronic modulation during natural behaviours.	Facilitates study of plasticity in freely moving animals and supports translational neurorehabilitation applications.
Overall Significance	Provides causal insights into relationships between neural circuit activity and exercise-driven functional outcomes.	Critical for advancing neurorehabilitation and brain-machine interface technologies.

Note. Optogenetics enables the dissection of motor-related neural circuits by selectively activating or inhibiting the excitatory neurons that participate in motor planning, execution, and learning.

Regulatory role of the gut microbiota-brain axis

Rising reports suggest the presence of a gut microbiota-brain axis that is capable of significantly modulating neuroplasticity, with physical exercise being a powerful influencer of gut microbial composition and function. Changes in the gut microbiome induced by exercise result in the modulation of microbial metabolites such as short-chain fatty acids and precursors of neurotransmitters that are capable of crossing the gut barrier and influencing brain function. These metabolites modulate neuroinflammatory responses, neurogenesis, and synaptic plasticity to confer cognitive and motor improvements following physical exercise. The gut microbiota also communicates with the enteric nervous system and central nervous system through neural, immune, and endocrine pathways to form a bidirectional communication network that influences brain health. It is worth noting that exercise can modulate populations of microbial life in the body to bestow enhancements in the production of neuroactive steroids and other classes of signalling molecules that modulate neuronal excitability and plasticity. This microbiota-gut-brain axis represents a previously unknown means by which exercise imparts neuroprotectant and neuroplastic effects and provides new opportunities to treat neurological disease. Modulation of the gut microbiota through probiotics or other dietary manipulations in combination with exercise may confer additive effects that enhance plasticity and cognitive resilience. Modulation of the gut microbiota alters multiple gut microbiota–brain interactions, which must be carefully considered when designing exercise-based interventions (Blair et al., 2025; Cryan et al., 2019; Lee et al., 2023).

Clinical applications and future directions

Applications in neurodegenerative diseases

Exercise has exhibited promising potential as a non-pharmacological intervention to preserve and improve cognitive and motor functions in neurodegenerative diseases such as Alzheimer's disease (AD) and Parkinson's disease (PD). Meta-analyses and systematic reviews have demonstrated that exercise interventions can improve cognitive function, activities of daily living, and neuropsychiatric symptoms in individuals with AD. For instance, aerobic, resistance, and multicomponent exercises can improve the Mini-Mental State Examination (MMSE) scores and decrease the Neuropsychiatric Inventory (NPI) scores. Longer exercise interventions (>16 weeks) showed greater improvements (López-Ortiz et al., 2021; Roy et al., 2023; Z. Xu et al., 2024). In PD, exercise can induce neuroplastic changes that may delay disease progression and improve motor symptoms, such as gait, balance, and motor scores after aerobic, resistance, dance, and task-oriented training (Lorenzo-García et al., 2024; Sandroff et al., 2020; Yang et al., 2025). The molecular basis underlying the protective effects of exercise on neurodegenerative diseases includes exercise-induced upregulation of neurotrophic factors, including brain-derived neurotrophic factor (BDNF) (Müller et al., 2020), insulin-like growth factor-1 (IGF-1) (Oyovwi et al., 2025), and exerkines, which can promote synaptogenesis, neurogenesis, and long-term potentiation, and further enhance neuroplasticity (Vints et al., 2022). Exercise can also modulate neuroinflammation and oxidative stress, two hallmarks of neurodegenerative pathology (Ribarič 2022). Furthermore, exercise can improve cerebrovascular function and brain metabolism to facilitate neural repair and functional recovery (Huang et al. 2022; Hwang et al. 2023). Sex differences in exercise effects were also found in AD, with women showing larger cognitive improvements and neurotrophic support after exercise, highlighting the importance of sex-specific exercise prescriptions. New technologies, including virtual reality and neuroimaging, were applied to improve exercise interventions and neuroplastic changes (Huang et al. 2022; Yi et al. 2022). In summary, exercise provides comprehensive neuroprotective effects on NDs by modulating neuroplasticity, neuroinflammation, and vascular and metabolic brain health to preserve cognitive and motor functions.

Application in mental disorders and brain injury rehabilitation

Exercise interventions improve neurofunctional outcomes and emotional regulation in rehabilitation of mental disorders and brain injury. Exercise interventions also contribute to neural function in mood disorders (depression and anxiety) via modulation of neuroplasticity-related pathways and neurotrophic factors, which subsequently alleviate mood disorders and improve cognitive function (Bendau et al., 2024; Deng et al., 2024; Pascoe et al., 2020). Exercise reduces symptoms of anxiety and depression by acting on the endocannabinoid system, enhancing endorphin release, and improving self-esteem and body image (Pujari, 2024). Moreover, exercise also improves cognitive impairment and executive function in psychiatric populations (Ashdown-Franks et al., 2020).

Brain injury includes TBI and stroke. Exercise improves neuroplasticity via modulation of neurotrophic factors, facilitating synaptic remodelling, neural regeneration, and interhemispheric connectivity, which subsequently improve motor and cognitive recovery (Singaravelu Jaganathan & Sullivan, 2022; Snowden et al., 2023; Xing & Bai, 2020). Early mobilization and individualized exercise programs including aerobic, resistance, and task-specific training after brain injury could improve physical function, cognition, and quality of life (Nakamura, 2021; Romanov et al., 2021). In addition, exercise intensity and timing critically affect the outcomes of rehabilitation programs. Moderate intensity programs could induce maximal neuroplasticity with minimal adverse effects (Taguchi et al., 2019; White et al., 2023). Moreover, both cognitive training and motor training in virtual reality and exercise could further enhance brain health and functional outcomes (Sakhare et al., 2021). Exercise could alleviate anxiety, depression and fatigue in end-stage renal disease patients and other

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chronic patients (Zhao et al., 2019) and improve cognitive impairment and executive function (Deng et al., 2024).

Challenges and prospects of personalized exercise prescription

Personalized exercise prescriptions, based on individual genetic, epigenetic and neurofunctional profiles, present opportunities and challenges. Variability in response to exercise has been demonstrated within and between individuals and is influenced by intrinsic factors (sex, age, hormonal status, genetics) and extrinsic factors (exercise dose, time of day, circadian rhythms, diet, medication) (Noone et al., 2024).

Evidence is emerging for the use of biomarkers such as neurotrophic factors (BDNF, IGF-1), myokines and neuroimaging features to guide personalized interventions (Gao et al., 2024; Savettiere et al., 2025). Figure 3 shows an integration of multi-dimensional data and technology. We outline a personalized exercise-prescription framework that includes core concepts (genetic, epigenetic and neurofunctional profiles), individual modifiers (intrinsic and extrinsic), actionable biomarkers (for example: BDNF, IGF-1, myokines) and enabling technologies (computational tools, wearables, AI, telehealth) and challenges and future opportunities.

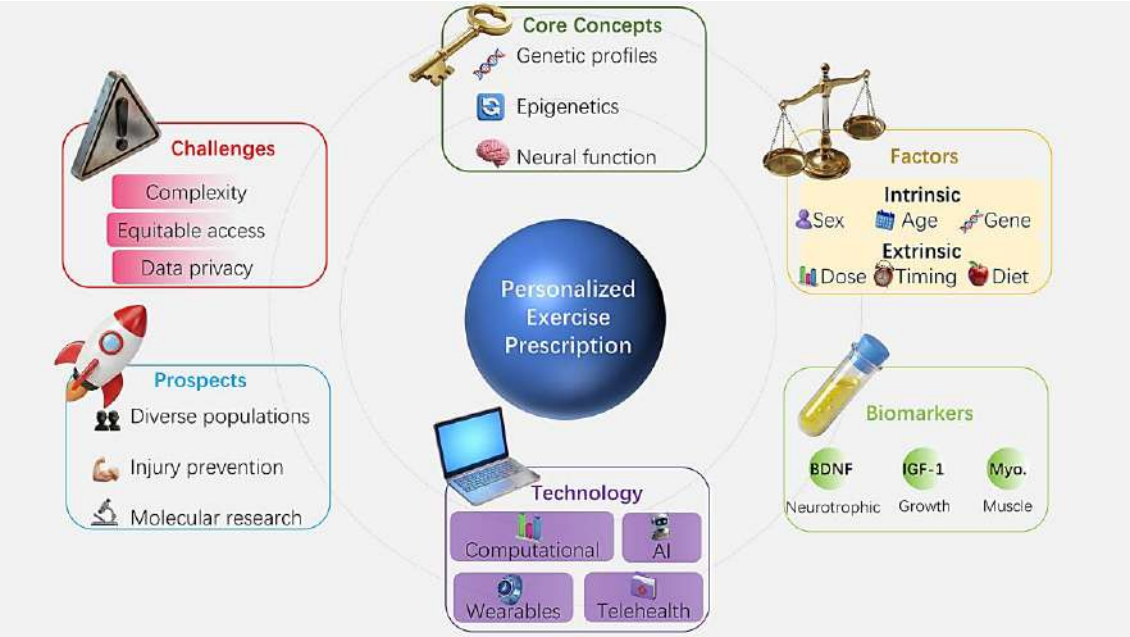


Figure 3. Challenges and prospects of personalized exercise prescription.

Given the complexity of interactions between these modifiers, computational models will be required to optimize the intensity, time and modality of exercise for individuals (Yuan et al., 2025; Zou & Hao, 2024). The adoption of personalized exercise prescriptions will raise ethical and social challenges around access, data privacy and consent, and adherence monitoring that will require multidisciplinary input to address (Xu et al., 2024). The feasibility and acceptability of digital interventions have been demonstrated across different populations, including individuals with Long COVID and Parkinson's disease, enabling remote monitoring and personalized intervention modifications (Ha et al., 2024; Xu et al., 2024).

Personalized prescriptions based on tendon strain and muscle-tendon balance have shown promise in injury prevention and rehabilitation, with potential for use throughout the rehabilitation process from acute injury

through to return to sport and prevention of re-injury (Mersmann et al., 2025; Weidlich et al., 2024). Standardized protocols and core outcome sets will be required to improve reproducibility and clinical translation (Peng et al., 2025; Playle et al., 2019). Future research should focus on understanding the underlying molecular mechanisms and refining predictive biomarkers and adaptive, user-centred exercise programs that take motivational and behavioural factors into account to improve long-term adherence and therapeutic outcomes (Wackerhage & Schoenfeld, 2021; Yang et al., 2021).

CONCLUSION

Investigation of exercise-induced neuroplasticity is an emerging interdisciplinary area that bridges neuroscience, exercise science and epigenetics. The review delineates the basic principles of complicated molecular signalling pathways and cell type-specific regulatory mechanisms underlying the beneficial effects of physical activity on brain function. The complexity of these biological processes requires an integrated multidisciplinary approach to comprehensively understand the mechanisms by which exercise modulates neuroplasticity. Figure 4 is a conceptual integration of multiple disciplines, crucial basic mechanisms (i.e., gut-microbiota-brain axis, advanced technology, and clinical application), an evolutionary perspective, and the potential of exercise-induced neuroplasticity. The combination of powerful techniques, such as single-cell sequencing and optogenetics, has enabled us to understand how exercise influences brain circuit function with previously hard-to-attain resolution. These tools allow us to dissect neural heterogeneity and circuit dynamics with great care, revealing previously inaccessible insights into activity input-induced neural remodelling. As the cumulative knowledge of the gut microbiota-brain axis gradually widens our conceptual space, we suggest that the influence of exercise on cognition and mental health may be through systemic, bidirectional processes that go beyond the central nervous system. Integration of multiple research perspectives, ranging from molecular to cellular to systemic levels, is required for an integrated understanding of the multifaceted effects of exercise on brain health.

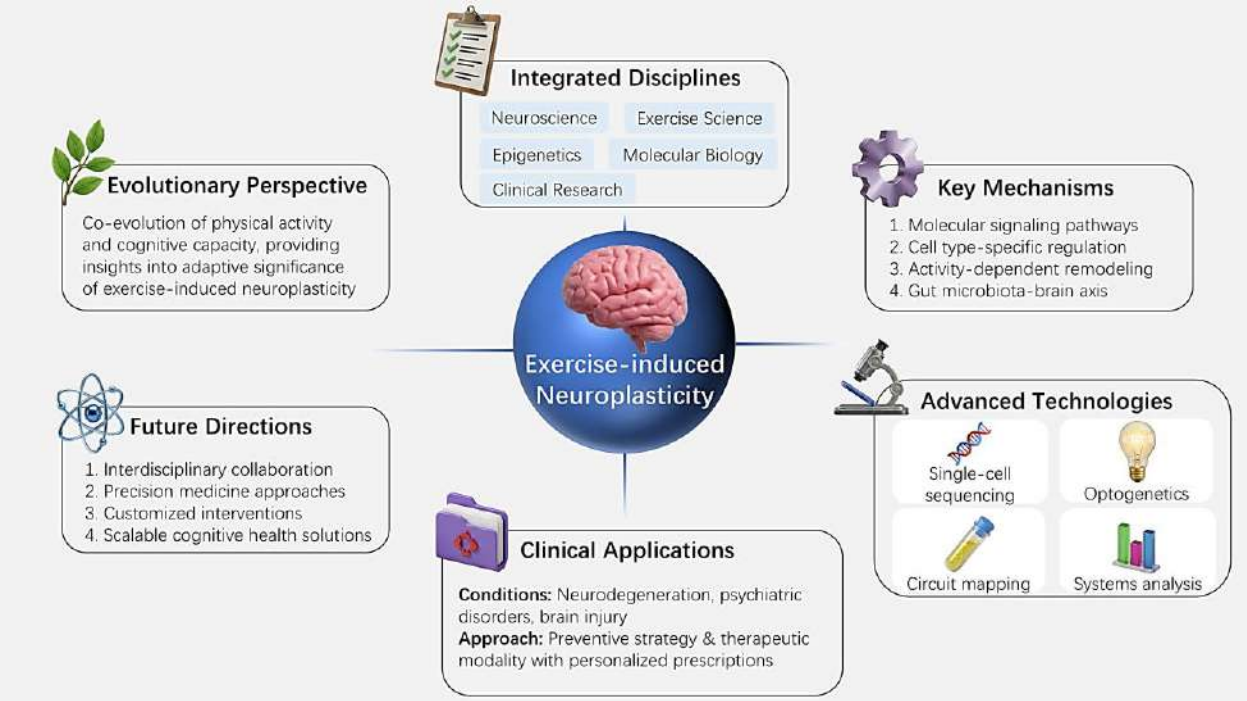


Figure 4. Exercise-induced neuroplasticity: integration and future directions.

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The evidence supports the effectiveness of exercise as both a preventive and a therapeutic modality that promotes neuroplasticity and functional recovery, which has considerably facilitated the development of highly personalized exercise programs tailored to individual patient profiles with the potential for enhanced treatment effects. The presence of patient population heterogeneity and exercise protocol variability suggests the need for highly standardized methodologies to resolve conflicting findings and improve clinical guidelines.

From an evolutionary biological perspective, the coevolution of physical activity and cognitive capacity highlights the adaptive role of exercise-induced neuroplasticity. The understanding of this interaction facilitates researchers' and clinicians' ability to confront modern public health issues caused by sedentary behaviour and cognitive degeneration. Contemporary research models emphasize the relevance of an evolutionary perspective. Future progress in this domain hinges on robust interdisciplinary engagement between molecular biologists, clinical researchers, modelers, and behavioural scientists. Enhanced mechanistic comprehension is poised to expedite the evolution of exercise neuroscience into personalized medicine, enabling customized exercise interventions aligned with genetic, epigenetic, and environmental variables. The progression would unveil prospects for paradigm-shifting, scalable methods aimed at improving cognitive health on a global scale, alongside diminishing the impact of neurological and psychiatric ailments.

The integration underscores the dynamic and rapidly evolving landscape of exercise-induced neuroplasticity research. The convergence of varied research perspectives and the employment of cutting-edge technologies positions the scientific community to uncover new therapeutic avenues and to foster a shift towards personalized, mechanism-based exercise interventions. The integrative approach is crucial for promoting lifelong brain health and cognitive resilience amidst global complexities and aging demographics.

AUTHOR CONTRIBUTIONS

Conceptualization: MZ; Writing - original draft preparation: HC, JL, LY, SZ, ZJ, YX and WZ; Writing - review & editing: YL, YS and JL; Visualization: YS,JL and ZM; Supervision: MZ; Project administration: MZ; Funding acquisition: MZ. HC and JL have made equal contributions to this paper.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

Emerging sports science technologies in decoding and preventing joint injuries: A new era for athletics in China and Asia

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ABSTRACT

Sports injuries are a major issue for all athletes, but joint injuries particularly so for athletes in the rigorous sport of athletics, whose very sustainability depends on the sustainability of athletes. New sports science technologies are turning joint injuries into a transparent box problem with new understanding of their causes and new efficacy in preventing them. In this article, we review the state of the art in sports science technologies such as wearable sensors, artificial intelligence, computer vision and biomechanical modelling which work together to decode the micro-mechanics of joint damage. With an application and current research perspective centred around China and Asia, this article addresses the challenges remaining in these technologies including data integration, accessibility of technology, and development of intervention solutions tailored to individuals. Through the discussion of representative case studies, this review highlights how these new technologies enable personalised and precise joint management for improved injury prevention and rehabilitation. This review aims to drive the development of an intelligent prevention ecosystem which can not only improve the performance of Asian athletes but also protect their musculoskeletal health in the new era of sports medicine and athletics training.

Keywords: Sports science technology, Joint injury, Wearable sensors, Artificial intelligence, Biomechanics, Chinese athletics, Sports injury prevention.

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INTRODUCTION

Joint injuries are among the most common and most disabling categories of sports injuries in sports that require joint injuries with high demand, repetitive, complex and specific joint movements, and athletics is no exception. In particular, joint injuries and the related problems associated with the knee, ankle and shoulder are major obstacles to performance and career longevity in athletics and other sports events. Epidemiological studies in different populations have provided evidence for high incidences of joint injuries in sports. For example, in a prospective cohort of adolescents participating in sports in South Africa, lower limb injuries represented 61% of all injuries, and sprains of joints and muscles formed a large proportion (van Loggerenberg et al., 2025). In addition, injuries in Olympic sports have shown that the most commonly injured joints are the knee and shoulder, with injury prevalence rates of 28% for the former and 14% for the latter (Lambert et al., 2022, 2024). These injuries result in both acute time loss from training and competition, and lifelong sequelae such as osteoarthritis, persistent pain and functional disability. High cumulative injury burdens and persistent musculoskeletal problems associated with previous joint injuries are also commonly reported by retired national-level athletes (Cooper et al., 2021; Hind et al., 2020). As joints play a crucial role in athletic performance and joint injuries have serious consequences, effective prevention and treatment strategies are of great importance in sports medicine.

Traditionally, the prevention and diagnosis of joint injuries in athletics has been largely driven by clinical experience, physical examination, and relatively simple assessment tools. Traditional approaches have included subjective measures, passive range of motion assessments, manual tests, and conventional radiographs and magnetic resonance imaging (MRI). These approaches may yield useful information; however, they are episodic, provide no feedback, and do not consider the dynamic biomechanical factors that lead to injury. For example, MRI can localize damage, such as rotator cuff tears, cartilage lesions, etc., but it is most often used to diagnose injury that has already occurred rather than as a preventative measure (Lusi et al., 2025; Sarin et al., 2021); Clinical assessments of joint laxity and muscle strength have been suggested as potential predictors of injury risk (e.g. hamstring-to-quadriceps [H:Q] strength ratios) (Kellis et al., 2023); however, recent systematic reviews have found them to have poor predictive value when used alone. Traditional approaches to athlete injury surveillance may also be lacking in precision and comparison accuracy, particularly in populations with limb deficiencies (i.e. Paralympians) (Heneghan et al., 2021; Heneghan et al., 2020); here, traditional methods will likely be inadequate to provide the detailed individual-focused monitoring needed to prevent joint injuries in elite and developing athletes.

The recent advent of sports science technologies represents a revolution in how we prevent joint injuries from an experience-based knowledge to one based on data. Advances in wearable sensor technology, machine learning and imaging in recent years have allowed for the continuous, accurate and real-time monitoring of joint biomechanics and tissue properties. For example, deep learning models have been applied to data recorded from IMUs to predict the lower limb kinematics and vGRF during running and other activities which offer new knowledge of the joint loading pattern(s) that lead to injury (Chen et al., 2025; Patra et al., 2023). Deep learning models applied to infrared thermography have been applied to non-invasively characterise the knee joint thermal profile during exercise which may correlate with underlying pathological condition (e.g. inflammation, early degenerative changes) (Crisafulli et al., 2024).Machine learning application on electronic foetal monitoring and EEG data demonstrate the potential of artificial intelligence in identifying patterns from complex biological data and predicting future outcomes which can be extended to musculoskeletal injury prediction (Aghaeeaval et al., 2021; McCoy et al., 2025); While near-infrared spectroscopy (NIRS) coupled with machine learning has shown potential for in vivo arthroscopic monitoring of cartilage properties and longitudinal assessment of cartilage degeneration after injury (Sarin et al., 2021).

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These tools used in conjunction with the advances made in micro physiological systems like organ-on-a-chip models, provides new opportunities to investigate joint pathologies and drug responses in ex vivo platforms that mimic the in vivo environment at microscale (Ajalik et al., 2022).

Given the context and circumstances of China and Asian sports, the use of modern sports science technology is of utmost significance. Given the increasing number and frequency of Chinese and Asian athletes competing successfully in international athletics, ethnic-based injury prevention programmes are necessary for this population after taking into account ethnic, biomechanical and cultural factors. In terms of Asian athletes, research has found several intrinsic risk factors for joint injuries, including lower hamstring-to-quadriceps strength ratios and body composition characteristics associated with ACL injury risk in male American football players and young female soccer players in Japan (Taketomi, Kawaguchi, Mizutani, Takei, Yamagami, Kono, Murakami, Arakawa, et al., 2024; Taketomi, Kawaguchi, Mizutani, Takei, Yamagami, Kono, Murakami, Kage, et al., 2024). However, surveillance and advanced biomechanical monitoring are limited in these populations. Novel wearable sensor technologies, machine learning-based predictive models, and advanced imaging can fill this gap, enabling precision sports medicine for Chinese and Asian athletes with characteristics in terms of their physiology and biomechanics. Additionally, the development of monitoring tools that are accessible, non-invasive, and cost-effective is essential for a wide range of training environments commonly found across Asia.

This review is to systematically synthesize the current emerging sports science technologies in decoding and preventing joint injuries in athletics with a special emphasis on their usage and potential in China and Asia. We will review the emerging technologies in various forms of wearable sensors, artificial intelligence, imaging modalities, and bioengineered models, and relate them to the distinctive aspects of Asian athletes. With the epidemiological information, biomechanical knowledge, and innovative technologies, we would like to give birth to a new chapter in sports medicine which uses advanced technologies to support athlete health, performance, and career in the region of Asia. At last, we will also discuss the future directions of technology fusion, research roadmaps, and implementation strategies to optimize the usage of technologies in China and Asia athletics.

APPLICATION OF WEARABLE TECHNOLOGY IN JOINT INJURY MONITORING

Inertial sensor technology and its role in monitoring exercise load

Inertial Measurement Units (IMUs) encompassing accelerometers and gyroscopes have recently enabled real-time assessment of joint kinematics (angles, angular velocities and accelerations) and thus provided new means to monitor athletes' three-dimensional movement patterns. Being worn typically around the lower limb, IMUs produce continuous joint-related signals that can be used to evaluate the biomechanical demands imposed by training and competitive activities on the joint and therefore to investigate injury and fatigue loads. For example, as shown in Figure 1 "*Comparison of Knee Joint Angle in Sagittal Plane Between IMU Measurements and Optical System Measurement*" (correlation > .94), IMUs have been compared against gold-standard optoelectronic systems and demonstrated good agreement in the sagittal plane kinematics of the knee and hip during a complex high-speed task, which involved the drop jump, sprint and directional change actions (correlation coefficients > .94 and coefficients of multiple correlation > .96) (Di Paolo et al., 2021). Such high levels of agreement highlight the potential of IMUs to provide accurate information on clinically relevant joint kinematics that are fundamental to the rehabilitation and return-to-sport following an injury, e.g. anterior cruciate ligament (ACL) injury.

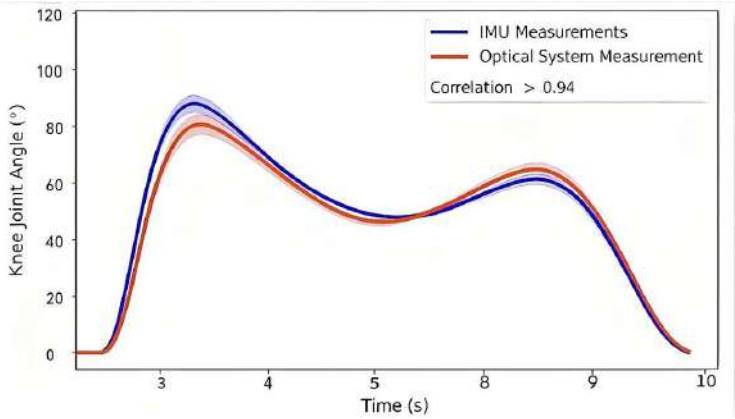
In addition to kinematic data, IMUs enable accurate assessment of movement intensity and asymmetry. These parameters can indicate fatigue and overuse, which predispose athletes to joint injuries.

For instance, in hockey skaters, IMU-predicted three-dimensional joint angles have been used to distinguish between high- and low-calibre hockey players, highlighting performance-related biomechanical differences that may contribute to injury risk (Khandan et al., 2022).

Machine learning on raw IMU data has improved joint loading characteristic signals and enabled accurate estimation of joint torque and loading with good fidelity in real-time (Chang et al., 2025). Thus, the combination of AI and IMU data enables accurate, low-cost, wearable technology that can provide joint torque information in a natural setting beyond the lab.

By enabling real-time data acquisition, IMUs play a crucial role in injury anticipation through the early detection of asymmetries and aberrant loading patterns that precede joint injury. For example, IMU wearable technology has been used to estimate knee joint function following ACL reconstruction and objective biomechanical measures extracted from these assessments can be correlated with patient-reported outcome measures to inform rehabilitation (Ptaszyk et al., 2025). Similar to the gait lab, convolutional neural networks applied to IMU kinematic data have reproduced gait lab quality kinematic data, showing the potential of IMUs married with advanced analytical approaches to longitudinally assess knee function in the clinical and field environment (Bini et al., 2025).

Although significant advances have been made in regards to data accuracy and sensor positions, recent studies in sensor fusion, calibration methods, and machine learning have enhanced the accuracy and reliability of IMU data measurements. For instance, when using spatial geometric equations in single-sensor systems, joint angle error in terms of the ratio to dual-sensor and camera-based systems was 5°, indicating a step towards more accurate and minimalistic wearable IMUs (Shiao et al., 2024). This enables the widespread use of IMUs for the continuous monitoring of exercise load, asymmetry, and fatigue, which are crucial for the prevention of joint injuries in athletes. Such athletes, who are frequently injured due to high demands for specific sports, include athletes, footballers, and badminton players (Davidoviča et al., 2025; Yu et al., 2023).



Note. This figure depicts the knee joint angle over time in the sagittal plane, comparing measurements from Inertial Measurement Units (IMUs) and a gold-standard optical system. The correlation coefficient between the two measurement methods exceeds .94, demonstrating the high accuracy of IMUs in capturing knee joint kinematics, consistent with the findings of (Di Paolo et al., 2021).

Figure 1. Comparison of knee joint angle in sagittal plane between imu measurements and optical system measurement.

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In a nutshell, inertial sensors provide a potent, portable and economical solution to analyse joint biomechanics and exercise load in real time. By revealing injury risk factors such as asymmetry and accumulation of fatigue on kinematic and kinetic parameters, IMUs identify the early warning signs that can be turned into prevention and rehabilitation actions with the help of AI and machine learning technologies. This is how inertial sensors are changing the game in sports science and athlete training & rehabilitation in China and Asia.

Pressure insoles and analysis of plantar pressure distribution

Pressure insole is an instrument to evaluate the plantar pressure distribution and the biomechanical joint reaction to this pressure which helps to forecast gait abnormalities and possible injuries in athletes. These insoles with pressure sensors can tell you what the dynamic pressure pattern over the foot during gait is by recording the dynamic pressure distribution pattern over the foot during gait and detect any abnormal loading pattern that may lead to stress on the knee and ankle joint. That is, the plantar pressure can be used as a surrogate parameter of joint loading and neuromuscular control if the relationship between joint kinematics and plantar pressure is correlated. For example, researchers discovered that there were significant correlations between kinematic parameters of hip and knee joints and medial-lateral plantar pressure distribution pattern during functional over-ground activities in youth athletes by combining use of smart sock system and inertial sensors (Davidoviča et al., 2025).

The plantar pressure information from insoles could expose the gait deviations (asymmetrical unloading, increased pressures at specific areas at the plantar surface) which would increase the risks of overuse injuries of joints, e.g. osteoarthritis, ligamentous injuries.

Insoles could be formed based on the foot morphology and pressure mapping analysis information. The insoles could be used to redistribute the loads at the plantar surface, decrease the peak pressure at specific areas at the plantar surface (i.e. metatarsal heads, heels), and correct the biomechanics of the foot (Lin et al., 2025; Wang et al., 2025).

Populations with foot morphology deformities (i.e. flatfoot, cavus foot). The pressure insoles could be used to assess the effectiveness of the orthotic interventions. The interventions were designed to normalize the pressures at specific areas at the plantar surface and reduce the joint stress (Ma et al., 2024; Wang et al., 2020).

When applying the pressure insole technology for Chinese and Asian athletes, we should also take the regional physiological foot characteristics into account. There are arch height and foot morphology variations for Chinese and Asian population, and the insoles application and insoles design should also consider these regional characteristics. It has been proved that the customized insoles including the insoles fabricated by 3D printing technology can be prepared to satisfy the above requirements (Nouman et al., 2019; Xu et al., 2019). Furthermore, the variations of plantar pressure can be used to detect the training load and the athletes' fatigue even to predict the joint injury ahead of time.

The combination of pressure insole data and other wearable sensor information, such as IMUs and electromyography, will extend the biomechanical assessment information and help to construct individualized training and rehabilitation programs based on specific biomechanical deficits and prevent joint injuries (Davidoviča et al., 2025).

Because the pressure insole technology is a non-invasive technology that can collect real-time information of plantar pressure distribution and its effects on the health of the knee and ankle joints, it has been extensively used in early joint injury screening and prevention due to its ability to reflect gait abnormalities and loading area asymmetries. In addition, because the pressure insole technology can adapt to the characteristics of the feet of Chinese and Asian athletes, it also has great application prospects in the clinical and sports fields to enhance athletic performance and decrease the injury rate.

Advantages and challenges of multisensory fusion technology

Multisensory fusion methods that integrate data from various types of wearable sensors, such as IMU kinematics information, plantar pressure information, EMG information, and others, can supply richer information for joint injury monitoring. The complementary biomechanical and physiological information from different sensors improve the understanding of joint injury mechanisms and loading conditions of the joint compared to a single sensor (Davidoviča et al., 2025) (Table1).

Table1. Comparison of core parameters, advantages, and limitations for IMU, pressure insoles, and EMG sensors.

Attribute	**IMU (Inertial Measurement Unit)**	**Pressure Insoles**	**Electromyography (EMG)**
Measurement metrics	Acceleration, angular velocity, orientation (kinematic parameters)	Plantar pressure distribution, force values, load centre	Muscle electrical activity, contraction intensity, fatigue indicators
Sampling rate range	50-1000 Hz (typical: 100-200 Hz)	10-100 Hz (typical: 20-50 Hz)	1000-2000 Hz(typical: 1000-1500 Hz)
Advantages	Portable, real-time motion capture, cost-effective, easy integration	Direct biomechanical load measurement, assesses balance/gait, non-invasive	High temporal resolution, reflects neuromuscular control, detects muscle fatigue
Limitations	Signal drift, magnetic interference, requires calibration, noise-sensitive	Comfort issues, affected by humidity/temperature, limited battery life	High signal noise, requires skin preparation, motion artifacts, higher cost
Application scenarios	Motion analysis, gait assessment, joint angle monitoring, real-time feedback systems	Foot biomechanics research, rehabilitation training, athletic footwear design, injury risk assessment	Muscle function evaluation, rehabilitation monitoring, sports performance analysis, neurological disease research

Note. IMU: Inertial Measurement Unit; EMG: Electromyography. Sampling rate ranges are based on typical values used in research and practical applications. The parameters highlight the complementary nature of each sensor type in multisensory fusion for joint injury monitoring.

Even the process of integrating heterogeneous sensor information poses challenges in data handling such as the need for sophisticated algorithms to integrate data from sensors with varying sampling rates (Table1), signals noise and drift, and portability issues and athlete comfort concerns. For instance, the number of sensors on a wearable system may impact the sensor number and athlete's willingness to wear the device (Lloyd et al., 2023). An increase in the number of sensors on a wearable system may result in a decrease in data richness and wearability of the device, which may impact athlete's performance.

Techniques such as machine learning and artificial intelligence, categorized under advanced data fusion methods, have been proposed to overcome these issues due to their abilities to extract features, reduce noises, and recognize patterns from multiple sensors. These approaches can provide immediate feedback information to athletes and coaches about biomechanical deviations and injury-prone factors during training and matches for further correction and rehabilitation (Chang et al., 2025; Jung et al., 2024). The creation of individualized biomechanical models named digital twins (updated with sensor data information) is feasible

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with the assistance of multisensory data fusion and intelligent algorithms, which might be the future of individualized injury prevention strategies (Lloyd et al., 2023).

The realization of closed-loop systems with multisensory data fusion and feedback information is technically complex and demands the support of specific algorithms, devices with low delays, and a user experience. In addition, data privacy and security issues should be taken into account for the wireless wearable systems, particularly when they are used in field settings. These issues can be solved by the current rapid evolution of microelectronic devices, wireless communication technologies, and computing power, which are enabling practical applications of multisensory data fusion in sports.

Multisensory fusion technology has a broad application perspective in detecting and preventing joint injuries for Chinese/Asian athletics because of their variety in their movements and environment. It is necessary to localise the technologies to local situations, i.e. training approaches and athletes' body features, to popularize and apply the technologies well. Interdisciplinary research and development are needed to solve the current problems of multisensory fusion technology.

AI-DRIVEN FRAMEWORK FOR SPORTS INJURY MONITORING AND PREVENTION

Multimodal data integration and feature extraction techniques

The integration of various data sources like wearable sensors, biomechanical data and training logs is key to enhance the accuracy of injury risk prediction in athletics. Wearable sensors can generate continuous recordings of kinematic and physiological signals and have the potential to register biomechanical deviations that may precede injury. Motion capture and the force plates provide information on movement patterns and applied loads. Training logs can offer additional information on the athlete's state with regards to workload, fatigue and recovery. Integrating data from all these sources will result in a 'holistic' picture of the athlete's physical state.

Feature engineering is the process of extracting meaningful information from raw signals. Time-domain features (e.g. mean, variance, peak values) describe properties of the signal amplitude and variability. Features in the frequency domain (e.g. power spectral density, dominant frequencies) describe periodicities and oscillatory behaviour that might be related to neuromuscular control. Other nonlinear features (e.g. entropy measures, fractal dimensions) describe signal properties concerning signal complexity and irregularity patterns that might be related to neuromotor adaptations or dysfunctions that predate injury.

Feature selection is the process of finding a subset of input variables that are most relevant for the prediction targets. It is an important step to reduce the dimensionality of a dataset and therefore improve model performance and reduce overfitting. Methods like recursive feature elimination, mutual information measures and embedded methods within machine learning algorithms are implemented.

Studies have demonstrated that combining data from multiple sources, in combination with strong feature extraction approaches, can enhance the sensitivity and specificity of injury-prediction models (Claudino et al., 2019; Jiang et al., 2022; Musat et al., 2024), which can subsequently be used to deliver personalised and dynamic injury-risk assessment within large athletic cohorts.

Regardless of the setting in which they are applied, it is probable that different approaches to data integration will be required when working with Chinese and wider Asian athletic populations because of the different training regimens and biomechanical characteristics that these athletes exhibit. This will necessitate an

understanding of appropriate data fusion approaches that enable us to decode injury information and facilitate prevention.

Machine learning model development and validation

Supervised machine learning algorithms have been used in the field of sports injury risk prediction with labelled datasets from various labelled multiple inputs. The most widely used algorithms are Random Forest (RF) , Support Vector Machine (SVM) and Deep Neural Networks (DNN). Each of these algorithms have their own advantages. RF, which is an ensemble algorithm, is capable of dealing with high dimensional data and learns nonlinear relationships from the data and also gives feature importance along with the labels which makes it more interpretable. SVM is capable of handling high dimensional data and also handles over fitting well, when using proper kernel functions which map inputs to a higher dimensional feature space.

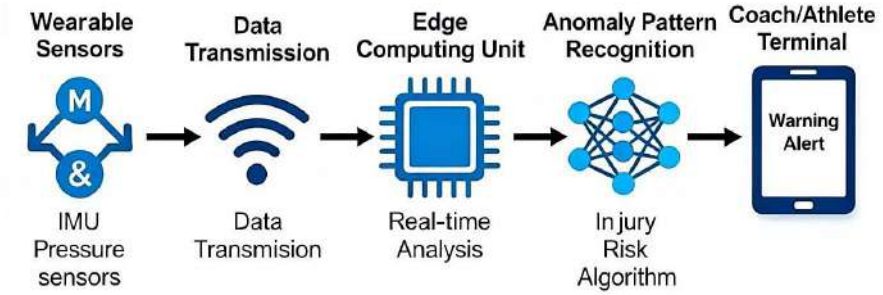
DNNs i.e. deep learning is well suited for modelling complicated hierarchical representations of the features. This comes at the cost of requiring a large amount of data and computational power. The training process of the models includes data preprocessing, feature scaling, and tuning of hyperparameters. Subsequently, cross-validation (e.g., k-fold or nested cross-validation) is used to reliably estimate the generalization performance of the models and avoid overfitting. Evaluation metrics such as area under the receiver operating characteristic curve (AUC), accuracy, sensitivity, specificity, and F1-score offer an overall evaluation of the models' performance. Recent research results show that the predictive accuracy of RF and gradient boosting models is high in clinical and sports injury settings and can reach over 0.8 for AUC, which shows a strong discriminative ability (Cai et al., 2022; Claudino et al., 2019; Musat et al., 2024). However, further work is needed to apply these models in Chinese and Asian athlete groups because there are many differences in genes, environment, and training. Limited external validation and data variation may also lead to limited transferability of models. Therefore, it is necessary to use culturally and regionally similar datasets to calibrate the model parameters and make the model more applicable. In addition, as machine learning models lack interpretability and transparency, they cannot be accepted by clinicians and may not be easily applied in sports settings. Therefore, explainable AI should be integrated into the models to make the machine intelligible and understandable to coaches and medical staff.

AI-assisted real-time injury warning systems

Artificial intelligence-based real-time monitoring and warning systems hold a game-changing potential for the prevention of injuries in athletics through the timely detection of atypical conditions manifested in physiological or movement-related signals. These systems are often realised as a combination of wearable sensor networks and cloud or edge computing platforms to provide continuous streams of data acquisition and processing. As depicted in Figure 2, the AI-Assisted Real-Time Injury Warning System operates through a structured workflow: wearable sensors (e.g., IMU, pressure sensors) collect physiological and movement data, which is transmitted to an edge computing unit for real-time analysis. Subsequent anomaly pattern recognition via injury risk algorithms enables timely warning alerts at coach/athlete terminals, facilitating proactive injury prevention . The underlying design philosophy has tended to focus on the rapid implementation of anomaly detection algorithms to discern atypical patterns deviating from baseline or typical profiles of variation suggestive of heightened injury likelihood. Methods such as threshold monitoring, machine learning classification rules, and deep learning architectures have enabled the identification of early warning signals characterised by changes in gait, overloading, or neuromuscular fatigue. Subsequent risk notifications conveyed in the form of feedback have enabled athletes, coaches, and medical staff to take corrective actions to prevent injury onset and progression. Case studies have illustrated effective field deployments in training and competition settings with reported decreases in injury incidence and improved workload (Jiang et al., 2022; Musat et al., 2024). Additionally, the implementation of adaptive learning

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algorithms has enabled personalised system usage through the continuous updating of risk thresholds in response to individual athlete responses and contextualised usage. System accuracy has been iteratively improved through feedback loops enabled by user input and outcome tracking. Within the domain of Chinese and Asian athletics, the implementation of AI-enabled warning systems for athletes must account for infrastructural capacity, data privacy compliance, and cultural acceptance. Initial pilot implementations have demonstrated promising outcomes and have the potential to revolutionise injury prevention and athlete health outcomes in athletics across the region.



Note. This schematic illustrates the sequential process of the AI-enabled injury warning system, encompassing wearable sensor data acquisition, edge computing-based real-time analysis, anomaly pattern recognition via injury risk algorithms, and feedback delivery to coach/athlete terminals.

Figure 2. Workflow of AI-assisted real-time injury warning system.

BIOMECHANICAL ANALYSIS TECHNIQUES AND THEIR APPLICATIONS IN SPORTS INJURY DIAGNOSIS

Comparison of marker-based and marker less motion capture systems

Marker optical motion capture systems have been the 'gold standard' for biomechanical analysis within sports science for several decades. These systems involve the attachment of reflective markers to an athlete's body, which are then tracked around the environment by several calibrated cameras to determine three-dimensional kinematics with less than a millimetre of accuracy (Gu & Pandy, 2020). Marker optical motion capture systems can provide high spatial and temporal resolution information that can be used to calculate joint angles, segment velocities and muscle activity patterns to detect even subtle biomechanical impairments that predispose athletes to overuse injury.

There are several limitations associated with the use of marker optical motion capture systems. Marker optical motion capture systems are time consuming to set up, require a laboratory environment to be run by an experienced operator, which limits their utility in the modern sports setting (Suo et al., 2024). Additionally, soft tissue artifacts may be introduced as a result of skin moving over underlying bones (Gu & Pandy, 2020).

Alternatively, marker less motion capture systems, which benefit from recent advances in computer vision and deep learning, may offer a breakthrough solution. Marker less systems do not use markers and utilise multiple synchronized video cameras and pose estimation algorithms to localise anatomical landmarks and determine 3D motion (Kanko et al., 2021; Zhong & Di, 2025). Marker less systems have been demonstrated to have good to excellent reliability and validity for spatiotemporal gait parameters and joint kinematics have been shown to be particularly reliable in the sagittal plane (Nishikawa et al., 2025; Scataglini et al., 2024). Marker less systems may be less accurate when angular rotations of complex joints are quantified and this may be particularly the case in the frontal and transverse planes (Chaumeil et al., 2024; Scataglini et al., 2024). Marker less systems have several advantages as they are more flexible, have a lower cost

requirement and can be used to assess function in a more natural environment, i.e. on the field or during competition (Lahkar et al., 2022; Torvinen et al., 2024).

When discussing the application of such systems in Chinese and Asian athletic training facilities, the following technical issues need to be considered: the shortage of advanced laboratory equipment for such sports, the lack of portability and user-friendliness of marker-based systems, and the potential future widespread application of marker less systems (Zhong & Di, 2025). The key technical distinctions, summarized in Table 2, highlight these practical differences. Due to the relatively high cost and complicated usage, marker-based systems cannot be applied routinely, and marker less systems, owing to recent advances in algorithm robustness and hardware availability, can be applied routinely (Zhong & Di, 2025). However, more research is needed to solve problems such as joint angle estimation accuracy in more complicated movements and cross-population validation. It is hoped that the application of marker less systems in biomechanical modelling and machine learning could be used to further improve the diagnosis and prevention of injuries in Asian track and field athletes.

Table 2. Comparison of technical parameters between marker-based and marker less motion capture systems.

Parameter	Marker-Based Systems	Marker less Systems
Spatial Resolution	High (sub-millimetre accuracy)	Good (lower accuracy in complex joints)
Temporal Resolution	High (typically >100 Hz)	Good (camera frame rate dependent)
Equipment Cost	High	Lower
Operational Complexity	High (requires experienced operator, time-consuming setup)	Low (flexible, user-friendly)
Environmental Requirements	High (laboratory environment)	Low (applicable in field/competition settings)
Measurement Error (different planes)	Low (but affected by soft tissue artifacts, all planes)	Reliable in sagittal plane; lower accuracy in frontal/transverse planes

Note. Measurement errors are summarized based on existing literature; marker-based systems mainly suffer from marker displacement and soft-tissue artifacts. Maker less systems show high reliability in the sagittal plane (e.g., knee flexion-extension), but greater errors in frontal (e.g., abduction) and transverse (e.g., rotation) plane joint angle estimations. The lower cost reduced environmental requirements, and higher flexibility of maker less systems' no marker alignment make them more suitable for Asian sports settings with limited resources and need for rapid field deployment (Zhong & Di, 2025).

Joint mechanics modelling and injury mechanism analysis

Biomechanical modelling with motion capture data enables investigation of joint loading, stress, and injury mechanism in athletes.

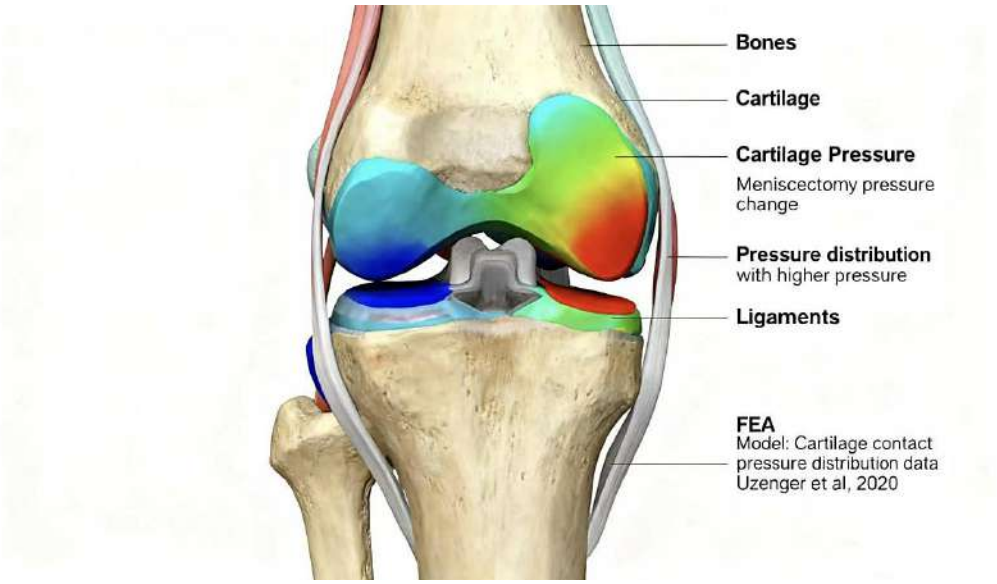
Three-dimensional joint mechanics models, usually constructed through finite element analysis (FEA) or multibody dynamics, contain parameters such as bone geometry, soft-tissue material properties, and kinematic inputs to predict the physiological mechanics within a joint under dynamic loading conditions (Arredondo-Soto et al., 2021; Gu & Pandy, 2020).

These models have shown how abnormal joint loading and stress patterns can result from injury. For instance, as illustrated in Figure 3, FEA models of the knee joint have shown that meniscectomy induces changes in load sharing that increase cartilage contact pressures and promote osteoarthritis (Uzuner et al., 2020). Modelling of ankle fractures has shown how fibular malrotation can alter the mechanics of tibiotalar contact and how achieving adequate anatomical reduction can prevent posttraumatic arthritis (Ayala et al., 2024). Modelling in shoulder biomechanics has shown how different reconstruction techniques can alter joint stability and stress distributions (Bedard et al., 2025).

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Recent progress in subject-specific musculoskeletal models that include realistic models of the ligaments and muscles to predict joint kinematics and kinetics during sport-specific activities (Zhong & Di, 2025). These models can predict the joint contact reaction forces and loading of the ligaments that provide information on potential mechanism of injury and rehabilitation for optimalization. Recent progress in the development of new optimization algorithms to estimate muscle pre-tension and joint range of motion to improve model accuracy (Avci & Röhrle, 2024).

It is possible for Asian athletics to develop proper biomechanical models based on Asian and Chinese anthropomorphic characteristics and motions patterns. It is also possible to noninvasively predict the internal stresses of joints using marker less motion capture data and validated joint mechanics models during training and competition, find out the harmful loading and related technique patterns and make suggestions for technique correction to prevent injuries.



Note. This FEA model illustrates the structural components of the knee (bones, cartilage, ligaments) and visualizes cartilage contact pressure distribution changes following meniscectomy, with colour gradients indicating pressure variations (data from (Uzuner et al., 2020)). It aids in understanding the biomechanical mechanisms of injury and disease progression.

Figure 3. Finite Element Analysis (FEA) model of the knee joint.

Biomechanical technologies and training program optimization

The application of biomechanical analysis technologies to guide training and rehabilitation programmes in sports medicine is rapidly growing in popularity. Biomechanical analysis technologies can provide coaches and clinicians with data on joint kinematics, kinetics and muscle activity that can be used to prescribe joint unloading interventions to improve movement patterns and reduce the loading through injured joints and prevent recurrence (Arauz et al., 2024; Laupattarakasem et al., 2024).

Biomechanical feedback can therefore help coaches and clinicians to change an athlete's movement strategy e.g. reduce knee valgus at landing to reduce the risk of an anterior cruciate ligament injury (Bender et al., 2021). In rehabilitation, the latter can be realised by using biomechanical assessments to provide progressions, through assessment of recovery of joint function and muscle strength (Silveira et al., 2023). Marker less motion capture can be used in field settings to provide this information and feedback to the athlete, without interrupting the training session (Lahkar et al., 2022).

There are also challenges to large-scale adoption of biomechanical technologies in general. These have been highlighted previously and include issues around data accuracy and stream data streaming, practitioner learning curves (Jiang & Shen, 2025). In China and Asia, availability of equipment and practitioners may also be limited. Solutions such as development of corresponding low-cost portable marker less systems and locally adapted software platforms may be required.

In addition, the use of biomechanical data to guide meaningful changes in training will require the involvement of biomechanists, coaches, and medical specialists, and the education and training of these groups will be important to ensure the correct use of the power of biomechanical technologies for injury prevention. These challenges must be addressed to make the use of biomechanical analysis a routine practice in athletic training and rehabilitation in China and Asia.

CONCLUSION

In conclusion, the rise of emerging sports science technologies has greatly transformed the landscape of joint injury decoding and prevention, making the experiential-based model of the past looks like and replacing it with a robust data-based model. From an expert's point of view, this is more than a technology. It is a comprehensive redefinition of what joint health is, how joint health is assessed, and what actions should be taken when deviations are observed within Chinese and Asian athletics, in particular.

Wearable sensors. Artificial intelligence. Biomechanical analysis. The list seems to be endless. These technologies enable us to be at the bedside and know in real time, predict injury risk with high accuracy, and offer intervention opportunities that are timely and personalized.

This enables us to address the fine-grained biomechanical stresses and physiological responses that lead to athletes being placed at risk for joint injuries and to provide timely and personalized interventions in response. Even a few milliseconds can mean the difference between gold and no medal for an athlete in Asian athletics, so precision medicine holds great promise.

Of course, the application of these technologies to sports practice also brings challenges. First, cost is high, making these technologies inaccessible, particularly, to low- and middle-income settings. Second, privacy and security issues surrounding biometric and health data are considerable and need to be considered and protected. Third, the lack of consensus around standardized protocols for data collection, analysis, and interpretation remains a major bottleneck to translating the research into practice. Finally, the rich experiential knowledge of the coaches and athletes participating in the sporting activity needs to be coupled with state-of-the-art technological inputs for intervention strategies. These differences need to be bridged to avoid a "*silo effect*" that may hinder the adoption and acceptance of these technologies. To do so will require sports science, engineering, data analytics, ethics, and clinical medicine experts to collaborate and embrace localized innovation that considers cultural, infrastructural, and sport-related factors that are unique to China and Asia.

It may one day be reasonably anticipated that, in the not too distant future, the development and application of an intelligent prevention ecosystem, consisting of connected technologies and data platforms, allowing for joint health management that is both personalised and responsive to athlete characteristics and changing conditions would be achieved. Reducing the precision and personalization of injury prevention may lead to a reduction in incidence and severity of joint injuries, and subsequently an improvement in performance.

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On the whole, if we apply a range of innovative sports science technologies wisely, we can ensure that Chinese and Asian athletes are ahead of the game and win with joint health management that is scientifically correct and technology enabled. It will be important to get the best of both of these approaches and to link the mass of research output from all these viewpoints productively with the realities of practice.

AUTHOR CONTRIBUTIONS

Conceptualization: JL. Writing – Original – Draft & Preparation: SX. Writing – Review & Editing: JL. Visualization: SX. Supervision: JL. Project Administration: JL. Funding acquisition: SX.

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ORIGINAL ARTICLE

Games for the to familiarize before to the initiation of the handball in the age school

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ABSTRACT

This study aimed to design and validate a system of games for familiarization with handball initiation in five-year-old preschool children from the Mella-Jayama district of Camagüey municipality. The research was structured in three phases: diagnosis, design, and practical validation. The diagnosis phase, conducted using an adapted TGMD-3 battery, assessed a population of 32 children (from a total of 58) and revealed significant deficits in object manipulation skills (catching and throwing) and their integration (0% success rate in precision and space adaptation indicators), despite adequate development of locomotor skills. This finding justified the need for a specific intervention. The design phase was based on the principles of play-based learning and the Teaching Games for Understanding (TGfU) model, resulting in a structured system of games focused on sensory-motor familiarization with the ball, basic technical actions, and simplified game situations. The validation phase, based on implementation by educators and perceived utility surveys (Likert scale 1-5), showed an exceptional consensus among practitioners. The system received median scores of 5/5 in clarity, age-appropriateness, children's enjoyment, and perceived contribution to motor development, and 4.5/5 in practical feasibility. Qualitative analysis from a focus group highlighted high levels of child motivation and observable progress in initially deficient skills. The study concludes that the proposed game system is a pedagogically sound, effective, and highly motivating tool that addresses specific psychomotor needs in preschoolers, providing a solid foundation for inclusive and enjoyable handball initiation through play. It represents a practical and validated resource for early childhood physical education specialists.

Keywords: Physical education, Motor development, Preschool education, Play-based learning, Teaching Games for Understanding (TGfU), Psychomotricity.

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INTRODUCTION

Since its origins, Physical Education has been a fundamental pillar in the holistic development of human beings, transcending its merely biological dimension to establish itself as a complex pedagogical discipline that impacts cognitive, social, affective, and motor domains. At the heart of its didactic evolution lies a historical and still ongoing debate: the role of sport as educational content. This debate is articulated between two seemingly antagonistic poles. On one side are those who defend its formative value, highlighting its potential for developing motor skills, social values, and healthy habits. On the other, critical voices warn of the risks of replacing the educational with the competitive, fostering aggressiveness, early selection, and exclusion, thereby distorting the aims of schooling (Castejón et al., 2003). This tension has given rise to a broad spectrum of teaching models, from the most technical and traditional to the most comprehensive and play-based, reflecting a constant search for a pedagogy that leverages the virtues of sport while mitigating its potential dysfunctions.

Handball, as a team sport, is not immune to this crossroads. Despite its recognized value for developing coordination, simple tactical decision-making, and cooperation, its institutional presence in the school setting has traditionally been lower compared to other team sports, relegating it to specific contexts where there is community roots and adequate infrastructure (Frías, 2016). Nevertheless, its dynamic and accessible essence makes it an invaluable pedagogical resource. The contemporary consensus in sports pedagogy advocates for stripping handball instruction of the rigid schemes of high performance and focusing it from an adapted, play-based perspective, where play stands as the primary vehicle for learning, allowing the practice to be tailored to the psycho-evolutionary characteristics of students (Salvador et al., 2021; Casáis, Domínguez & Lago, 2013).

However, this innovative approach encounters a scarcely explored frontier: the preschool stage (0-6 years). The discussion on sports initiation has historically focused on school age, with proposals that, even when advanced, place the start between 8 and 13 years (Antón, 1990; Román, 1989; cited in Gómez, 2015). Meanwhile, the International Handball Federation (IHF) boldly promotes familiarization from the age of five (Lund et al., n.d.), a horizon that formal educational practice rarely reaches systematically. This gap is particularly serious considering that early childhood represents the most sensitive and critical period for human development. It is during this stage that the foundations of personality, intelligence, and motor skills are built through interaction with the environment and bodily experience (Anchía-Umaña, 2024; Orona et al., 2021).

The importance of intervening in this period with quality proposals is, therefore, paramount. Scientific evidence is conclusive: well-structured Physical Education in the preschool stage produces multifaceted benefits. At the motor level, it is crucial for the development of fundamental motor skills (locomotion, jumps, turns, throws, receptions), coordination, balance, and body awareness (Bernate, 2021; Piña et al., 2020). Cognitively, it stimulates executive functions such as attention, memory, and problem-solving, while enriching language and the understanding of spatial and temporal concepts (Arufe et al., 2021). Socio-affectively, rule-based and cooperative play becomes an ideal scenario for learning to manage emotions, follow rules, respect turns, work in teams, and build a positive self-image (Miraflores y Rojas, 2023; Muentes Llerena & Vásquez Solórzano, 2023). Ignoring this potential is to waste a unique opportunity to positively impact an individual's life trajectory.

It is here that the fundamental challenge of this study emerges: to bridge the gap between the recognized potential of adapted handball and its real application in the preschool classroom. The challenge is not trivial.

It involves moving from mere motor recreation or the sporadic application of generic pre-sport games towards the design of a specific, rigorous, and evolutionary pedagogical system for familiarization with handball. This system must answer crucial questions: How to transform the structural elements of handball (the ball, the goal, the space, ¿the basic rules) into meaningful and comprehensible experiences for a 3 to 5-year-old child? How to do this by prioritizing symbolic play, sensory exploration, and cooperation over technical execution and competition? How to ensure it is a tool for educational inclusion, attending to the diversity of developmental paces and abilities, and not just another mechanism for early selection? (Arufe, 2020; Espoz-Lazo et al., 2023).

Answering these questions requires a proposal that draws from the sources of psychomotricity, the pedagogy of play, and specific didactics, creating a sequence of activities that, in a progressive and fun way, allow the child to "*inhabit*" the universe of handball. The goal is not to create little athletes, but rather motor-competent children who are confident, socialized, and have a positive attitude towards physical activity (Arufe et al., 2021).

Therefore, this article aims to design and substantiate a System of Games for familiarization with handball initiation in preschool age. This research not only intends to fill a theoretical-practical vacuum but also to offer early childhood educators and Physical Education specialists a concrete instrument, grounded in the most current evidence, to enrich their daily practice. The ultimate goal is to contribute to preschool Physical Education fulfilling its maximum potential: to be the privileged space where the holistic development of childhood is driven through play, movement, and the excitement of discovering a sport, laying the foundations for an active, healthy, and socially enriched life.

MATERIALS AND METHODS

The present study was structured around a methodological design of educational development and innovation, organized into three sequential and integrated stages: diagnosis, elaboration, and practical validation. The process was carried out with the complete population of 58 five-year-old children (32 females, 26 males) from the "*círculos infantiles*" (daycare centres) in the Mella-Jayama district of Camagüey, following obtaining informed consent from the institution and the guardians.

The first stage (diagnosis) was conducted between February and April 2024 with the objective of characterizing the current state of motor development and teaching practices. A mixed-methods approach was adopted for this purpose. Quantitatively, the level of development of fundamental motor skills precursors to handball (throwing, catching, lateral and multi-directional displacements, dynamic balance) was assessed using a contextualized adaptation of the TGMD-3 (Test of Gross Motor Development-3) battery. The test items were filmed and evaluated by two observers to ensure data reliability. Qualitatively, semi-structured interviews were conducted with the six educators from the "*círculos infantiles*", using a script designed to explore their conceptions, methodologies used, and perceptions regarding the feasibility of handball initiation in preschool. The interviews were transcribed and subjected to categorical content analysis to identify central themes and points of consensus or conflict.

The second stage (elaboration) took place from May to July 2024. Based on the diagnostic findings and grounded in the principles of play-based pedagogy (Huizinga) and the Teaching Games for Understanding (TGfU) model, the game system was designed. The creation process was guided by specific criteria of progressivity (from simple to complex), adaptation (safe and appropriately sized materials), inclusion (cooperative games with multiple challenge levels), and cultural pertinence. The final product was a didactic

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manual containing a sequence of 25 games organized into three progressive modules: sensorimotor familiarization with the ball, basic collaboration-opposition games, and simplified target situations.

For the third stage (validation), an evaluation method focused on face validity and practical feasibility through pilot implementation and feedback from end-users was chosen, overcoming the limitations of a theoretical expert validation. During September 2024, the educators themselves implemented the game system in their regular motor activity sessions. After a four-week application period, the assessment was carried out using two complementary instruments. First, a focus group was organized with the educators to gather their qualitative perceptions regarding children's acceptance, ease of implementation, and encountered obstacles. Second, a perceived utility survey using a 1-5 Likert scale was administered, where the educators rated specific aspects such as clarity of instructions, age-appropriateness, children's enjoyment, and perceived contribution to motor development. The analysis of the quantitative survey data was performed by calculating medians and modes for each item, providing a robust measure of the central tendency of the practical assessment by the direct users of the proposal.

RESULTS

The assessment of fundamental motor skills (FMS) development, conducted using an adapted version of the TGMD-3 battery, provided a precise profile of the capabilities and weaknesses within the study population. The results, broken down into isolated and combined skills, are presented below.

Table 1. Results of the assessment of fundamental motor skills performed in isolation (N = 32).

Basic skills	1 Stability			2 Range of motion			3 Alignment			4 Alternation			5 Direction			6 Control			7 Rhythm		
	L	M	N	L	M	N	L	M	N	L	M	N	L	M	N	L	M	N	L	M	N
Throw	7	10	15	0	4	28	0	0	32	0	0	32	1	8	23	1	8	23	2	6	24
Jump	8	9	15	2	3	27	8	9	15	0	0	32	32	0	0	8	9	15	12	9	11
Run	32	0	0	21	10	1	21	10	1	32	0	0	32	0	0	21	10	1	21	10	1
Catch	0	2	30	1	2	29	0	2	30	0	2	30	32	0	0	0	2	30	0	2	30

Note. L: Achieved; M: Partially Achieved; N: Not Achieved. Note. The data are original to this study.

Analysis of Table 1 reveals a heterogeneous profile of motor development. The skill of running is fully consolidated, with 100% of children (N = 32) demonstrating complete mastery in stability, alternation, and direction indicators. This automated pattern constitutes a foundational strength upon which to support other learning.

Conversely, manipulative skills present serious difficulties. Catching is the most deficient skill, with over 90% of children (N = 30) in the "*Not Achieved*" category across nearly all indicators, highlighting a significant lack of hand-eye coordination and anticipation. Similarly, in throwing, while body stability (indicator 1) shows relative progress (21.9% achieved), key technical indicators such as body alignment (3) and arm-leg alternation (4) show a 100% rate of non-achievement, indicating that the movement is performed with a static body and without efficient technique. The results for skills performed in combination, which are crucial for sports practice, are presented in Table 2.

Table 2 provides the most compelling evidence from the diagnostic assessment. While the combination of running-jumping shows high success rates (above 78% across all indicators), confirming the solidity of locomotor skills, the combination of throwing-running-catching—which simulates the basic handball action of receiving a pass in motion and culminating with a throw—yields critical results. The 0% achievement rate in

Precision and Space Adaptation indicators, and only 6.3% in Fluid Transition, confirm that integrating these three skills into a complex motor sequence represents a nearly insurmountable difficulty for the vast majority of children.

Table 2. Assessment of achieved fundamental motor skills performed in combination.

Combined skills	No. of children	1 Global coordination		2 Object control		3 Fluid transition		4 Precision		5 Space adaptation	
		N	%	N	%	N	%	N	%	N	%
Throw-run-catch	32	1	3.1	1	3.1	2	6.3	0	0.0	0	0.0
Run-jump	32	28	87.5	25	78.1	27	84.4	26	81.3	32	100.0

Note. L: Number of children who Achieved the indicator; %: Percentage of achievement. The data are original to this study.

This diagnosis validates the urgent need for pedagogical intervention. The children possess an adequate motor foundation for locomotion but demonstrate severe deficits in manipulative skills and, most importantly, in their integration. Therefore, the proposed game system must prioritize the development of hand-eye coordination, basic throwing and receiving technique, and the gradual progression toward combining these skills within simplified play contexts, using play as the primary vehicle to address these deficiencies**.**

Games to promote familiarization with handball initiation in preschool age

The game system comprises the theoretical foundation, general objective, the games themselves, and general guidelines for their application in physical education classes.

Theoretical foundation

Preschool age in Cuba is considered to be from three to six years. It is proposed that at this stage, motor activities delivered in physical education should be planned in a way that leads the child to constantly seek solutions to tasks and problems, showing initiative and creativity. These activities should emphasize group dynamics and, above all, require collaboration, self-regulation of behaviour, and the maintenance of appropriate relationships with peers.

This approach is based on the understanding that children between four and six years old are dynamic, spontaneous, and, as a product of their physical and mental activity, are capable of acquiring the necessary elements to gain knowledge and enhance their motor development.

In line with the above, a system of games has been developed to be implemented during the programmed activities of children attending the "*círculo infantil*" (daycare centre), who are five years old and enrolled in preschool at this institution.

General Objective: To enhance the development of fundamental motor skills that contribute to familiarization with handball initiation, through movement games, as a means of enjoyment in the systematic performance of activities and the demonstration of appropriate behaviour in daily activities.

Concrete games for familiarization with handball initiation

- Ball Handling Game.
- Game Name: Ball Handling.

Specific Objective: To handle the ball in a stationary position with coordination, maintaining body balance.

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Development: A figure eight is drawn on the ground. The child stands inside the eight, with each foot on the outer edge of the eight. With legs shoulder-width apart and toes pointing forward, the child assumes a semi-squat position. The ball is placed on the ground, touching one foot, on the line that forms the eight. At the teacher's command, the child rolls the ball along the entire line through their legs, forming a figure eight.

Rules:

- Feet cannot be lifted off the ground or moved from their position.
- The ball cannot be rolled too forcefully.
- Hands must be alternated; meaning when the ball reaches the left foot, the left hand is used to carry the ball to the right leg, and vice versa.
- The ball must always remain on the line that forms the eight.

Game variant:

- Ball handling is performed by moving it from one foot to the other in a straight line.
- Game Name: The Journey.

Objective: To handle the ball while moving with coordination and spatial orientation, maintaining body balance.

Development: Three hoops are placed on the ground in a straight line, one meter apart. The child stands next to the first hoop with the ball on the ground touching the outer edge of the hoop. At the teacher's command, the child rolls the ball around the first hoop, describing a circle, then moves to the second hoop, describes a circle, and does the same at the third hoop.

Rules:

- The ball must always be rolled close to the hand.
- Hands must be alternated when making circles around the hoop, always using the hand closest to the hoop.
- One circle must be made to the right and the next to the left, or vice versa.

Game variant:

- Ball handling is performed using only one hoop.
- Game Name: The Little Car.

Objective: To handle the ball while moving with coordination, spatial orientation, and differentiation, maintaining body balance.

Development: A straight line (five centimetres wide) one meter long is drawn on the ground. The child is placed at the start of the line on all fours. The ball (the little car) is placed on the line. At the teacher's command, the child must roll the ball (the little car) along the line, keeping it close to their hands so it doesn't leave the line. Upon reaching the end of the line, they pick up the ball and bring it to their teammate.

Rules:

- The ball (little car) cannot leave the line.
- Upon reaching the end, they must grab the ball and hand it directly to their teammate's hand.
- They cannot start before the ball is placed in their hand.

Game variant:

- A line with two curves is drawn.
- Game for Ball Adaptation and Handling.

Game Name: The Drawer.

Objective: To correctly adapt the ball in the hand, regulating upper limb movements with coordination.
Development: A starting line is placed two meters from a wall. A ball is placed on the ground near the wall, inside a circle drawn on the ground or a hoop. At the teacher's signal, the child runs to the ball and picks it up with one hand (adaptation). They imitate drawing their preferred geometric shape (from those being taught in class) on the wall. Upon finishing the drawing, they must name the shape, place the ball back inside the circle, and run back.

Rules:

- They must start from behind the line.
- The next teammate starts when they are tapped on the shoulder after crossing the starting line.
- A minimum of two rounds must be performed to ensure the child alternates hands.
- The drawn shape must match the named shape.
- If the ball drops during the drawing, they must start the drawing over.

Game variant:

- The teacher specifies which shape to draw.

Game Name: The Puppy.

Objective: To correctly adapt the ball in the hand, regulating upper limb movements with coordination.

Development: Teams are formed, lining up facing each other one meter apart. Two balls are used. The child, on all fours, with a ball correctly adapted in each hand (resting on the ground), moves on all fours with the balls in hand towards their teammate one meter away. Upon arrival, they hand over the balls, and their teammate performs the exercise.

Rules:

- The child must correctly adapt the ball.
- The child cannot move on their knees.
- They must start from behind the line.
- The next teammate starts when tapped on the shoulder after crossing the starting line.

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- A minimum of two rounds must be performed.

Game variant:

- Move, but around obstacles.

Game Name: The Wolf.

Objective: To correctly adapt the ball in the hand, regulating upper limb movements during coordinated handling.

Development: One ball is used per child. A circle is defined as the children's "*home*." The child must adapt the ball. One child is designated as the "*wolf*," whose task is to catch the other children.

Rules:

- The ball must be held naturally.
- No one can be caught inside the "*home*."
- The ball cannot be dropped.
- The wolf must touch another child with the ball.

Game variant:

- Multiple wolves are used.
- Games for Reception, Passing, Dribbling, Throwing

Game Name: Ball to the Goal.

Objective: To throw at the goal after dribbling, passing, and receiving with coordination, emphasizing segmental differentiation.

Development: A goal is placed four meters away. A hoop is placed on the ground two meters from the end line, which is one meter from the goal. Level with the hoop, 60 cm away, a rebound wall is placed. The group is organized into teams, lined up behind the starting line. At the teacher's signal, the first child in line, who has the ball, dribbles the ball moving towards the hoop, jumps on one foot into the hoop, upon landing, passes the ball against the rebound wall and receives it, dribbles to the end line, and throws towards the goal. The child must retrieve the ball after throwing and run it back to the line, handing it to the next teammate.

Rules:

- The end line cannot be stepped on; doing so nullifies the goal.
- The throw must be performed with one hand.
- The child cannot start before the ball is placed in their hand.

Game variant:

- The game is played by adding another hoop (i.e., with two hoops).

Game Name: The Throwing Cat.

Objective: To throw at the goal, demonstrating coordination, emphasizing segmental differentiation.

Development: A goal is placed at the end of the area, and a starting line is drawn five meters from the goal. A line is drawn one meter from the goal. A bench two or three meters long is placed one meter from the starting line. The group is organized into teams, formed in lines, each team with a ball. At the teacher's signal, the first child with the ball moves on all fours, with the ball adapted in one hand, until reaching the bench, bounces the ball on the bench, upon reaching the end of the bench, adapts the ball, dribbles to the end line, and performs the throw at the goal. They retrieve the ball and run back to the starting line, where they hand the ball to the next teammate.

Rules:

- The end line cannot be stepped on; doing so nullifies the goal.
- The throw must be performed with one hand.
- The child cannot start before the ball is placed in their hand.
- The ball cannot fall off the bench during the bounce.

Game variant:

- The bench is replaced by a 10 cm wide line painted on the ground.

Game Name: Shapes.

Objective: To throw at the goal, demonstrating coordination, emphasizing the coupling of the segments involved in the action.

Development: Different geometric shapes (painted or made of cardboard) are placed on the ground, distributed in a zigzag pattern towards the goal at the end of the area. At the end of the shape path, a semicircle is drawn on the ground one meter from the goal. The children line up behind a starting line. Teams are formed. At the teacher's signal, the first child in formation dribbles the ball towards the shape called out by the teacher. That is, the teacher calls out the shapes, and the child must dribble the ball to each shape. Upon reaching the semicircle, they throw at the goal, retrieve the ball, and run back with the ball adapted and hand it to the next teammate.

Rules:

- The final semicircle cannot be stepped on; doing so nullifies the goal.
- The throw must be performed with one hand.
- The child cannot start before the ball is placed in their hand.
- They must follow the path indicated by the teacher.

Game variant:

- Place objects on the ground describing a path in different directions.
- General Guidelines for Application in Physical Education Class

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- The games are applied during the scheduled program activity.
- They can be applied on the two days of the week when the program activity takes place.
- Only two games should be used in one program activity and maintained for 15 days, modifying their conditions and complexity depending on the children's assimilation.
- The games are taught in the same order as described in this document.
- The number of repetitions for each game will depend on the development of the children's physical condition.
- A pleasant atmosphere should be fostered during the games.
- The teacher must allow children to be creative during play.
- Rule enforcement should be as flexible as possible, as the important thing is for the child to play while performing motor skills.
- The teacher must pay special attention to the level of coordination shown by the children in each game and, if necessary, modify the complexity so that they do not become discouraged if they cannot enjoy the game.
- Goals and other equipment needed to play should be made of soft material that does not harm the child's anatomy.
- The number of teams formed for each game will depend on the number of balls and equipment available. It is important to keep all children playing at the same time.
- The teacher should not overemphasize error correction; the important thing is for the child to play and create during the game.
- Game planning must allow children to play enough to satisfy their movement needs and practice the acquired motor skills.
- Games should be organized to promote collective work and mutual aid.
- When organizing games, optimal use of the available space must be considered.

Their direction initially involves adequate motivation and organization of the children, followed by a simple explanation of what is to be done. If the actions are considered complex, a demonstration with some children can be used; otherwise, proceed directly to playing.

The teacher must be attentive to the motivation shown by the children, and if a lack of motivation is detected, the game should be suspended.

During the organization of the play area, if possible, try to mark and enclose the area with boxes or similar objects to prevent balls from rolling into other areas.

During the organization of the play area, benches or other equipment should be placed; for example, mats or barrier tape can be used as dividers/demarcations of zone areas; bars that pose a danger should not be used.

Results of the practical validation stage

The pilot implementation of the game system over four weeks allowed for the collection of robust evidence regarding its face validity and practical feasibility through the perceptions of the educators and direct observation of its application. The results, both qualitative and quantitative, confirm the high potential of the proposal.

Qualitative perception of the educators: Focus group
Content analysis of the focus group session revealed four main emerging categories:

High Motivation and Acceptance by the Children: The educators unanimously highlighted the enjoyment and enthusiasm shown by the children during the sessions. They stated that "*the children constantly asked when they would play handball again*" and that "*games like 'The Wolf' and 'Ball to the Goal' became their favourites*." This high motivation was identified as a key factor for active and persistent participation.

Observable Motor Progression: Significant improvements were reported in the initially deficient skills. The educators noticed a palpable improvement in the ability to catch ("*before the ball would hit their body, now they try to catch it with their hands*") and greater ease in handling and throwing the ball ("*they seemed more coordinated when rolling the ball in 'The Journey' and when throwing*").

Feasibility and Clarity of the Proposal: The users positively valued the clear structure of the games and the methodological guidelines. They considered the rules to be "*adapted to their age*" and the progressions (e.g., from 'Ball Handling' to 'The Journey') to be "*logical and easy to follow*." The flexibility in rule enforcement, suggested in the guidelines, was noted as a success for maintaining the flow of the game.

Difficulties and Recommendations: The main difficulty reported was the management of space and materials when games were played with all children simultaneously. They suggested the need for more foam balls of different sizes and better demarcation of play areas to avoid collisions. They also recommended including more cooperative game variants for large groups.

Survey results on perceived utility
The six educators completed a 5-item survey using a Likert scale (1: Very Low, 5: Very High). The results, summarized in Table 3, show an exceptionally positive assessment.

Table 3. Survey results on perceived utility by educators (N = 6).

Clarity of instructions	**Median**	**Mode**	**Interquartile Range (IQR)**
1. Clarity of instructions	5	5	0
2. Age appropriateness (5 years old)	5	5	0
3. Children's Enjoyment and Motivation	5	5	0
4. Contribution to Motor Development	5	5	0
5. Practical Application Feasibility	4.5	5	0.5 (Q1 = 4.5, Q3 = 5)
Global score (Median of Medians)	5		

Note. The data are original to this study.

As shown in Table 3, the items related to the pedagogical quality of the proposal (clarity, appropriateness, enjoyment, and motor contribution) received the highest possible score (Median = 5, Mode = 5), with an Interquartile Range (IQR) of 0, indicating absolute consensus among all educators in their excellent assessment.

The item on practical feasibility received a slightly lower median score (4.5), although the mode remained at 5. The IQR of 0.5 reflects that, while the majority considered it very high, some educators noted—consistent with the focus group comments—minor logistical challenges that justified a score of 4 ("*High*") instead of 5. The triangulation of qualitative and quantitative data allows us to conclude that the proposed game system is highly effective, relevant, and feasible for implementation in the preschool context.

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The quantitative evaluation demonstrates an overwhelmingly positive consensus on its core aspects, while the qualitative evaluation not only corroborates this excellent perception but also adds depth by explaining why it works: it generates high intrinsic motivation in children and produces observable progress in their motor development, particularly in the manipulation skills that the initial diagnosis identified as critical.

The only limitation noted, related to resource and space management, does not invalidate the proposal but instead offers a valuable recommendation for its future optimization (e.g., provision of more materials, detailed space planning).

In summary, the practical validation confirms that the game system far exceeds its goal of being a useful, fun, and effective tool for teachers, and a meaningful and motivating experience for children, playfully and inclusively laying the groundwork for familiarization with handball in preschool age.

DISCUSSION

The main objective of this study was to design and validate a system of games for introducing handball to preschool-aged children. The results obtained in the three research phases (diagnostic, development, and validation) provide significant findings that deserve to be discussed in light of current scientific literature, highlighting both the convergences and original contributions of this proposal.

The results of the diagnostic phase, which revealed consolidated development of locomotion skills (running and jumping) compared to a severe deficit in manipulation skills (catching and throwing) and their integration, are consistent with literature indicating that motor development is not homogeneous and that object control skills often present greater challenges in early childhood (Orona et al., 2021; Bernate, 2021). The most critical finding—the nearly non-existent ability to integrate throwing, running, and catching into a fluid sequence—is particularly relevant. This result fully validates the warning from authors such as Arufe (2020) and Anchía-Umaña (2024) about the risk of introducing sports prematurely without a solid motor foundation and justifies the need for specific interventions like the one proposed here. Our findings support the stance of the IHF (Lund et al., n.d.) to begin familiarization at early ages but clarify that this should focus on addressing these specific deficiencies through play, rather than through formal technical instruction.

The developed game system aligns with the latest trends in early childhood Physical Education pedagogy and sports initiation. Its design, centred on play as a vehicle for learning, directly responds to the call by authors such as Arufe (2020) and Anchía-Umaña (2024) to prioritize playful experience, exploration, and fun over technical instruction and competition. The progression of the games—from sensorimotor familiarization with the ball ("*Handle the Ball*") to simplified situations integrating various elements ("*Ball to the Goal*")—is grounded in the principles of the Teaching Games for Understanding (TGfU) model (González-Víllora, 2021) and Experiential Psychomotricity (Miraflores & Rojas, 2023), which advocate for meaningful learning contexts adapted to the child's cognitive and motor development.

This approach contrasts with more traditional and technical methodologies still present in sports initiation (Antón, 1997) and places itself at the forefront of proposals for preschool—an educational level where specialized Physical Education is still incipient (Arufe et al., 2021). By including methodological guidelines that prioritize flexibility, inclusion, and creativity over error correction, our proposal also stands as a tool for educational inclusion, as advocated by Muentes Llerena & Vásquez Solórzano (2023), allowing each child to participate according to their abilities.

The results of the validation phase are highly encouraging. The quantitative assessment showed absolute consensus (IQR = 0) among educators regarding the clarity, age-appropriateness, contribution to motor development, and crucially, the children's enjoyment. The latter point is essential, as intrinsic motivation is the main driver of learning and adherence to physical activity at this age (Piña et al., 2020).

Qualitatively, the observation of progress in specifically deficient skills (such as catching) suggests that the game system is not only fun but also effective. This corroborates the findings of previous research demonstrating that well-structured, play-based Physical Education programs have significant positive impacts on children's motor development (Arufe et al., 2021; Piña et al., 2020).

The only limitation noted, related to logistical management (space and materials), is not a flaw of the design itself but rather a reflection of a common reality in preschool educational contexts. This observation, far from weakening the proposal, offers valuable guidance for its optimal implementation and is consistent with the practical challenges reported in other studies (Arufe, 2020).

This study transcends the theoretical realm by offering a concrete and validated tool for educators. The game manual, with its clear structure and precise guidelines, addresses the need expressed by Espoz-Lazo et al. (2023) for specific didactic resources for teaching handball at early ages. Its success lies in the fact that it does not require handball specialists, but rather educators who are sensitive to the logic of play and child development.

A future direction derived from this research would be to measure the objective effectiveness of the system through a quasi-experimental design with pre-test and post-test, using standardized instruments such as the TGMD-3, to quantify the real impact on children's overall motor development. Likewise, it would be valuable to adapt and validate this proposal in other socio-educational contexts.

CONCLUSION

In light of the discussed results, it can be concluded that this study achieved its main objective. A pedagogically sound, practical, and highly motivating game system for familiarizing preschool children with handball was successfully designed and validated.

The research demonstrated that:

- There is a real need for interventions that specifically address the deficit in manipulation and motor integration skills in preschoolers.
- A play-based approach, with a well-designed progression and focused on the child's experience, is not only viable but also profoundly effective in addressing these deficiencies.
- The proposal is perceived by educators as a highly useful, clear tool with great potential to enrich their teaching practice, successfully achieving the difficult balance between children's enjoyment and progress in motor development.

AUTHOR CONTRIBUTIONS

Reidel Cordoves Peinado: original conception of the study; overall methodological design; coordination of the diagnosis, elaboration, and validation stages; initial drafting of the manuscript and critical revision of the final version. Luciano Mesa Sánchez: support in designing the instruments for motor assessment;

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coordination of the application of the adapted TGMD-3; quantitative data analysis and inter-observer reliability validation. Beymer Aguilera Ramírez: development of the semi-structured interview guide; conducting interviews with educators; transcription, categorization, and qualitative content analysis. Antonio José Juárez López: participation in the pedagogical design of the game system; development of the didactic manual; organization of the progressive modules and criteria for adaptation and inclusion. Rusbelin Larios Núñez: coordination of the validation pilot with the educators; data collection during implementation; processing of the utility surveys and analysis of medians and modes. Daylanis Gutiérrez Cruzata: theoretical review on play pedagogy and the TGfU model; support in writing the conceptual framework and discussing the results; academic style editing of the manuscript. All authors participated in the review and approval of the final manuscript, as well as in ensuring the integrity and accuracy of the content presented.

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ORIGINAL ARTICLE

Validity and reliability of MATS integrated with sensors and IoT to measure locomotor skills of 3-6 year old children

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ABSTRACT

Considering that traditional musical instruments are subjective and ineffective in developing the locomotor skills of children aged 3-6 years. The main objective of this study is to develop a Motor Assessment Test Station (MATS) that uses sensors and the Internet of Things (IoT) to measure children's locomotor movements automatically and in real-time. Using the Borg & Gall model, the research and development (R&D) approach includes needs analysis, design, expert validation, limited trials, and field tests. Three experts were involved (motor, Media/IT, measurement) and thirty early childhood participants. MATS is an appropriate and reliable measurement tool, based on the results of the study, which also revealed that the instrument has excellent reliability (r = 0.95 – 0.96) and high validity (V = .886). A unique feature of MATS is its ability to integrate sensors and IoT, which allows it to efficiently and objectively process, process, and display children's movement data. By offering a digital assessment model that follows technological developments, this research empowerment makes a substantial contribution to the field of early childhood education. Socially, this technique can help researchers, parents, and educators identify children's motor development reliably and sustainably. The development of comparable systems for manipulative and non-locomotor skills, as well as validation testing with larger and more diverse samples, are the primary goals of this research recommendation. The development of technology-based evaluation tools that enhance the integration of science, technology, and early childhood education toward data-driven and sustainable physical education is a key contribution of this research.

Keywords: Physical education, Measuring instruments, Locomotor, Early childhood, Sensors, IoT.

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INTRODUCTION

Motor skills are the basic foundation of a child's life (Brons et al. 2021). Locomotor movements are an essential element in early childhood development (Sutapa et al. 2021; Szeszulski et al. 2022). In early childhood, children begin to demonstrate various forms of movement, such as walking, running, jumping, hopping, and crawling (Biino, Pesce, and Martins 2025; Grillner et al. 2021; O'Hagan et al. 2022). These movements not only help improve physical skills but also encourage balance, coordination, and confidence in interacting with their environment (Logan et al. 2018; Madu et al. 2025). Mastering locomotor skills is one solution for developing more complex motor skills at a later stage, such as sports and physical activities (Chen et al. 2023). However, a lack of attention to early detection has a negative impact on children throughout their lives. Detecting children's motor skills as early as possible is essential to support achievement in sports, physical activity, and daily activities (Roscoe et al. 2024). Therefore, in physical education and health during early childhood, the ability to accurately observe and monitor the development of locomotor movements in children is crucial.

Several previous studies have attempted to develop measurement tools to evaluate children's motor skills, both in educational contexts and in child development research. In various countries, many tools have been widely used, such as the Test of Gross Motor Development (TGMD) to measure gross motor skills in children aged 3–10 years (Ezzelle and Moutoux 1993; Valentini 2012), the Movement Assessment Battery for Children (MABC) (Staples, MacDonald, and Zimmer 2012), and the Pre-School Motor Assessment. These tools evaluate children's basic motor skills through direct observation of motor performance. Although proven effective, most measurements still rely on manual observations made by the examiner, which introduces the possibility of subjectivity in the assessment. In addition, the results of the measurements are often time-consuming to analyse, making them less effective when applied to large populations of children or in long-term studies.

Although various traditional measurement tools are widely used, most still have limitations in terms of objectivity, efficiency, and the ability to display data in real time. Measurement processes that rely on human observation have a high potential for error, as assessors can have differing perceptions (Viswanathan et al. 2017). Furthermore, the lack of technological integration makes it impossible to directly process or analyse data collected in digital format. This presents a barrier when accurate, comparable, and rapid results are required over time. In an increasingly digital world, to ensure that child development assessment processes are sustainable and measurable, the need for more modern and automated measurement systems is increasingly urgent. Therefore, the manual calculation system needs to be updated with technology-based calculations in order to achieve better and more efficient calculations (Frevel, Beiderbeck, and Schmidt 2022). Advances in digital technology bring changes in the scope of education and sports; technological innovation has a significant impact on life (Timotheou et al. 2022). Such is the use of sensor technology in obtaining hand-eye coordination test data that produces precise and accurate calculations (Irawan et al. 2024).

Developing a technology-based measurement system in response to these limitations is a strategic step. One proposed solution is the Model Evaluation Tool System (MATS), which focuses on measuring the locomotor skills of children aged 3-6 years, connected to sensors and the Internet of Things (IoT) (Swain et al. 2023). This system is designed to automatically and objectively identify, record, and analyse children's movements. Sensor integration allows for highly accurate recording of each child's locomotor activity (Fischer et al. 2021), while Internet of Things (IoT) technology facilitates the direct transmission and monitoring of data via electronic devices (Swain et al. 2023). This methodology not only optimizes measurement efficiency but also reduces the possibility of observer bias. Measurements involving technological assistance are

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becoming easier, and it can be said that technology plays an important role in supporting the improvement of the quality and efficiency of measuring instruments. Utilizing technology in sports is an important part of innovation (Alnedral et al. 2023; Handayani et al. 2023) to reduce calculation errors in measurements (Komaini et al. 2022). Therefore, MATS is expected to become a new innovation for evaluating children's motor skills with greater relevance in the digital era.

The purpose of this study is to develop a measurement tool for the locomotor skills of children aged 3-6 years. This measurement tool is specifically designed for early childhood with varying levels of ability and background. This tool not only evaluates locomotor skills but also integrates locomotor activities into children's daily activities. It is hoped that with this method, empirical evidence can be obtained regarding the precision and consistency of the system in objectively measuring children's motor skills. In addition, this study also aims to introduce a new measurement model that can help teachers, researchers, and physical education professionals in monitoring children's motor development on an ongoing basis. It is hoped that the findings of this study can provide an important contribution to the development of more standardized and modern assessment tools that are appropriate to the needs of today's technology-based learning.

MATERIALS AND METHODS

Research design and participant

This research is a research and development (R&D) process, this development process adopts the Brog and Gall model which has several stages, such as needs analysis, design and development, testing and revision of the instrument. Participants involved in this study were children aged 3-6 years. A total of 15 children were involved in the needs analysis stage, 9 children in the initial testing stage, and 30 children in the final testing stage of the tool testing stage. And This study involved 3 experts, such as 1 motor expert, 1 media/IT expert and 1 measurement expert.

Procedures

The needs analysis phase began with a comprehensive literature review covering all aspects of research on children's motor skill development, developmental movement theory, and locomotor standards. Additionally, a survey was conducted with early childhood education teachers and students to determine the extent to which existing research methods align with the goals of fundamental motor education. The results showed that most teachers lacked standards for assessing children's motor skills, and 90% of respondents agreed that assessments should be conducted using technology-based systems. More specifically, 51% of respondents stated that these methods did not fully evaluate children's learning experiences. Variations in assessments across educators also highlighted the need for objective and reliable assessment tools.

Motor Assessment Test Stations (MATS), integrated with sensors and the Internet of Things (IoT), were developed during the design and development phase. This tool is designed to improve three key locomotor aspects: running, jumping, gliding, and long jump. The initial design was visualized using a digital presentation application that displayed the tool layout, implementation process, and scoring system. The initial draft was validated by child development and technology experts to ensure validity, practicality, and feasibility.

An initial trial was then conducted with 15 children aged 3 to 6 years to evaluate the tool's reliability and ability to differentiate ability levels. A further 15 children were used for further trials to ensure consistency of results and identify technical improvements. After the refinement phase, an operational trial was conducted with 60

children. The collected data was analysed using descriptive and inferential methods to evaluate implementation time, score distribution, and the stability of the IoT-based system.

This revision phase of the tool focused on improving usability and accuracy. Adjustments were made to the sensor sensitivity for recording children's movements, as well as to the detection threshold, to better reflect the characteristics of childhood. The track layout was expanded to better reflect real-world conditions, while movement accuracy, rather than just speed, became the focus of the implementation instructions. The scoring system was also improved by balancing movement time and accuracy, resulting in a fair and comprehensive evaluation.

Analysis

The sensor- and IoT-enabled Motor Assessment Test System (MATS), developed and implemented in the 2019 ACM, has undergone a refinement phase based on quantitative data analysis, participant feedback, and expert recommendations. The system focuses on reliability and validity to evaluate the effectiveness of the measurement tool, providing an accurate picture of the appropriateness of MATS for measuring motor skills in children aged 3 to 6 years. To verify validity, a product-moment correlation test was used, which aims to observe the consistency of each measurement element with the locomotor skill construct being evaluated. Furthermore, internal reliability was evaluated using the r-correlation method, which is used to assess the stability of MATS measurement results when repeatedly applied to different groups of children. All statistical analyses were performed using SPSS V24 software.

RESULTS

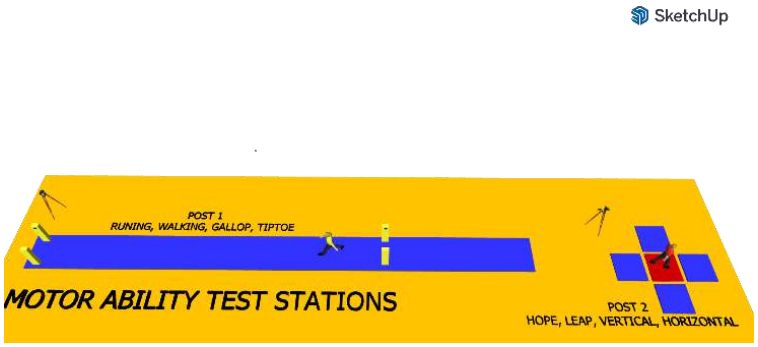


Figure 1. Locomotor skills test series.

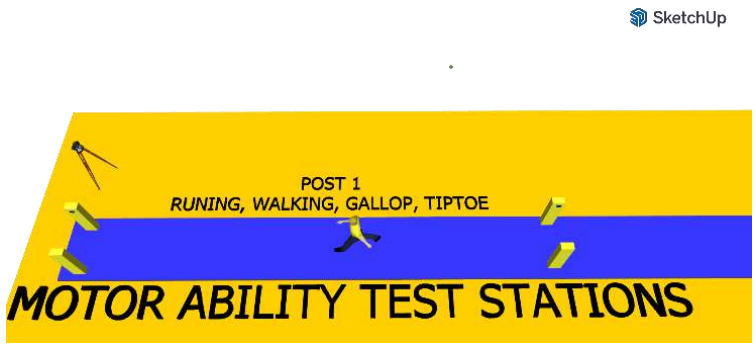


Figure 2. Locomotor test (running, walking, gallop, tiptoe).

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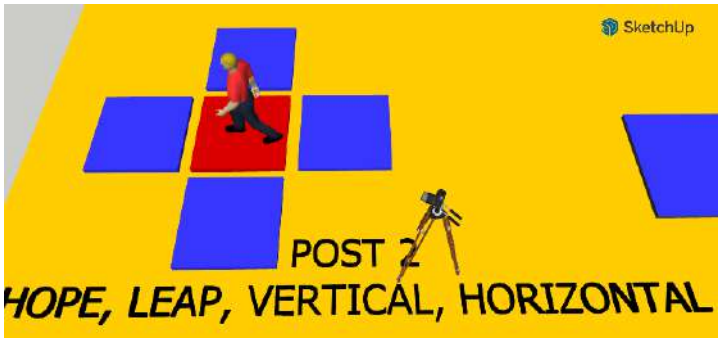


Figure 3. Locomotor test (hope, leap, vertical, horizontal).

The research results show that the Motor Ability Test Stations design, consisting of two test stations, successfully provides a comprehensive overview of children's basic motor abilities. At Station 1, activities such as running, walking, galloping, and tiptoeing focus on locomotor skills, assessing coordination, balance, and the ability to transition from fast to slow motion. Meanwhile, Station 2, which includes hop, leap, vertical, and horizontal jump activities, functions to measure leg muscle strength, explosive power, and body control when changing direction.

Validity

Research and development of sensor- and technology-based motor skill measurement tools have gone through seven stages according to the Borg & Gall model. The results of the study indicate that the developed product has gone through a validation process, limited trials, and field trials and is declared feasible, practical, and reliable for use in measuring locomotor skills. Product validity is based on three experts, namely motor experts, media/IT experts, and measurement experts. Expert assessment of sensor- and IoT-based locomotor skill instruments obtained (V = .886) or in the high category. For suitability in the aspects of Suitability (V = .950), Accuracy (V = .875), Ease (V = .896), and Practicality (V = .833), which can be seen in Table 1. Internal validity was used with a sample of 30 children aged 3-6 years.

Table 1. Validity index.

Aspect	**Raters**				**∑**	**n(c-1)**	**V Index**	**M ± SD**
	Items	S1	S2	S3				
Suitability	1	4	4	3	11	12	.917	.950 ± 0.075
	2	4	4	4	12	12	1.000	
	3	4	4	4	12	12	1.000	
	4	4	4	4	12	12	1.000	
	5	3	4	3	10	12	.833	
Accuracy	1	4	3	4	11	12	.917	.875 ± 0.046
	2	4	3	3	10	12	.833	
	3	4	3	3	10	12	.833	
	4	4	3	3	10	12	.833	
	5	3	4	4	11	12	.917	
	6	4	3	4	11	12	.917	
Ease	1	4	4	3	11	12	.917	.896 ± 0.42
	2	4	3	4	11	12	.917	
	3	4	3	3	10	12	.833	
	4	4	4	3	11	12	.917	

Practicality	1	4	4	4	12	12	1.000	.833 ± 0.102
	2	2	3	4	9	12	.750	
	3	3	3	4	10	12	.833	
	4	4	3	3	10	12	.833	
	5	2	3	4	9	12	.750	
All aspect		73	69	71	213	12		.886 ± 0.078

Note. "V" is the rater agreement index, and "S" is the score given to each rater minus the lowest score in the category.

From the calculation results of three experts, a value of .886 was obtained or a high level of validity, meaning that the sensor-based and IoT locomotor skill measurement instrument can be continued to the next stage, namely field trials. For reliability, it is carried out after the tool is valid and continued with field tests on samples involving 30 children with an age range of 3-6 years.

Table 2. Reliability results with test and retest method.

Day	n	Correlation coefficient	Reliability
First day	30	.96	Very high
Second day	30	.95	Very high

Based on the results of the correlation coefficient test of the reliability test, the sensor-based and IoT locomotor skill measurement instrument is said to be reliable and consistent in collecting research data. This study obtained positive results in the development of motor skill instruments, such as making it easier for researchers to collect data, minimizing bias in researcher observations.

DISCUSSION

Numerous studies have proven that sensors and IoT have the potential to be highly effective in assisting in research measurement. Based on validity and reliability tests, the next step was a small-group trial. This study found effective and efficient results in measuring children's locomotor skills. The results indicate that sensor- and IoT-based MATS has the potential to be highly effective in measuring children's locomotor skills.

Based on the results of the research conducted, it was found that the sensor- and IoT-based children's locomotor skills measurement tool obtained a high level of validity with a "*good*" categorization. The results of this validation measurement were obtained from three experts: motor experts, media/IT experts, and measurement experts. The resulting tool is feasible and valid, so it can be applied to children according to age. Absolute assessment in developing an instrument/measuring tool must have a level of validity and reliability. Validity is the accuracy of what is to be measured on the instrument (Rifki et al. 2022; Susiono et al. 2024), while reliability indicates how well the items correlate and are consistent in producing scores (Belita et al. 2022). Validity and Reliability in the instrument are parts that must be fulfilled in the measurement that ensures the accuracy and usefulness of feedback to participants in knowing the training they are doing (Amirzadeh, Rasouli, and Dargahi 2024).

The main results in this study conveyed in the small group and large group testing high alpha coefficients, so that the Sensor and IoT-based locomotor skill measurement tool is consistent and reliable in measurement. The researcher's validity measurement involved three experts in their fields such as 1 motor expert, 1 media/IT expert and 1 measurement expert, in order to obtain optimal content (García-Ceberino et al. 2020), from three experts said that the resulting product had a very good category (Phillips et al. 2021). The results of the study found positive things in conducting research and encouraging the application of technology in

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sports, which means that the use of technology can minimize bias in manual observation, seen in the study (Almohanna et al. 2022) that reliable and valid instruments are very important for measuring accurately, measurement accuracy has a positive impact on research (Abdelrasoul et al. 2015), such as collecting SMAS ability data using sensors that produce accurate research data (Rifki et al. 2022), and collecting hand-eye coordination data based on sensors can make it easier for researchers to calculate and data can be seen directly by research samples (Irawan et al. 2024), as stated in previous research that technological advances provide convenience and accuracy in data collection and become more complex, easy to manage and easier to understand (Dellaserra, Gao, and Ransdell 2014; Measurement, Control, and Tracking Technologies Used in Soccer Players' Training: A Review 2023; Sandbakk 2020).

The results of the study that combined technology and sports successfully created a modern measuring instrument that was able to reduce bias in observation, the results of this study when compared to manual or conventional calculation methods, were able to provide new solutions and breakthroughs in collecting data and developments that researchers had carefully collected. This is a unique design for measuring locomotor capabilities based on sensor technology and IoT which is used to advance measurement and enable real-time data collection. This measurement was successfully provided in order to enable measurable evaluation combined with analytical data to provide direct evaluation and feedback to children.

The advanced technology design of this locomotor measuring instrument creates a more creative method, offering much greater efficacy in producing research calculations. The creation of a locomotor skill measuring instrument that can specifically make this research innovative, effective and evidential in measurement. It is clear that technological advances in the field of sensors and IoT have a positive impact on researchers, teachers and other stakeholders, with the implementation of this research we hope that it can be a guideline, reference, and can realize the instruments/ measuring instruments that we design according to the age that researchers recommend. Although this study found positive things in the study, we have limitations such as the sample that researchers use is not yet extensive and the categorization of children's ages is limited, we provide recommendations for future research such as focusing more on object control skills, age categorization and involving sensor technology and IoT.

CONCLUSIONS

The research that has been conducted shows that the use of sensor technology and IoT has succeeded in creating an effective and efficient measurement tool for locomotor skills in producing data on locomotor skills in children aged 3-6 years. The resulting measurement tool has been validated by three experts and continued with field tests on children, which obtained high reliability. With the creation of this tool, it is expected to be able to help teachers, researchers and stakeholders in evaluating the locomotor skills of children aged 3-6 years, with a younger and more accurate measurement process.

To expand the scope of research and increase validity, it is recommended that future research be conducted on a wider and more varied sample. The creation of a sensor and IoT-based locomotor skills assessment tool is a substantial advance in the fields of education and research, which offers instruments that can be trusted and useful for assessing children's locomotor abilities more effectively and efficiently. In addition to being used for locomotor skills, sensor technology and IoT serve as a basis for future advances in motor learning, including other motor skills that require real-time assessment and measurement.

AUTHOR CONTRIBUTIONS

Anton Komaini and Qorry Armen Gemael designed and reviewed the investigation, analysed and interpreted the data, and drafted the manuscript; Eka Sahputra and Krismadinata, methodology and validation; Asrul Huda and Heru Andika collected and interpreted the data. All authors participated in the review and approval of the final manuscript, as well as in ensuring the integrity and accuracy of the content presented.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Perceived quality in health and fitness assessment in fitness centres: Perspectives of users and instructors

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ABSTRACT

The assessment of health and physical fitness in fitness centres plays a central role in personalizing the service and improving customer experience, working as a starting point for an exercise prescription adjusted to the needs, preferences and goals of the user. This research aims to characterize and compare the perception of quality of the fitness instructor's intervention, from the perspective of users and instructors. Data were collected from 148 users and 32 instructors from five gyms of a fitness chain in Portugal, through an online ad hoc questionnaire consisting of 10 items. Descriptive statistics (mean and standard deviation) were used for characterization, inferential (Student's t-test) for comparison and calculation of the effect size dimension (Cohen's d), for a significance level of 5% ($p < .05$). The results revealed significantly different and more positive perceptions of users in three items: timely contact to schedule the evaluation ($p = .030$; $d = 0.426$); ease of scheduling process ($p = .001$; $d = 1.474$); instructor's technical knowledge ($p = .018$; $d = 0.465$). In the 10 items, users evaluated the service more positively than the instructors themselves. The data suggests that professionals tend to underestimate their technical intervention, which may be associated with high demands, whether they are their own or institutional. The results reinforce the importance of assessing health and physical fitness and point to the need to promote greater awareness of performance and self-confidence among fitness professionals.

Keywords: Fitness service, Quality, Professional intervention, Exercise prescription.

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INTRODUCTION

The fitness sector has experienced significant growth in recent years, establishing itself as one of the most dynamic segments of the exercise and health industry. This increase in demand for healthy and active lifestyles has driven the diversification of services offered by gyms and fitness centres, with new trends emerging year after year (Newsome et al., 2024; Franco et al., 2025), encompassing a wide range of activities and programs tailored to different user profiles (EuropeActive & Deloitte, 2024; Pedragosa & Ferreira, 2025). This scenario of expansion and increasing complexity requires professional approaches based on technical and scientific evidences, focused on service quality, user satisfaction, and client retention (Dias et al., 2019; Eskiler & Safak, 2022; Ferreira-Barbosa et al., 2020a; García-Fernández et al., 2018; Gonçalves & Diniz, 2015; Huang & Kim, 2023; Xu et al., 2021).

Among the most sought-after services by fitness users are group classes, personal training, and exercise room (Cardoso, 2022; Filingeri & Rieger, 2016; Gaspar, 2021; Pedragosa & Ferreira, 2024; Silva et al., 2022), which align with the main fitness trends in recent years, particularly in Portugal (Franco et al., 2021, 2022, 2023, 2024, 2025). These services play a key role in user adherence and loyalty, especially when recognized by users as being of high quality. One of the variables that can most strongly influence perceived quality, positively or negatively, is the intervention and characteristics of the fitness instructor (Barbosa et al., 2023; Braga-Pereira et al., 2024, 2025; Campos et al., 2023; Glaveli et al., 2021; Santos et al., 2021).

Regardless of their specific role(s), exercise and health professionals working in fitness centres (e.g., gyms, health clubs) must master the fundamental principles of fitness assessment and exercise prescription. They must know how to use the results of fitness tests to design scientifically grounded, individualized programs that meet the needs, preferences, and abilities of their clients (EuropeActive, 2023; Simões & Furtado, 2021). Fitness assessment is a common and appropriate practice when planning exercise programs and should pursue the following objectives: to educate users about their current health and fitness status, according to age- and gender-specific standards; to obtain relevant data to design individualized prescriptions; to collect baseline and follow-up information to monitor progress; and to enhance user motivation by setting measurable, realistic, and achievable goals (Heyward & Gibson, 2018; Simões & Furtado, 2021; Teixeira, 2021; Zebre, 2022).

Assessing variables related to health and physical fitness is essential to the technical intervention of any instructor. Only through an initial assessment can professionals deliver adequate and individualized service (Pimenta et al., 2016). Overall, health and fitness assessment (HFA) enables fitness professionals to design safer, personalized, and goal-oriented programs, to set realistic objectives, accurately monitor client progress, and adjust initial plans when necessary (Pimenta et al., 2016). According to Zebre (2022), assuming these procedures should be conducted for all clients starting an exercise program, at least a basic evaluation should be carried out, including: health assessment (e.g., pre-exercise screening, medical history, cardiovascular risk factors, resting parameters) and physical fitness assessment (e.g., body composition, cardiorespiratory fitness, muscular strength, flexibility). This recommendation, also supported by several Portuguese technical manuals (Simões & Furtado, 2021; Teixeira, 2021), is aligned with the guidelines of the American College of Sports Medicine (2025).

The assessment of health and physical fitness parameters directly influences the intervention strategies adopted by fitness professionals, allowing them to adjust pedagogical and motivational approaches to the specific needs of each client (Campos et al., 2020). Every client is a unique individual, with distinctive characteristics. Users satisfaction may result from the congruence between perceived service quality and

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individual preferences, as emphasized in Franco et al. (2012). Recent studies highlight that perceived service quality, particularly of technical intervention, is intrinsically linked to users' profiles and preferences, and may vary depending on sociodemographic variables such as gender, age, or income (Campos et al., 2021; Ortega-Martínez et al., 2021). Other studies, such as Franco et al. (2013), have compared user perception with instructors' self-perception, showing discrepancies in various behavioural dimensions. While several studies have focused on fitness instructors' behaviour during group classes (Campos et al., 2017; Dias et al., 2020; Luís et al., 2021; Simões et al., 2023), there is a noticeable lack of research exploring instructor intervention during HFA. This gap underscores the relevance of the present study, which aims to better understand how users and instructors perceive HFA intervention.

The structural and organizational heterogeneity of fitness centres directly affect the services provided and the users' perceptions. Estrada-Marcén et al. (2019) found significant variability in the implementation of procedures related to functional assessment and safety (only 67% performed HFA and only 22% required prior medical evaluation). These data suggest that perceived quality of technical services, such as HFA, may be influenced not only by the instructor's competence but also by institutional models. In this sense, understanding how users and instructors evaluate technical intervention becomes essential to promote standardized practices, aligned with the expectations of diverse target groups. Therefore, the present study aims to characterize the perceived quality of HFA services provided by instructors to users of a fitness chain in Portugal, and to compare both perspectives (instructors and users). Specifically, the study examines aspects directly associated with the instructor's intervention (e.g., concern for identifying clients' physical limitations). Understanding the possible discrepancies between the two perspectives may help define and implement strategies that improve professional performance and, consequently, overall service quality and users satisfaction, aligning it more closely with users' expectations, preferences, and needs.

MATERIAL AND METHODS

Participants

The study involved 148 users and 32 instructors from five gyms belonging to a fitness chain in Portugal. The users were aged between 18 and 80 years [Mean (M) ± Standard-deviation (SD) = 41.21 ± 13.55), with 106 females (71.62%) and 42 males (28.38%). As for the instructors, their ages ranged from 19 to 43 years (26.41 ± 6.44), with 13 females (40.63%) and 19 males (59.37%). The inclusion criteria were: for users – being at least 18 years old, attending one of the gyms at least once a week, and having undergone a HFA within the last month; for instructors – being at least 18 years old, working professionally in one of the clubs, and having at least one month of professional experience at the club. All participants (users and instructors) were informed about the study's objectives and signed a free and informed consent form. The study was approved by the Ethics Committee of the Polytechnic Institute of Coimbra (Portugal) (approval no. D40/2024).

Measures

To collect data, an ad hoc questionnaire was developed by the research group, in collaboration with the fitness chain. The initial version was adapted from Campos et al. (2016) questionnaire, incorporating 10 key items related to the perceived quality of HFA. The selection of items was discussed and refined through structured discussion panels with the fitness chain's management, technical directors and HFA instructors, ensuring contextual relevance and alignment with the study's objectives. Two versions were constructed: the perception version (Pv), applied to users, and the self-perception version (SPv), applied to instructors. After its initial construction in an online format, the questionnaire was submitted for review to a panel of two experts, both PhD in Sport Sciences with relevant research experience for a face-validity (Hill & Hill, 2008). Their feedback and suggestions were incorporated into a revised version, which was then reviewed by a second

panel of experts with similar qualifications. The final instrument included 10 items, rated on a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree), as presented in Table 1.

Table 1. Assessed items in the HFA service.

1.	Timely contact to schedule the first assessment. (*Contact*)
2.	Ease of the scheduling process. (*Scheduling*)
3.	Instructor's punctuality for the assessment. (*Punctuality*)
4.	Instructor's concern about identifying users' physical limitations. (*Limitations*)
5.	Instructor's empathy during the assessment. (*Empathy*)
6.	Clear explanation of the data obtained by the instructor. (*Explanation*)
7.	Comparison of the results with normative values by the instructor. (*Comparison*)
8.	Definition of a plan by the instructor to help the user achieve their goals. (*Plan*)
9.	Instructor's demonstrated knowledge in the area of sport. (*Knowledge*)
10.	Usefulness of the ZAPPY app to schedule future assessments. (*App*)

The items were phrased according to the respondent's role. For example, item 1 in Pv was: "*I was contacted in a timely manner to schedule the first assessment*"; in SPv: "*The client was contacted in a timely manner to schedule the first assessment.*"

Procedures

To meet the study's objectives, a data collection protocol was established in coordination with the gym chain management, which was responsible for introducing the study and encouraging the participation of all instructors working at the five gyms. These instructors, in turn, promoted research among users during group classes, personal training sessions, and exercise room, reinforcing its relevance to improving service quality and better addressing user needs. Questionnaires were distributed via the Customer Relationship Management (CRM) software Salesforce, allowing the appropriate version (Pv or SPv) to be directed to each respondent type (user or instructor). Data collection occurred over approximately one month, from November 25 to December 20, 2024.

Analysis

Descriptive statistics (M and SD) were used for data characterization. To compare groups, Student's *t*-test was applied after verifying assumptions of normality and homogeneity (Marôco, 2021; Pestana & Gageiro, 2008). For samples under 30 participants, normality was assessed using the Shapiro-Wilk test (Pestana & Gageiro, 2008; Laureano, 2013; Marôco, 2021). When this assumption was not met, skewness analysis was used as an alternative (Pestana & Gageiro, 2008). The Levene test was employed to assess homogeneity of variances. Effect size (ES) was calculated using Cohen's d and classified according to O'Donoghue (2013): *small* ($d < .20$), *moderate* ($.20 \leq d < .80$), and *large* ($d \geq .80$). All analyses were conducted in SPSS (version 28), with the significance level set at 5% ($p < .05$).

RESULTS

The following section presents the results concerning the perceived quality of the HFA service, from the perspectives of users and instructors. A comparative summary of the 10 assessed items is presented in Table 2. In terms of descriptive statistics, users rated the highest items as follows: instructor's punctuality for the assessment (6.75 ± 0.89), concern about identifying the user's physical limitations (6.74 ± 0.74), demonstrated knowledge in the area of sport (6.72 ± 0.82), definition of a plan to achieve the user's goals (6.70 ± 0.89), and clear explanation of the data obtained by the instructor (6.66 ± 0.88). Instructor empathy

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during the assessment also received a high rating (6.66 ± 1.10). Although still high within the 1-to-7 scale, the lowest-rated item among users was the usefulness of the ZAPPY app for scheduling future assessments (5.79 ± 1.57).

Among instructors, the highest-rated items were concerned about identifying users' physical limitations (6.71 ± 0.58), empathy during the assessment (6.65 ± 0.54), definition of a plan to help users achieve their goals (6.62 ± 0.60), and punctuality for the assessment (6.56 ± 0.71). The lowest-rated items were also the usefulness of the ZAPPY app (5.62 ± 1.40) and ease of the scheduling process (4.96 ± 1.42).

Statistically significant differences between users and instructors were found in three of the 10 evaluated items: timely contact for scheduling the first assessment (t = 2.185, p = .030, d = 0.426, *moderate* ES); ease of the scheduling process (t = 6.100, p = .001, d = 1.474, *large* ES); demonstrated knowledge in the area of sport (t = 2.387, p = .018, d = 0.465, *moderate* ES). Across all items, even when differences were not statistically significant, user ratings were consistently higher than instructors' self-assessments.

Table 2. Perceived quality of the HFA service (users vs. instructors).

Item	U	I	t	p	d
1. Contact	6.54 ± 1.16	6.06 ± 1.01	2.185	.030*	0.426
2. Scheduling	6.58 ± 1.01	4.96 ± 1.42	6.100	.001*	1.474
3. Punctuality	6.75 ± 0.89	6.56 ± 0.71	1.110	.268	0.216
4. Limitations	6.74 ± 0.74	6.71 ± 0.58	0.174	.862	0.034
5. Empathy	6.66 ± 1.02	6.65 ± 0.54	0.032	.975	0.006
6. Explanation	6.66 ± 0.88	6.43 ± 0.75	1.333	.184	0.260
7. Comparison	6.56 ± 1.10	6.34 ± 0.93	1.068	.287	0.208
8. Plan	6.70 ± 0.89	6.62 ± 0.60	0.466	.642	0.091
9. Knowledge	6.72 ± 0.82	6.34 ± 0.82	2.387	.018*	0.465
10. App	5.79 ± 1.57	5.62 ± 1.40	0.572	.568	0.111

*Note. *statistically significant at p < .05; U: Users; I: Instructors.*

DISCUSSION

The results of this study, which characterized and compared the perceived quality of HFA services among users and instructors from a fitness chain in Portugal, revealed some discrepancies between the two perspectives. Specifically, users consistently rated the quality of the HFA service more positively than the instructors themselves did. Rather than indicating a service failure, this difference may reflect a critical factor in users satisfaction: the alignment between service delivery and users' expectations and preferences. This finding reinforces prior literature highlighting perception gaps in fitness service contexts and their implications for personalized service (Franco et al., 2013).

The items rated most highly by both users and instructors included punctuality, concern with identifying the user's physical limitations, and the definition of a personalized plan to help achieve goals. These findings are consistent with existing research that emphasizes these variables as key determinants of user satisfaction and loyalty in fitness environments (Campos et al., 2020; Cardoso, 2022; Filingeri & Rieger, 2016; Gaspar, 2021). Punctuality (Campos et al., 2020), personalization (Cardoso, 2022; Filingeri & Rieger, 2016), and individual attention (Gaspar, 2021) are seen as essential factors for the consolidation and credibility of the fitness sector (EuropeActive & Deloitte, 2024).

The item that received the lowest average score from users was the usefulness of the ZAPPY app for scheduling future reassessments. It was also the second lowest for instructors. This is consistent with research pointing to challenges in adopting technology within fitness services (e.g., Ferreira-Barbosa et al., 2020b; Huang & Kim, 2023), particularly when digital tools are perceived as unintuitive or ineffective. These findings suggest that improving the user experience of digital systems used for scheduling may be a relevant point of intervention.

Among the 10 evaluated items, three revealed statistically significant differences in perception. The most pronounced discrepancy was found in the ease of the scheduling process, with instructors giving a significantly lower rating compared to users. Although this element is highly valued by users, it also reflects a logistical challenge for instructors and facilities. Ease of scheduling and service accessibility are critical to user satisfaction and retention (Ferreira-Barbosa et al., 2020a). Improving scheduling platforms may therefore serve not only users but also relieve operational burdens on instructors. Similarly, timely contact for scheduling the initial assessment showed a significant difference in perception. The lower score attributed by instructors compared to users may suggest communication bottlenecks or institutional constraints that hinder effective follow-up. It would be advisable for fitness centre management teams to examine and address such discrepancies from an operational and service design perspective. The other item with a significant difference between groups was the perceived level of sport-specific knowledge demonstrated by instructors. Users rated this higher than instructors did themselves. This may reflect a self-critical stance by instructors, a lack of confidence in communicating technical knowledge, or a mismatch between actual competence and its perception. Prior research has emphasized that technical competence, and the ability to communicate it clearly, are fundamental to perceived quality in fitness services (Campos et al., 2020), helping establish trust and professional credibility (Barbosa et al., 2023; Simões & Furtado, 2021).

Although the perception differences observed are significant, they may also reflect a natural tendency for instructors to adopt a more critical self-assessment. Such tendencies can be linked to high professional standards and an aspiration for continuous improvement, as suggested in the literature (García-Fernández et al., 2018; Heyward & Gibson, 2018). However, given the relatively young average age of the instructors in this sample (26.41 years), this self-critical view may also result from limited professional experience or a lack of confidence in their technical intervention.

It is important to emphasize that users' high ratings of aspects such as punctuality, concern for limitations, and empathy underscore the idea that service quality is not based solely on technical knowledge. Emotional and interpersonal aspects, such as empathy and personalized attention, are increasingly seen as key elements in enhancing client experience and motivation (Braga-Pereira et al., 2024, 2025; Campos et al., 2020; Ferreira-Barbosa et al., 2020a). These relational dimensions contribute to adherence, satisfaction, and long-term commitment to exercise programs (Teixeira, 2021; Zebre, 2022).

The results suggest that instructors tend to underestimate their perception of quality, which reinforces the importance of collecting more regular and systematic information, as it allows professionals to better align their self-perception with users' expectations, identify areas for improvement, and continuously enhance the quality of the services provided. Valuing aspects such as empathy, punctuality and individualized monitoring points to the need to strengthen relational and communication skills of professionals, in addition to technical skills. In this sense, continuous training assumes a strategic role that could be explored, not only in scientific updating, but also in improving the quality of professional intervention in sports and exercise areas (Pérez-Camarero et al., 2022).

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CONCLUSIONS

This study allowed for the characterization and comparison of perceived quality in HFA services between users and instructors from a fitness chain in Portugal. Based on the results and discussion presented, the following key findings are highlighted:

a) Overall satisfaction with the HFA service: Both users and instructors assigned high ratings to key aspects, such as instructor punctuality, attention to users' physical limitations, technical knowledge, and the development of personalized exercise plans.
b) Discrepancy between users and instructors perceptions: Significant differences were identified in three of the 10 evaluated items. Instructors consistently rated the service lower than users did, revealing a more critical self-assessment. This discrepancy may stem from high professional standards or a tendency among instructors to underestimate their own knowledge and technical competencies.
c) Area for improvement in HFA service: The perceived usefulness of the ZAPPY app for scheduling reassessments received the lowest ratings from both groups. This suggests challenges in the implementation of mobile technologies within fitness settings, particularly concerning usability and perceived value. Improving the interface, offering better guidance on usage, or considering alternative digital tools may be necessary.
d) Importance of empathy and personalized attention: The results reinforce the notion that service quality is not determined solely by technical competencies but also by relational factors. Emotional engagement and individualized interaction between instructor and user play a critical role in enhancing the exercise experience and user motivation, which are essential for adherence and sustained participation.

In practical terms, this study emphasizes the need for continuous improvement of HFA services, particularly regarding scheduling processes and the integration of intuitive digital tools. Despite the overall positive evaluations, these findings point to relevant operational and pedagogical challenges that should be addressed.

Although the methodology was sound and rigorously applied, this study has limitations. The sample was limited to users and instructors from a single fitness chain in the central coastal region of Portugal, which restricts the generalizability of the results. Furthermore, the evaluation relied on a perception-based questionnaire, which may be subject to response biases. Future research should consider these limitations and aim to broaden the scope of data collection to include diverse fitness settings and mixed methods.

AUTHOR CONTRIBUTIONS

Conceptualization, F.C. and J.A.; methodology, F.C. and J.A.; data curation, F.C., D.A. and J.A.; writing - original draft preparation, D.A. and V.S.; writing - review and editing, S.F. and F.C.; supervision, F.C.; project administration, F.C. and J.A. All authors have read and agreed to the published version of the manuscript.

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ORIGINAL ARTICLE

Correlation of the caloric contribution of macronutrients and the corporal composition in baseball players

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ABSTRACT

Objective: To determine the correlation between the kilocalories provided by macro-nutrients and the body composition of baseball players from the Camagüey team participating in the National Series 63. Methodology: A field study was conducted using a quantitative, descriptive, and longitudinal approach. Analytical-synthetic, inductive-deductive, and measurement methods were employed, following protocols established by the National Institute of Sports Medicine. Results: No significant differences were found in the caloric contribution of macronutrients across different player positions. A strong correlation between body composition and macronutrients was observed only in catchers, specifically regarding fats and carbohydrates. Discussion: Out-fielders maintained stable body composition, indicating metabolic balance between energy intake and expenditure, which supported an appropriate health status for their athletic activities. Their body fat percentages aligned with recommendations from the Division of Sports Science and Technology of the United States Olympic Committee. Conclusions: Nutritional strategies did not account for positional differences in game-play. The correlation between macronutrient intake and body composition varied across different assessment periods, indicating a lack of consistency in dietary management.

Keywords: Sport medicine, Body composition, Nutrients, Caloric contributions, Metabolic balance.

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INTRODUCTION

The proportion between the different components of the body is referred to as body composition (Ponce-Garcia et al., 2025). The scientific community agrees that for research purposes, it is essentially expressed as the distribution of fat-free mass and fat mass within the organism (de Almeida-Neto et al., 2021; Ponce-Garcia et al., 2025).

Fat-free mass is a variable comprising muscle tissue, bones, internal organs, and water; whereas fat mass, as the name indicates, is that which is composed of the body's fats (Ponce-Garcia et al., 2025).

Body composition is considered a relevant variable when assessing the influence of training on the organism, as it allows for the analysis of the effectiveness of the systems used (Figueiredo et al., 2020). The study of body composition makes it possible to determine the proportion of fat and muscle in a person's body. This knowledge enables coaches to plan athletes' nutrient intake in such a way that it is carried out appropriately based on their individual needs, thereby increasing muscle mass (Sanga Dwi et al., 2024). Therefore, the study of body composition is considered a necessary indicator during the assessment of an individual's nutritional status (Hernández et al., 2024) and is regarded as a fundamental indicator for evaluating health and physical performance (Meshtel et al., 2024), particularly in the context of sports, where it directly influences physical development and performance (Hector & Phillips, 2018).

Achieving adequate physical development for each sporting discipline and specific preparation phase is a complex task that demands multiple areas of expertise to aid in making correct decisions. Achieving the objectives of physical development requires knowledge of the energy demands of each athlete's organism. Therefore, it is necessary to systematically evaluate body composition as a component of physical development, in addition to assessing the intake of macronutrients that guarantee the energy required to perform sporting activities. All this allows for the adjustment of training programs to individual needs and the demands of the sport (Ramírez-Campillo et al., 2022).

Achieving adequate nutrition for athletes demands the application of scientific knowledge from the field to maintain a proper state of health during competition. This is achieved by providing foods that supply macronutrients in the necessary quantities based on the physiological demands of the specific sport being practiced (Sanga Dwi et al., 2024).

Sports specialists agree on the need to maintain an adequate diet that guarantees sufficient amounts of carbohydrates, as they constitute the primary source of energy during competitions. Furthermore, the consumption of foods that provide necessary amounts of fats is essential, as they represent a reserve energy source utilized once carbohydrates are depleted during endurance exercises. Likewise, consuming adequate proportions of proteins is necessary to guarantee muscular development, as they constitute an important factor in reconstruction processes during training. In this regard, the diet must be sufficient in protein quantities, as it also enhances adaptation to training loads, recovery, and tissue repair (Di Corcia et al., 2022).

Evidence demonstrates the importance the scientific community has placed on research into body composition and nutrition separately, as well as by relating the results of the former through inferences about diet and nutrition. In this respect, Narváez et al. (2022) conducted a study concluding that body composition conditions performance.

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For their part, Yaguachi-Alarcón et al. (2025), while investigating the relationship between diet and caloric intake in law enforcement officers, reached a conclusion valid for sports activity by stating that the calories consumed must correspond to the physical activity performed. Adhering to this principle allows for the individualization of physical activity based on nutritional requirements, providing the organism with necessary nutrients through an appropriate dietary strategy, which favours the development of physical capacities (Rebelo et al., 2025).

In team sports involving cooperation and opposition, research related to body composition has been carried out, determining that a relationship exists with performance, as well as with the specific sport practiced (Corredor-Serrano et al., 2023).

In this sense, Hermosilla-Palma et al. (2024) state that a correlation exists between muscle mass and strength, as well as between decreased fat and adequate bone mineralization with the development of strength in young soccer players.

Similarly, it is also proposed that in soccer players, body composition is related to the player's position on the field, with goalkeepers and central defenders obtaining the highest values (Tereso et al., 2024).

In sports practice, an increase in body weight was observed at the expense of increased muscle mass (Figueiredo et al., 2020; Henriksson et al., 2020; Ortega et al., 2023). In this regard, research has been conducted correlating muscle mass and physical development, showing a strong correlation (Horta-Gim et al., 2025).

Regarding body composition, the investigations by Rahma et al. (2024) were also found; these make significant contributions to the topic. However, scientific evidence found in baseball is not extensive. In this regard, Barajas-Ramón et al. (2015) conducted studies on body composition in female athletes; Zamora-Mota et al. (2022) developed a study on nutrition in the prevention of sports injuries in baseball pitchers; while Mesa et al. (2024) addressed the impact of training on body composition.

The scientific evidence reveals the role macronutrients play in the morphological development of athletes, favouring osteo-muscular development, to mention just one example. However, although research contributions indicate that macronutrients are related to the morphological development of athletes, in Camagüey there are limited studies linking macronutrients to the body composition behaviour of baseball players participating in the national series.

In this sense, evidence pointing to the study of body composition has been found; however, establishing the relationship between the kilocaloric contribution of macronutrients and the body composition of baseball players participating in the national series has not been found.

Given the importance of adequate body composition development and the proper intake of macronutrients—which provide the organism with the energy necessary to achieve functional physical performances according to the competitive demands of the sport in question—during the sports preparation process and competition, it is essential to understand the relationship between body composition and macronutrients.

The results of this study could contribute to the improvement of training programs for baseball players during competition, aiming to maintain performances adequate to the demands of each competitive moment or

segment of the competitive season, in addition to adopting strategies related to macronutrient intake during competition.

In accordance with the above, the main objective of the present study is to determine the correlation between the kilocalories provided by macronutrients and the body composition of players from the Camagüey baseball team participating in the 63rd National Series.

MATERIALS AND METHODS

Research design

The research presented for consideration is a field study, conducted quantitatively with descriptive characteristics and a longitudinal scope. The inquiry process was carried out using theoretical-level methods, including analytical-synthetic and inductive-deductive approaches. These methods enabled the decomposition of the problem as it manifests in concrete practice and reality, subsequently developing a solution through abstract thought and implementing it within the research framework. At the empirical level, measurement was employed to determine body composition values through protocols that ensure the integrity of the athletes under study. Furthermore, documentation analysis was used to verify the grams of different food types, which allowed for the determination of the quantity of macronutrients ingested by the sub-jects in each meal ration. The process was conducted in compliance with protocols established by the Cuban Ministry of Public Health and, specifically, the National Institute of Sports Medicine. The research was carried out from March to May 2024, spanning the 12 weeks from the start to the end of the second third of the competition (50 games).

Participants

The study involved the 40 baseball athletes constituting the population of the team participating in the 63rd National Baseball Series. A non-probabilistic, intentional sampling method was used to select 19 field players, representing 47.5% of the total. The sample type is one of convenience. The inclusion criteria were players who performed in various field positions (catchers, infielders, and outfielders) and had systematic participation during the competition. The exclusion criteria were set to omit pitchers and players who had sporadic participation during the evaluated period (two sub-series). The average age of the participants was (26.4 ± 5.5 years). All participants received comprehensive information regarding the objectives, risks, importance, and procedures to be used and provided informed consent.

Variables

The anthropometric variables necessary to determine the players' body composition were studied. These were: percentage of fat (% Fat), kilograms of active body mass (kg ABM), and the active substance index (AKS). Furthermore, the proportions of food constituting the rations provided to the players during the analysis period were studied to determine the quantity in grams of the macronutrients: Proteins (P), Lipids (Lip), and Carbohydrates (Car).

Procedures and measurement instruments

The process of monitoring the players' body composition indicators was conduct-ed at three time points during the competition: first, at the start of the tournament (March 8th); second, upon the conclusion of game 25 (April 11th), termed for this study as the end of the first third of the competition (End 1st Third); and third, upon the conclusion of game 50 (May 18th), termed the end of the second third of the com-petition (End 2nd Third).

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At each of these time points, measurements of the anthropometric variables enabling the determination of body composition were taken, following the standardized and validated methodological procedures established by the International Society for the Advancement of Kinanthropometry. (Esparza *et. al,* 2021)
The values for the variables were determined as follows: height, using a portable Seca 213 stadiometer (60-200 cm; precision 1mm); body weight, using a Terraillon Fitness Coach Premium scale (0-160 kg; precision 100 grams); skinfold measurements (triceps, subscapular, suprailiac, front thigh, abdominal, medial calf) were taken using a Slim Guide calliper (0-75 mm; precision 0.5 mm). The measurement procedure was preceded by verification of the calibration standards for each instrument.

Each skinfold measurement was taken after locating and marking its specific site to avoid bias in the results. Specifically: the triceps was measured at the mid-acromiale-radiale point on the posterior aspect of the arm; the subscapular, at the inferior angle of the scapula, two centimetres from the subscapulare point; the suprailiac, using the iliospinale landmark to the anterior axillary line and the iliocristale line. The abdominal skinfold was measured five centimetres from the omphalion; the front thigh skinfold was determined at the midpoint between the inguinal point and the patellare point; finally, the medial calf skinfold was located on the most medial area of the calf at the level of its maximum perimeter. All skinfolds were measured on the right side of the subjects' bodies.

The skinfold measurements allowed for the determination of body composition component proportions using the methodological procedure established by the Cuban National Institute of Sports Medicine. Mathematically, the equations by Withers et al. were used, as they are the standard reference for these studies in Cuban athletes for determining body composition (Carvajar, 2021).

Measurements were performed by anthropometry specialists from the Camagüey Center of Sports Medicine; one specialist performed the measurements while the other assisted by recording the data. Both possess proven expertise supported by over 16 years of experience in anthropometry and are certified by the National Institute of Sports Medicine. Necessary conditions for determining the value of each anthropo-metric variable were guaranteed. Upon completion of each measurement session, an approval form was signed by the ethics committee of the Institute of Sports Medicine.

Measurements were conducted in a designated room at the Provincial Center of Sports Medicine, allowing for compliance with established technical and hygienic requirements. Measurements were always performed on the first day of the week (Mon-day). Before starting the measurement procedure, each player was instructed on the necessary details to ensure correct execution. Visual inspection and clinical manoeuvres were performed to detect any alterations that could bias the results. Measurements were taken in the morning, after a minimum of eight hours since the last meal (before breakfast), and after voiding the bladder and bowels.

Regarding macronutrients, the procedure used was document analysis, reviewing daily reports issued by the sports medicine specialist (team physician) on the control of the gram quantities constituting the food rations from the first day of the competition until the end of the second third. This allowed for the determination of the quantity in grams of carbohydrates, proteins, and lipids comprising the food ration provided to each player. From this data, the caloric contribution was determined by multiplying the quantity in grams by the kilocalorie contribution of each macronutrient: lipids = gLip * 9 kcal, proteins = gP * 4 kcal, and carbohydrates = gCar * 4 kcal. This procedure complied with the standards established by the Institute of Sports Medicine.

Statistical analysis

For the statistical procedure, players were grouped by their playing positions into three areas: catchers, infielders, and outfielders. Data collected from the anthropometric measurements to determine body composition values were processed in a spreadsheet using Microsoft Excel, standardized by the Cuban National Institute of Sports Medicine. Data analysis was performed using SPSS software (IBM Corporation, USA) version 26.0 for MAC. Normality of the data was analysed using the Shapiro-Wilk test. Descriptive statistics were used to represent the results as mean and standard deviation for both body composition and macronutrients.

Inferential statistics were used to determine if there were significant differences between body composition indicators at the different competition time points. As the data were normally distributed ($\alpha = .111$), a paired Student's t-test was applied, with a significance level of $\alpha < .05$.

Subsequently, inferential statistics were applied using the correlation coefficient to determine whether a correlation existed between body composition and the kilocalories provided by macronutrients at each of the studied time points. The correlation levels were established according to Gómez (2020) no correlation (.0), minimal (.0 – .2), low (.2 – .4), moderate (.4 – .6), good (.6 – .8), very good (.8 – .99), and perfect (1.00).

The assumed statistical hypotheses state that:

- H_0 (Null Hypothesis): There is a correlation between the components of body composition and the kilocalories provided by macronutrients at the two studied time points.
- H_1 (Alternative Hypothesis): There is no correlation between the components of body composition and the kilocalories provided by macronutrients at the two studied time points.

RESULTS

Table 1 presents the mean body composition results for players performing as catchers in baseball games, along with comparisons across different measured time points. Regarding body fat percentage (% Fat), the mean values were 16.2% at baseline and 14.37% by the end of the second third of the season.

Table 1. Body composition and caloric intake from macronutrients in catchers.

Body composition	Baseline	End 1st third	End 2nd third	BL vs E1T (*p*-value)	BL vs E2T (*p*-value)	E1T vs E2T (*p*-value)
% Fat	16.2	14.90	14.37	.1	.07	.1
kg ABM	83.00	82.70	83.30	.4	.3	.09
AKS	1.39	1.39	1.38	.3	.3	.4
Protein (P)	809.99	809.99	847.3	-	.1	.1
Lipids (Lip)	1388.01	1388.01	1539.3	-	.05	.05
Carbohydrates (Car)	2572.46	2572.46	2795.8	-	.03	.03
Total calories (T. Cal)	**4770.45**	**4770.45**	**5182.5**	**-**	**.007**	**.007**

Note: BL = Baseline; E1T = End of the First Third; E2T = End of the Second Third. p-values result from paired t-tests. A dash (-) indicates no statistical test was performed due to identical values.

The mean active body mass (kg ABM) was 83.00 kg at baseline, 82.70 kg at the end of the first third, and 83.30 kg at the end of the second third. The active substance index (AKS) showed mean values of 1.39 at both baseline and the end of the first third, decreasing slightly to 1.38 by the end of the second third.

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As shown in Table 1, the caloric intake from macronutrients remained consistent between baseline and the end of the first third, with proteins (809.99 kcal), lipids (1388.01 kcal), and carbohydrates (2572.46 kcal) displaying identical values. In contrast, all macronutrient caloric values increased by the end of the second third of the competitive period.

Table 2 presents the correlation results between body composition components and macronutrient intake for catchers at the end of the first and second thirds of the competition.

Table 2. Correlation between body composition and macronutrient intake in catchers.

Comparison	1st third of the competition				2nd third of the competition			
	P	Lip	Car	T. Cal	P	Lip	Car	T. Cal
Fat percentage vs. Macronutrient Kcal	.0	.2	.9	.2	.3	1.00	.1	.5
Active Body Mass (kg ABM) vs. Kcal	-.7	-.5	1.00	-.5	-.5	.7	-.7	-.4
Active Substance Index (AKS) vs. Kcal	-.2	.0	.9	.1	.3	1.00	.0	.4

Note: Protein (P); Lipids (Lip); Carbohydrates (Car); Total Kilocalories (T. Cal).

At the end of the first third, no correlation was observed between fat percentage (%) and kilocalories from proteins (P). A minimal direct correlation was found between fat percentage and lipids (Lip), while a very strong direct correlation was observed between fat percentage and carbohydrates (Car). The correlation with total kilocalories (T. Cal) was minimal.

By the end of the second third, a low direct correlation was found between fat percentage and proteins (P). The correlation with lipids (Lip) was perfect and direct, whereas with carbohydrates (Car), it was minimal. Total, kilocalories (T. Cal) showed a moderate direct correlation with fat percentage during this period.

Regarding active body mass (ABM), Table 2 shows that at the end of the first third, its correlation with proteins (P) was moderate and inverse. With lipids (Lip), the correlation was strong and direct, while with carbohydrates (Car), it was strong and inverse. The correlation with total kilocalories (T. Cal) was moderate and inverse. At the end of the second third, the correlation with proteins remained moderate and in-verse, with lipids it was strong and direct, and with carbohydrates, it was strong but inverse. The correlation with total kilocalories was low and inverse.

Concerning the active substance index (AKS), at the end of the first third, a minimal inverse correlation was observed with proteins, while no correlation was found with lipids. However, a very strong direct correlation was detected with carbohydrates (Car), and a minimal correlation with total kilocalories. In the second third, the correlation with proteins was low and direct, with lipids it was perfect, and with carbohydrates, no correlation was observed. Additionally, a moderate direct correlation was found with total kilocalories.

Table 3 presents the body composition results of the infield players. The data indicate that the mean values for body fat percentage ranged between 12.0% and 12.4%. Meanwhile, the mean values for active body mass (kg ABM) ranged from 66.7 kg to 68.2 kg. Regarding the active substance index (AKS), the mean values fell within the range of 1.26 to 1.29.

Table 4 shows that for infield players during the first third of the competition, a moderate direct correlation was observed between fat percentage and protein intake (P), as well as with lipids (Lip) (r = 0.6). The relationship with carbohydrates (Car) was low and direct, while the correlation with total kilocalories (T. Cal) was moderate and direct.

Table 3. Body composition and caloric intake from macronutrients in infield players.

Body composition	Baseline	End 1st third	End 2nd third	BL vs E1T (*p*-value)	BL vs E2T (*p*-value)	E1T vs E2T (*p*-value)
% Fat	12.4	12.0	12.1	.04	.10	.36
kg ABM	66.7	67.4	68.2	.03	.10	.24
AKS	1.26	1.28	1.29	.05	.09	.37
Protein (P)	809.99	809.99	847.3	-	.1	.1
Lipids (Lip)	1388.01	1388.01	1539.3	-	.05	.05
Carbohydrates (Car)	2572.46	2572.46	2795.8	-	.03	.03
Total calories (T. Cal)	**4770.45**	**4770.45**	**5182.5**	**-**	**.007**	**.007**

Note: BL = Baseline; E1T = End of the First Third; E2T = End of the Second Third. p-values result from paired t-tests. A dash (-) indicates no statistical test was performed due to identical values.

Table 4. Comparison between body composition and macronutrient intake in infield players.

Comparison	1st third of the competition				2nd third of the competition			
	P	Lip	Car	T. Cal	P	Lip	Car	T. Cal
Fat percentage vs. Macronutrient Kcal	.5	.6	.4	.5	.5	.5	.5	.5
Active Body Mass (kg ABM) vs. Kcal	-.8	-.8	.3	-.8	-.8	-.5	-.8	-.8
Active Substance Index (AKS) vs. Kcal	-.2	-.2	.2	-.2	-.3	-.4	-.2	-.3

Note: Protein (P); Lipids (Lip); Carbohydrates (Car); Total Kilocalories (T. Cal).

Regarding the correlation between active body mass (ABM) and kilocalories during the first third, a strong inverse correlation was found with proteins (P) and lipids (Lip). The correlation with carbohydrates (Car) was low, while the correlation with total kilocalories (T. Cal) was strong and inverse. In the second third, fat percentage showed moderate direct correlations with proteins, lipids, carbohydrates, and total kilocalories.

For active body mass (ABM) in the second third, the correlation was strong and inverse with proteins, carbohydrates, and total kilocalories, while it was moderate and inverse with lipids.

Regarding the active substance index (AKS) during the first third, minimal correlations were observed with all macronutrients. These correlations were inverse for proteins and lipids but direct for carbohydrates. In the second third, the correlations remained low for all macronutrients.

Table 5. Body composition and caloric intake from macronutrients in outfield players.

Body composition	Baseline	End 1st third	End 2nd third	BL vs E1T (*p*-value)	BL vs E2T (*p*-value)	E1T vs E2T (*p*-value)
% Fat	10.3	10.0	10.5	.18	.34	.04
kg ABM	73.2	73.2	73.5	.46	.36	.29
AKS	1.30	1.30	1.30	.50	.47	.42
Protein (P)	809.99	809.99	847.3	-	.1	.1
Lipids (Lip)	1388.01	1388.01	1539.3	-	.05	.05
Carbohydrates (Car)	2572.46	2572.46	2795.8	-	.03	.03
Total calories (T. Cal)	**4770.45**	**4770.45**	**5182.5**	**-**	**.007**	**.007**

Note: BL = Baseline; E1T = End of the First Third; E2T = End of the Second Third. p-values result from paired t-tests. A dash (-) indicates no statistical test was performed due to identical values.

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Table 5 presents the body composition results of the outfield players. As shown, the mean body fat percentage was 10.3% at the beginning of the competition and 10.5% at the end. Analysis of active body mass (kg ABM) indicates that it remained stable at 73.0 kg across all measured time points. Similarly, the active substance index (AKS) maintained a consistent mean value of 1.30 throughout the three measurement periods, with no significant differences observed.

Table 6 presents the correlation analysis between body composition and macronutrient intake for outfield players. The results indicate that during the first third of the competition, fat percentage showed a low inverse correlation with protein (P), lipids (Lip), and total kilocalories (T. Cal), while demonstrating a low direct correlation with carbohydrates (Car). In the second third, the correlation remained low and inverse for proteins, carbohydrates, and total kilocalories, while no significant correlation was observed with lipids.

Regarding active body mass (ABM), moderate direct correlations were observed with proteins, lipids, and total kilocalories during the first third, while a minimal inverse correlation was found with carbohydrates. In the second third, correlations with proteins, carbohydrates, and total kilocalories were moderate, while lipids showed a minimal correlation.

Finally, the active substance index (AKS) exhibited a low correlation with proteins, a moderate correlation with lipids and total kilocalories, and a minimal correlation with carbohydrates during the first third. In the second third, correlations were low for all macronutrients.

Table 6. Comparison between body composition and macronutrient intake in outfield players.

Comparison	1st third of the competition				2nd third of the competition			
	P	Lip	Car	T. Cal	P	Lip	Car	T. Cal
Fat percentage vs. Macronutrient Kcal	-.3	-.3	.3	-.3	-.3	.0	-.3	-.3
Active Body Mass (kg ABM) vs. Kcal	.6	.6	-.2	.6	.5	.2	.5	.5
Active Substance Index (AKS) vs. Kcal	.4	.5	.1	.5	.4	.3	.4	.4

Note: Protein (P); Lipids (Lip); Carbohydrates (Car); Total Kilocalories (T. Cal).

DISCUSSION

The present study aimed to determine the correlation between the kilocalories provided by macronutrients and the body composition components of players from the Camagüey baseball team participating in the National Series. As previously stated, research directly correlating these specific variables in baseball players within this competition is scarce, which underscores the relevance of this investigation.

Catchers (Table 1) exhibited a decrease in fat percentage over the course of the competition that was not statistically significant according to the Student's t-test values. This aligns with findings by Wang et al. (2024), who reported no significant differences in body composition in the adolescent and adult population of China. This decrease could be related to the metabolic demands of their defensive role, compounded by games lasting two to three hours in the afternoon under direct sunlight. This result reinforces the thesis that the factors affecting body composition and physical condition are multifactorial, necessitating the individualization of both training and nutritional strategies (Tauda et al., 2025).

The initial fat percentage results for catchers at the start of the competitive season differ from those obtained for players in this position during the 62nd National Series, who showed a fat percentage of 11.83% (Mesa

et al., 2024). However, our findings are more similar to those reported by Sanga Dwi et al. (2024), where the mean fat percentage was 16.9%.

A comparison of the fat percentage results for catchers (Table 1), infielders (Table 3), and outfielders (Table 5) shows that catchers maintained higher fat levels than players in other positions. This supports the view that body composition development differs among athletes based on their playing position (Ceballos-Gurrola et al., 2020). Consequently, it is crucial to consider positional demands when creating nutritional strategies to ensure adequate energy availability during competition (Vázquez-Bautista et al., 2025).

We concur with Haq et al. (2025) that a reduction in fat percentage suggests that kilocaloric intake from macronutrients exceeded energy expenditure during competition for infielders and outfielders; however, this balance was not achieved for catchers.

The Active Body Mass (kg ABM) showed fluctuations from the beginning to the end of the second third, but no net increase in lean mass was observed. This indicates that individualized nutrient consumption needs were not fully met. We agree that if the specific needs of each catcher—based on game participation and individual characteristics—are considered, macronutrient intake can be optimized to support increases in muscle mass (Sanga Dwi et al., 2024). This approach allows for a synergy between the physical demands of the position and the athlete's individual profile, optimizing both preparation and in-game performance (Warneke et al., 2024).

The results of the Active Substance Index (AKS) showed that during the study period, infielders were the only group that managed to increase their results (Table 3), albeit not significantly. This suggests their macronutrient intake was more closely aligned with their needs, promoting muscular development, as macronutrients are essential for muscle growth (Sanga Dwi et al., 2024).

The assessment of the correlation between macronutrients and body composition for catchers (Table 2) reveals that the correlation between fat percentage and the kilocalories provided by proteins was not strong; therefore, changes in fat mass were not directly tied to protein intake.

However, a strong direct correlation was found with lipids, indicating that an increase in kilocaloric intake from lipids corresponded with an increase in fat percentage, or vice versa. This result suggests that the quantity of lipids consumed was sufficient to be utilized as an energy source during the competitive activities of these players (Di Corcia et al., 2022), who perform significant strength-endurance work.

A direct correlation was also noted between the total kilocalories provided by macronutrients and fat percentage, indicating these variables move in the same direction. This is a critical aspect that must be considered in nutritional planning.

Notably (Table 2), the correlation between the active body mass of catchers and protein intake was inverse, meaning that as one increased, the other decreased. While muscular development is known to be strongly related to adequate protein consumption (Sanga Dwi et al., 2024), the moderate strength of this inverse relationship suggests other factors were at play.

As shown in Table 1, there was a non-significant increase in caloric intake from proteins in the second third. In contrast, the intake of lipids, carbohydrates, and total calories increased significantly.

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In general, catchers exhibited strong correlations in the first third between body composition components and kilocalories from carbohydrates. In the second third, a strong correlation was found with lipids. Strong correlations were not consistently found between body composition components and total kilocalories from macronutrients, indicating that changes in body composition are not solely dependent on changes in macronutrient intake.

Infielders (Table 4) showed a direct correlation between fat percentage and macronutrients at both measured intervals. This means changes in fat percentage were responsive to changes in macronutrient intake, as nutrients are incorporated into the body and reflected in its composition (Ghiglione & López, 2022).

Infielders displayed an inverse correlation between active body mass (ABM) and lipids in both thirds. This indicates that as the values of this macronutrient increased, active body mass decreased, and vice versa. This association was moderate to strong. Therefore, it is necessary to systematically assess the needs for this macronutrient to regulate its intake to achieve physical development goals, adjusting nutritional loads to individual needs and the demands of the sport (Ramírez-Campillo et al., 2022).

It is noteworthy that active body mass (Table 4) had a low correlation with proteins, despite their known role in muscle tissue reconstruction. This necessitates a review of whether the nutritional provision was appropriate to determine if special dietary guidelines are needed (Di Corcia et al., 2022; Sanga Dwi et al., 2024).

Outfielders (Table 5) maintained stable values in their body composition components throughout the competitive period. This result indicates that macronutrient consumption maintained a metabolic balance with the energy expended during competition, which allowed for the maintenance of body composition and an adequate state of health for their athletic activity (Yaguachi-Alarcón et al., 2025).

The fat percentage of outfielders (Table 5) falls within the range suggested by the Division of Sports Science and Technology of the United States Olympic Committee, which states that for non-professional athletes, 11% adipose tissue is generally appropriate (Collins et al., 2021).

Outfielders (Table 6) showed a low correlation between fat percentage and macronutrients throughout the competition, with a direct relationship only with carbohydrates in the first third and with lipids in the second. This indicates that variations in body composition were not highly responsive to changes in macronutrient intake, and vice versa. Therefore, we agree that based on this result, the nutritional strategy should be refined to better target athletic performance conditions (Rebelo et al., 2025).

For active body mass (Table 6), the correlation in the first third was direct and moderate with proteins, lipids, and total calories, showing that as these macronutrients increased or decreased, ABM values followed suit. However, the correlation with carbohydrates was minimal and inverse. In the second third, proteins, carbohydrates, and total calories showed a moderate and direct correlation.

Regarding the Active Substance Index (AKS), the correlation was direct and moderate with lipids and total calories in the first third; while in the second, the correlation was low and direct in all cases.

It is observed across the tables (1, 3, and 5) that during the competition, players received a similar energy contribution from macronutrients, meaning that their specific positional demands were not a primary factor in

establishing the macronutrient consumption strategy. This individualization is essential for optimizing preparation during competition and enhancing recovery post-game.

As observed, the strength and direction of the correlation between macronutrients and body composition components were not constant across different time points because the kilocaloric intake was not constant, indicating that dietary provision lacked stability.

CONCLUSIONS

The results of the body composition components under study differ among the various playing positions, with catchers exhibiting the highest values for fat percentage, active body mass, and active substance index. It is significant to highlight that among the positions studied, catcher is the one with the highest energy demands.

The caloric intake from macronutrients showed no differences among players of different positions, leading to the conclusion that the implemented nutritional strategy did not take this aspect into account. A significant increase was observed between the first and second thirds for lipids, carbohydrates, and total calories.

The studied players only achieved strong correlations between body composition components and carbohydrates and lipids in the case of catchers. This pattern was not observed in the other positions. The classification of the correlation between macronutrients and body composition components was not consistent across different time points due to non-constant kilocalorie intake, indicating that the dietary provision lacked stability.

The results underscore the importance of monitoring and evaluating both macronutrient quantities and body composition to serve as indicators for designing strategies to maintain players' optimal health status during competition. Based on these findings, coaches should adopt relevant strategies to individualize caloric intake during the competitive season.

AUTHOR CONTRIBUTIONS

Conceptualization, L., and R.; methodology, L., and R., validation, L., B; formal analysis, R., and D. A; investigation, L., R. data curation, D .A. and A. J. All authors participated in the review and approval of the final manuscript, as well as in ensuring the integrity and accuracy of the content presented.

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During the preparation of this manuscript/study, the authors used https://chat.deepseek.com/ as an AI tool for the purpose of supporting the review and correction of writing and spelling. In this regard, the authors assume responsibility for the results and all overall content of this publication.

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ORIGINAL ARTICLE

The impact of physical activity participation on subjective well-being among middle-aged adults: The parallel mediating roles of perceived social fairness and aging anxiety

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ABSTRACT

The paper employs a large-scale dataset on physical exercise and subjective well-being in China to conduct an empirical analysis of the variables by using a national representative dataset of the society. Findings suggest the following: (1) physical exercise can be clearly shown to have significant positive effect on subjective well-being in middle-aged adults, (2) perceived social fairness and aging anxiety is shown to exhibit substantial mediating effects within the relationship that existed between physical exercise and subjective well-being, (3) demographic factors, such as gender, household registration, and educational level, are shown to have group differences in the specific pathways. The following policy suggestions can be offered: (1) the inclusion of sport participation space should be contributed to with an aim at making fairness perception well; (2) aged anxiety should be targeted by instituting interventions aimed at enhancing the conception of psychological resilience; (3) differentiated support strategies should be developed based on vulnerable groups; (4) institutional guarantee systems should be introduced to sustain participation; and (5) the cultural identity of the aging should be restructured to upgrade the concepts of values.

Keywords: Sport medicine, Physical exercise, Middle-aged adults, Subjective well-being, Perceived social fairness, Aging anxiety.

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INTRODUCTION

By the year 2023 the number of people aged 60 years or above in China is expected to be at 297 million which forms 21.1 percent of the total population of the country. This is a demographic shift that has made the issue of aging a high-priority socio-cultural matter and an important component of the national development program. In the 2023 report released by the China National Health Commission, it was stated that the elderly population would have exceeded 400 million in 2035 (which is over 30 percent of the total population) and thus clearly indicates the headlong rush towards a super-aged society. The improved happiness and fulfilment among older adults therefore has become a primary concern of the welfare of the people and a critical measure in the national action to the aging of the population.

Exercise has been generally recognized as an important factor of both physical and mental condition, and contributor to societal absorption. Empirical research proved that sports activities regularly lead to quality of life enhancement in various age and gender-based groups(Gill et al., 2013). A large amount of literature has established that there is a positive correlation between sports involvement and personal health(Bae, 2022; Balish, Conacher, & Dithurbide, 2016) , that support the positive impact of sports involvement in the lowering of social anxiety(Ustundag, Haydaroglu, Sayan, & Gungor, 2025), building up social capital(Biernat, Nalecz, Skrok, & Majcherek, 2020), and increasing life satisfaction(Dings & Spinath, 2024). A lot of the literature that exists however tends to favour either the younger or the older population and not necessarily between middle-aged cohorts. Moreover, the underlying mechanisms including physiological health, emotional control, and social connectedness have not been well investigated and differences between subgroups characterized by household registration (hukou) status or education level are rarely studied.

Using the biological, behavioural, and environmental factors in adopting a life-course perspective, aging is seen as a process that occurs over the whole lifespan(Cho, Martin, Poon, & Georgia Centenarian, 2015). In this regard, there is life-course approach to active age suggested by scholars who have stressed that interventions be enacted at early and middle life stages to counter health risks later in life(Foster & Walker, 2021). In line with this paradigm, the current research will consider the middle aged as the subject of the research to examine the mechanisms through which physical workouts affect subjective wellbeing among this group.

In order to fill these gaps, the present study applies the data collected in online survey using the Chinese General Social Survey (CGSS), 2021 to discuss the issue of the connection between frequency of exercising and self-reported well-being among middle-aged adults. In particular, the following research questions are established.

1. Do physical exercise and subjective well-being have a positive correlation among middle-aged adults?
2. How do the mechanisms of affecting the perceptions of happiness about individuals work on the background of physical activity?
3. Are these effects varying among subpopulations in terms of their health status, household registration and education level?

Answering these research questions, the current study contributes to the existing empirical knowledge in terms of active aging and provides evidence-based information about the possibility to improve well-being by means of involving in physical exercise. Additionally, the results have practical implications on the formulation of health promotion policies that target the ageing populations.

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Literature review and research hypothesis

Findings of impact of sports participation on well-being

Subjective well-being (SWB) is the overall judgment of life and living expressed by the individual in terms of his or her life satisfaction, moods, and meaning or sense in his or her life (Diener, 2012). A considerable amount of research has proven that the subjective wellbeing gives positive impacts on the physical and mental health outcomes. Precisely in the case of the older adult population, high subjective well-being has been associated with the reduced occurrence of long-term physical ailments, such as cardiovascular disease (CVD), diabetes, stroke, depression, cancer (Okely & Gale, 2016), and chronic lung disease (Stellar et al., 2015). Moreover, those who portray a greater level in subjective well-being would have more chances to participate in health-enhancing behaviours (Danner, Snowdon, & Friesen, 2001) and are in high levels of mental health status(De Souza, De Carvalho, & Ferreira, 2018).

The correlation of physical exercise and wellbeing has also been studied widely under various fields of study such as physiology, psychology, sociology, and economics (Balish et al., 2016; Woodman et al., 2009). Indicatively, Ruseski, et al (2014) determined that engagement in sporting activities is associated with high levels of well-being (Ruseski, Humphreys, & Hallmann, 2014). On the same note, a cross-sectional analysis conducted on 2,345 participants found that, there was a significant positive relationship between physical activity and life satisfaction as well as well-being among middle-aged and old individuals (An et al., 2020). Moreover, a randomization controlled trial revealed that a randomized regimen of Pilates exercises performed three times a week significantly improved the effects of depressive symptoms and well-being in the elderly (Ravari, Mirzaei, Bahremand, Raeisi, & Kamiab, 2021). As the evidence presented in favour of the positive correlation between an exercise regimen and subjective well-being is strong, the current study develops the following hypothesis:

H 1:Greater subjective well-being (SWB) is related to more frequent physical activity.

The intermediary role of perceived social equity

Perceived social fairness is the measure related to how individuals would assess the extent to which the allocation of societal resources is fair and equitable. Such idea involves judgements on what is right or fair on areas like the allocation of wealth and income, employment, and rights and treatment of rural-urban areas, pension and social security benefits (Gao & Zhao, 2021; Zhi et al., 2022). Empirical studies have shown that a continuous sense of injustice may give rise to strong negative emotion and make people more vulnerable to shape the negative or unforeseen consequences negatively, which impair both the physical and mental health. The effects are manifested through high levels of obesity and depression (Hunte & Williams, 2009; Meier, Semmer, & Hupfeld, 2009). In the equity theory introduced by Adams, (1963), people can have positive affective reactions when they view things as fair and negative emotional reactions when they view them as unfair (Adams, 1963). In line with empirical results on the association of increased perceptions of social fairness and better subjective well-being(Liu et al., 2021; Scarpa, Di Martino, & Prilleltensky, 2021), the current study presents the following hypothesis:

H 2: The subjective well-being of the individuals is positively related with their perception of social fairness.

Even though there are no direct empirical methods that can directly relate physical activity engagement to the perceived social fairness, the literature in this area indicates that regular exercise might enhance the perceived fairness of individuals in a variety of ways. In an illustration, exercise has been proved to increase physical and mental health along with encouraging social trust and prosocial behaviours (Di Bartolomeo & Papa, 2019) as well as perceived social support (Sui, Zhao, Na, Liu, & Zhang, 2024). Moreover, these health

and psychosocial resource influences linked to the exercise have been demonstrated to have positive influences on subjective well-being(Kim, Ryu, Lee, Kim, & Heo, 2021). Taking into consideration these results the following hypotheses are introduced:

H3: Perceived social fairness in frequent engagement in physical activity is positively related.

H4: Perceived social fairness acts as a beneficial mediator in the physical activity engagement to subjective wellbeing.

Mediating role of the aging concerns

Aging anxiety refers to the negative effects of emotions with respect to the aging process, such as fears of physical degradation, the freedom of action, fear of intellectual decline (Yawar et al., 2024). This construct represents fears of health decline, economic instability, and mental debilitation of individuals and can, thus, contribute to already existing negative stereotyping of ageing such as the assumption that loneliness and later life disability are inescapable, thus having a detrimental effect on perceptions of self-mental health (Lynch, 2000; Ramírez & Palacios-Espinosa, 2016). Empirical studies have shown that aging anxiety does not necessarily lead to a lowered subjective wellbeing, but actually can lead to further physical degradation, creating a vicious circle of effect of anxiety-health degradation precisely to the disadvantage of both physical and mental wellbeing (Lukaschek, Vanajan, Johar, Weiland, & Ladwig, 2017). Furthermore, according to Lukaschek, et al (2017), aging anxiety produced the greatest effect of the factors studied by influencing well-being negatively, and women were much more affected by this factor than men. Considering these findings, the given study has the following hypothesis:

H5: Aging anxiety has a negative and significant relationship between their subjective well-being and high levels of aging anxiety.

Socially, physical exercise has the potential to reduce anxiety of aging and to lead to improved life satisfaction, through improved social integration and reducing the sense of loneliness (de Oliveira, Souza, Rodrigues, Fett, & Piva, 2019; Yi & Hwang, 2015). Physiologically, exercise brings out the release of endorphins/neurotransmitters, which are associated with enhanced moods and suppression of stress, anxiety, and decrease depression symptoms, and hence it promotes relaxation and general wellness (Ferrer-Uris, Ramos, Busquets, & Angulo-Barroso, 2022; Goodwin & Stein, 2021). A recent literature review by Ewuzie and Aderinto (2024) further supported the idea that there are both the social and biological means that also reduce the level of anxiety among the elderly (Ewuzie, Ezeano, & Aderinto, 2024). On the ground of these insights, the hypotheses developed are as follows:

H6: When physical activities become more frequent, anxiety about aging becomes lower.

H7: There is an overall mediating role of anxiety in aging in the relationship between physical activity frequency and subjective well-being.

Several of the questions I have previously answered revolve around group differences in sports participation

The question of gender is one of the essential demographic factors of research on sports participation. Previous research has recorded the consistent increase in the rate of sports participation amongst men in relation to women (Moreno-Llamas & García-Mayor, 2022; Talebpour, Nazari Azad, & Kashani, 2019). However, to the contrary, a recent cross-sectional study of Chinese adults showed that the female gender was more inclined towards physical activity as compared with men and that the Han population was more

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likely to be involved in it as compared to ethnic minorities (Peng, Yang, Chang, & Liu, 2025). Regarding gender-related impacts, a study carried out in the United Kingdom showed that women who participate in athletics indicate greater amounts of well-being as compared to non-participants of the same sex with similar traits (McHale & Forrest, 2009). However, exercise is a factor in creating greater happiness in both genders, men seem to gain a greater level of happiness (Huang & Humphreys, 2010).

The effect of education level and the geographical area in sport participation has also been highlighted. There has been empirical evidence of people with higher education levels being more likely to engage in physical activity through the fact that education levels lead to increased awareness of health and appreciation of the positive effect of exercise (Hallmann, Breuer, & Beermann, 2023). Moreover, people in countryside are less interested in sports recreation than urban residents are (Chen et al., 2017). Taken together, the results of the most recent study that used the data provided by the China Social Survey estimated the relationships between sports participation and happiness empirically and showed that the positive advantages of engagement in physical activity towards well-being vary among different population subgroups (Li, Ning, & Xia, 2023).Taken together, the findings of the given studies mean that the mechanisms by which sports participation is related to happiness are statistically different between different population groups. Accordingly, we hypothesize:

H8: The pathways through which sports participation can influence the well-being of middle-aged adults are different based on gender and hukou status and educational level.

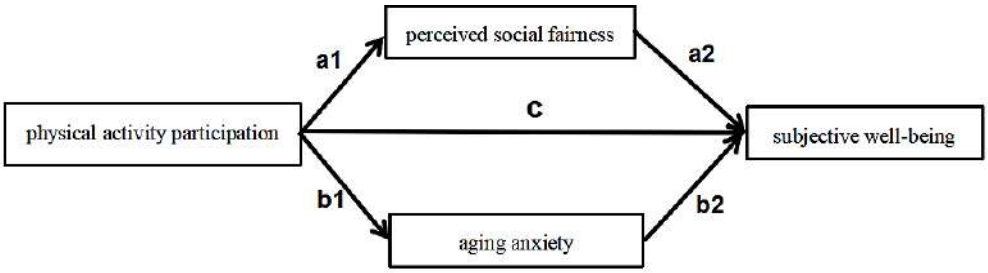


Figure 1. Research model flowchart.

RESEARCH DESIGN

Data source

The statistics used in this research were taken in 2021 as a result of the Chinese General Social Survey (CGSS). To select the sample population, a multi-stage stratified random sampling methodology was used. This survey covered 28 provincial-level administrative regions in China without considering the Xinjiang, Tibet, Hainan and the Hong Kong, Macao and Taiwan regions. The collected data were considered of excellent quality and representative following the rigorous quality control procedures. The demographic data, lifestyle, health status, and social attitude of the respondents were also sought through the survey instrument, which led to a final sample size of 8,148 people. To facilitate this study, the sample population was limited to people between the ages of 45 and 60 years. Having resolved missing data and reverse coded, and reclassified some variables, the analytic sample finally comprised 1,347 respondents.

Variable selection

This study has subjective well-being as the dependent variable. (1) The CGSS questionnaire can directly get subjective well-being. The question is A36 Overall, what are your general satisfaction with life? Points will be

rated as follows: "*Very happy*" = 5, "*Fairly happy*" = 4, "*Neither happy nor unhappy*" = 3, "*Fairly unhappy*" = 2, "*Very unhappy*" = 1.

An independent variable was used; participation in physical exercise. The question found in CGSS questionnaire; A30.9 How often do you exercise in your free time in the last one year? was inversed to provide an evaluation of participation. Options scoring was as follows; "*Every day*" = 5, "*Several times a week*" = 4, "*Several times a month*" = 3, "*Several times a year or less*" = 2, and "*Never*" = 1. Increased values were a sign of increased exercise.

These mediating variables are divided into two components: "*aging anxiety*" and the perceived social fairness. (1) In case with aging - related concerns, one uses the item E44 I worry that I will not be able to take care of myself when I am old). The answer options will have a mark of as follows: "*Completely disagree*" = 5, Disagree = 4, Neither agree nor disagree = 3, Agree = 2 and Completely agree = 1. The higher the scores, the less the aging-related apprehensions. (2) To the question of perceived social fairness, the question overall, how fair or unfair do you think the modern society is? is used. The following were the scores of the options; Completely fair = 5, Fair = 4, Neither fair nor unfair = 3, Unfair = 2, Completely unfair = 1. Such an increase in the score shows that the residents have a stronger sense of social fairness.

Table 1. Overview of sample distribution characteristics, n = 1347.

Category		**Frequency**	**Percentage**	**Cumulative percentage**
Gender	Male	626	46.5	46.5
	Female	721	53.5	100.0
Education Level	Junior high school or below	1098	81.5	81.5
	High school/ Technical secondary school	169	12.5	94.1
	College or above	80	5.9	100.0
Household Registration	Agricultural	1038	77.1	77.1
	Non-agricultural	309	22.9	100.0
Subjective well-being	Very unhappy	25	1.9	1.9
	Unhappy	74	5.5	7.3
	Neither happy nor unhappy	168	12.5	19.8
	Happy	720	53.5	73.3
	Very happy	360	26.7	100
Physical activity participation	Never	630	46.8	46.8
	Several times a year	121	9.0	55.8
	Several times a month	108	8.0	63.8
	Several times a week	155	11.5	75.3
	Daily	333	24.7	100
Aging anxiety	Strongly disagree	65	4.8	4.8
	Disagree	235	17.4	22.3
	Neither agree nor disagree	118	8.8	31.0
	Agree	568	42.2	73.2
	Strongly agree	361	26.8	100.0
Perceived social fairness	Completely unfair	65	4.8	4.8
	Fairly unfair	188	14.0	18.8
	Can't say it's fair but not unfair either	218	16.2	35.0
	Fairly fair	723	53.7	88.6
	Completely fair	153	11.4	100.0
	Total	1347	100.0	

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There were four demographic variables used including (1) Gender: 1s: male, 2s: female. (2) Education level 1 = lower secondary and below, 2 = upper secondary and vocation school and 3 = associate degree and higher. (3) Household registration: 1 agricultural, 2 non- agricultural. (4)Self rated socioeconomic status: Lower - middle is combined and rated 1, Middle rated 2, and Upper - middle/ upper rated 3. Table 1 displays the properties of sample distribution.

Statistical analysis

Statistical analysis was done using SPSS 20.0 and AMOS 24.0. The first one was the analysis of common method bias and multicollinearity via SPSS 20.0. After that, the fit and path coefficients of the structural equation model were tested with AMOS 24.0. Then, the mediating effect analysis was done by the Bootstrap methodology. Lastly, multigroup path analysis has been done concerning demographical variables.

RESULTS

Common method bias and collinearity

A single-factor test that was conducted by Harman was done before the analysis in order to achieve rigor. The first cause of variance, as shown by an unrotated principal component analysis of all the variables, was 37.01, which was less than the 40 percent mark. Also, all variable variance inflation factors (VIF), 1.0061.018, were significantly lower than 10 and did not cause any indication of intense common methods bias or multicollinearity.

Correlation analysis and descriptive statistics

Table 2 gives the means, standard deviations and Pearson correlation matrix of the variables. The findings showed that the frequency of exercise had a significant and positive association with perceived social fairness, perceived aging-related concerns, and perceived happiness, and also that perceived social fairness was associated with aged-related concerns and perceived happiness. These correlates facilitate the testing of hypotheses that follow.

Table 2. Descriptive statistics and correlations among variables, n = 1347.

Variable	Mean	Standard Deviation	1	2	3	4
Physical activity participation	2.58	1.701	1			
Perceived social fairness	3.53	1.137	.083**	1		
Aging anxiety	3.69	1.179	.069*	.046	1	
Subjective Well-being	3.98	.883	.167**	.335**	.121**	1

*Note: *p < .05, **p < .01,***p < .001.*

Model fit and path analysis

Structural equation modelling (SEM) was used to test hypothesized model, which involves a general test of model as well as a distance individual test on relationships between latent constructs. The outcomes showed that there is a good model data fit: CMIN /DF = 2.181, RMSEA = 0.030, CFI = 0.995, TLI = 0.967, NF I = 0.990, and it is possible to continue with the subsequent phases of analyses.

As illustrated in Table 3, the path analysis reveals that the physical exercise participation is directly positively predicted to perceived social fairness (-0.083, $p < .05$), aging-related concerns (-0.069, $p < .05$), and Subjective Well-being (-0.134, $p < .001$). There were also perceived social fairness and concerns about aging-related, which positively predicted Subjective Well-being using a direct effect (0.319, $p < .001$; 0.097, $p < .001$, respectively).

Table 3. Analysis of direct effects among overall variables, n = 1347.

Path	Estimate	S.E.	C.R.	*p* - Value	Label
Perceived social fairness <---physical activity participation	0.083	.016	3.059	.002	a1
Aging anxiety <---physical activity participation	0.069	.019	2.539	.011	a2
Subjective well-being <---perceived social fairness	0.319	.022	12.580	***	b1
Subjective well-being <---aging anxiety	0.097	.019	3.843	***	b2
Subjective well-being <---physical activity participation	0.134	.013	5.277	***	c

According to the model fit particularly, this research employed a bias corrected and non-parametric percentile bootstrap test to test out the mediating effects as well as to estimate confidence intervals. When the 95% interval fails to contain 0, then the indirect effect is said to be significant. Table 4 shows that perceived social fairness (95% CI: 0, 0.006) and aging anxiety (95% CI: 0.001, 0.007) were partially mediating the association between physical exercise and happiness. The two mediating effects combined three point two and four point six percent of the overall effect, respectively, and the difference between the two mediating effects of the two variables failed to give significant results ($p > .05$).

Table 4. Analysis of mediating effects, n = 1347.

Path	Mediating Effect	Proportion of Total Effect	95% Confidence Interval		
			Lower	Upper	*p* - Value
ind1:physical activity participation → perceived social fairness → subjective well-being	.002	3.2%	0.000	0.006	.014
ind2: physical activity participation → aging anxiety → subjective well-being	.003	4.6%	0.001	0.007	.014
Total Effect: ind1+ind2+c	.075		0.049	0.100	.001
Contrast Effect: ind1-ind2	-0.001		-0.004	0.001	.4

Multi-group path analysis of the effects of physical exercise on the elderly happiness

The result of the multi-group path analysis on demographic characteristics (gender, household registration, and the level of education) indicates that exercise is successful in improving the perceived social fairness of men but not women. Perceived social fairness and aging related issues increase happiness among rural inhabitants but this is not relevant to urban residents. Those people having junior high school education or lower will find exercising more advantageous. Perceived Social fairness affects Subjective Well-being among individuals who have a vocational or high school education. In case of people who have an associate degree or higher education, the direct and positive impact on Subjective Well-being was determined only by physical exercise. Table 5 provides the results of multigroup analysis.

Table 5. Results of multi-group analysis, n = 1347.

Category		a1	a2	b1	b2	c
Gender	Male	0.11**	**0.072**	0.341***	0.082*	0.157***
	Female	**0.051**	**0.055**	0.297***	0.107**	0.113**
Household Registration	Agricultural	0.064*	0.074*	0.341***	0.123***	0.085**
	Urban	0.17**	**0.02**	0.247***	**-0.007**	0.211***
Education Level	Low	0.076*	0.083**	0.335***	0.088**	0.126***
	Medium	**0.113**	-0.151*	0.29***	**0.053**	**-0.037**
	High	**0.116**	**0.006**	**0.119**	**0.2**	0.215*

*Note: *p < .05, **p < .01,***p < .001.*

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DISCUSSION

The direct impact of physical exercise on subjective well-being

Physical exercise enhanced the Subjective Well-being of middle-aged adults (β = 0.134, $p < .001$). This is in line with the analyses of many domestic and international scholars. Relevant studies have found a positive correlation between the subjective well-being of the elderly and their physical condition under the domain of physical function (Li et al., 2023; Patria, 2022). As the physical organs of the elderly gradually age and their self-care ability decreases, negative emotions such as helplessness and low self-esteem naturally reduce their Subjective Well-being (Baltes & Smith, 2003; Lara, Vazquez, Ogallar, & Godoy-Izquierdo, 2020). However, physical exercise can effectively improve the physical function of older adults and reduce negative emotions from both physiological and psychological perspectives. This study confirms the conclusions of previous research.

The mediating role of perceived social fairness and aging-related worries

Perceived social fairness (95% CI: 0.000, 0.006) and aging-related worries (95% CI: 0.001, 0.007) partially mediated the relationship between physical exercise and Subjective Well-being, accounting for 3.2% and 4.6% of the total effect, respectively. Physical exercise is an important means of promoting social equity (Adamson, Adamson, & Clarke, 2022). It mainly reconstructs social networks through participation in sports activities, enhances social capital, and thereby improves residents' sense of social fairness. Sui, Zhao and Liu (2023) empirically tested that participation in physical exercise significantly positively affects residents' sense of social fairness in China. Social fairness has also been shown to exert a significant positive influence on the subjective well-being of older adults (Sui, Zhao, & Liu, 2023). Physical exercise provides a platform for interaction, promoting contact and exchange among people of different sexes, occupations, and ages. This helps reduce stereotypes and prejudices, enhances social inclusiveness, and may improve the perception of fairness.

As age increases, social interaction decreases, and physical function declines, middle-aged adults gradually face the negative impacts of aging. However, physical exercise can enhance self-control over physical function and eliminate the interference of negative emotions, thereby effectively improving the Subjective Well-being of middle-aged adults. Asmundson, G. J, et al (2013)found that the elderly can promote communication and interaction with others by participating in various activities, reducing the likelihood of experiencing negative emotions such as loneliness, and thus having a higher level of Subjective Well-being (Asmundson et al., 2013). Older adults with higher levels of physical exercise can better enjoy life, improve their positive emotions, and reduce the generation of negative emotions (Powell, 2018). They can overcome age-related worries about future physical decline through a positive mindset and have a more positive evaluation of reality. Relevant research supports the existence of this mediating effect.

Heterogeneous analysis of the impact of physical exercise

Previous studies have noted that demographic and social characteristics, such as marital status, education level, occupation, and age, lead to differences in participation in physical exercise and its effects. This study further uses gender, household registration, and income as the basis for the multi-group analysis. Physical exercise can effectively enhance the sense of social fairness among males (β = 0.11, $p < .01$), but its impact on females' sense of social fairness is not significant (β = 0.051, $p > .05$), which is consistent with the findings of Sui et al.(2023). In terms of household registration, perceived social fairness (β = 0.074, $p < .05$) and aging-related worries (β = 0.123, $p < .001$) can effectively improve the Subjective Well-being of rural residents, while their impact on urban residents is not significant (β = 0.02, $p > .05$; β = -0.007, $p > .05$). The results also confirmed significant urban-rural differences in the impact of sports participation on residents' Subjective

Well-being in China. In terms of education level, physical exercise can effectively enhance the sense of social fairness among people with lower education levels and reduce aging-related worries, thereby increasing the Subjective Well-being of middle-aged adults. However, the effects were not significant for people with medium and higher education levels. Domestic and international research suggests that education level moderates sports participation, with higher education levels being associated with higher participation frequency and levels. This study divided educational levels into low, medium, and high groups to further analyse the differences in the mechanisms of sports participation among middle-aged adults. Fang et al (2024) conducted an empirical study based on CGSS (2010–2021) mixed cross-sectional data and found that sports participation has a more significant positive impact on the class identity of elderly people with lower education levels, while its positive impact on the class identity of elderly people with higher education levels is less obvious (Fang & An, 2024). This resonates with the findings of this study, indicating that the level of education is an important moderator of sports participation. Groups with higher education levels have relatively richer social resources; therefore, sports participation is not the only factor that enhances their sense of social fairness and Subjective Well-being. In contrast, groups with lower education levels have weaker risk resistance and higher demands for physical health; therefore, the promoting effects of sports are more significant.

CONCLUSIONS

As a reaction to the new global aging crisis, the subjective well-being of middle-aged adults has become the focus of the greatest pleasure of the society. This paper examined how physical exercise affects the subjective well-being of this group attribute based on the data of the China General Social Survey (CGSS). The relationship between physical exercise, perceived social fairness, aging-related concerns and happiness were empirically studied by the analysis. The main conclusions are as follows: First, there is a strong positive correlation between the frequency of physical exercise and subjective well-being among the middle-aged adults with higher levels of perceived well-being being associated with increased frequency of exercise. Second, physical exercise produces a direct influence on the subjective well-being as well as an indirect influence by increasing the sense of social fairness and reducing aging-related concerns. Third, it is interesting to note that the mechanisms by which physical exercise has an effect on subjective well-being differ significantly according to demographic characteristics, such as gender, degree of education, or status of household registration.

Implications

Theoretical implications

This paper extends the conceptual knowledge on the impact of physical exercise on the Subjective Well-being of middle-aged adults by affirming the concomitant mediation functions of perceived social fairness and age related concerns. This paper offers new findings to the research on health behaviours and social psychology.

To start with, it disrupts the one way health improvement pathway of the traditional theory of health promotion. This demonstrates that physical exercise has the capacity to enhance Subjective Well-being perception through rebuilding the social networks (e.g., increasing the perceived social fairness and mitigating aging-related concerns). This indicates that, the incorporation of a social-ecological approach along with the incorporation of structural social determinants (resource distribution as well as cultural values) should be incorporated in the health behaviour analysis model in future. Second, the assessment of the mediating role of aging-related concerns provided that physical exercise may improve the feeling of control over functions deterioration in individuals, diminish the presence of negative psychological expectancies, and transform the

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positive aging theory into the paradigm of active intervention rather than passive adaptation. Third, the analysis of the moderating effect of gender, household registration, and the educational level according to the social stratification theory presents their differences in terms of their effects. This verifies the structural limits of disparate access to resources opportunities to health behavioural outcomes and offers a theoretical foundation of the so-called social empowerment role of sports sociation and its compensation processes on the vulnerable populations. Lastly, the interdisciplinary validation of the physical exercise to perceived social fairness to Subjective Well-being is a favourable direction to combine the sociology of sports and positive psychology. It also takes into its accounts the social justice theory in health behaviour study by how institutional influences may determine health through individual perceptions and it presents a comprehensive explanation of how the Subjective Well-being generation processes in an aging society take place.

Practical implications

The multidimensional intervention approach can be used to effectively promote the Subjective Well-being of middle-aged adults with the help of physical exercise. Integrative sports engagement conditions are supposed to be applauded in an endeavour to fortify the incidence of fairness. The allocation of sports resources in the public should be optimized, the activities of interaction between the groups should also be designed, the policy of protection of the rights should be publicized. The measures may help to allow equal participation of various genders and household registration groups and increase the mediating effect of perceived social fairness. Aging-related concerns require specific interventions in order to increase psychological strength. Mental health services should be incorporated with the exercise prescriptions, and mutual-aid groups and intergenerational support networks developed in the community. Such programs may assist the middle-aged adults to overcome their anxiety about the decline of their functions via change mechanisms of science and psychology. Differentiation support measures will be applied in order to address the needs of the vulnerable groups of workers. As an illustration, the programs of low-intensity, social-oriented exercise interventions may be created in women, the plans of exercise simplification offered to rural and low-education populations, and adaptive courses offered to people having sub-health problems to address the psychological and physical barriers. The system of institutions should be enhanced to a sustainable level. Government performances should also provide the coverage level of community sports centres and the level of participation of middle aged and old citizens. The piloting of the policy of the sports-health integration should be provided and a dynamic database should be created to monitor the changes in the Subjective Well-being and perceived social fairness to guarantee the long-term efficiency of intervention measures. Lastly, cultural perceptions that are related to age ought to be transformed to promote the values. Stereotype of aging as decline can be dispersed by the media campaigns, and national senior sports competition brands could be developed in order to enhance group self-efficacy and social value recognition. This will eventually cause a system of happiness promotion which is an interaction between an individual, society and the institutions

AUTHOR CONTRIBUTIONS

Conceptualization, D.P., N.Z., and J.L.; methodology, D.P., N.Z.; software, D.P.,; validation, D.P., N.Z., T.C., and Z.M.; formal analysis, N.Z., Y.T., and T.C.; investigation, D.P., N.Z., Y.T.; resources, T.C., X.L., and Z.M.; data curation, T.C., and D.P.; writing — original draft preparation, D.P. and Z.M.; writing — review and editing, N.Z., and J.L.; visualization, Y.T., and T.C.; supervision, X.L. and J.L.; project administration, X.L.; funding acquisition, X.L. All authors have read and agreed to the published version of the manuscript.

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ORIGINAL ARTICLE

Study of the effect of FTO gene polymorphisms on physical performance indicators and the response to weight loss programs in obese athletes after a period of cessation of training

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ABSTRACT

Introduction. Polymorphisms in the fat mass and obesity-associated (FTO) gene, particularly the A allele, are associated with obesity and may reduce responsiveness to exercise programs. Investigating their effect on physical performance and weight loss in obese athletes after training cessation is important for tailoring effective interventions. Aim of Study. To examine the influence of FTO gene polymorphisms on physical performance indicators and weight loss outcomes in obese athletes following an 8–12-week structured training program after a period of inactivity. Material and Methods. Thirty obese Iraqi athletes (20–50 years) were genotyped for the FTO rs9939609 variant (AA, AT, TT) using PCR. Baseline and post-program assessments included body weight, BMI, body fat percentage, VO_{2max}, muscle strength, flexibility, and cardiac recovery rate. The training combined aerobic, resistance, flexibility, and balance exercises. Data were analysed using ANOVA with post hoc tests ($p < .05$). Results. TT genotype carriers had the greatest reductions in weight (−4.5 kg) and body fat percentage (−4.8%), and the largest improvements in VO_{2max} (+5.3 ml/kg/min), muscle strength (+4.6 kg), flexibility (+3.5 cm), and recovery rate (−12 bpm). AA genotype carriers showed the least improvement across all measures. Conclusions. FTO gene polymorphisms were associated with differential responses to weight loss and performance improvements, with TT carriers exhibiting the most favourable adaptations. Inco (Hashim et al., 2024, pp. 684-692) prorating genetic testing into training design may support the development of more individualized and potentially more effective exercise programs, particularly for individuals carrying the A allele. In practical terms, coaches and clinicians might consider adjusting training intensity and nutrition plans for A-allele carriers, focusing on enhancing metabolic flexibility and satiety signalling. The study was approved by the Research Ethics Committee of the University of Samarra, and all participants gave informed consent.
Keywords: Sport medicine, Physical performance, Weight loss, Aerobic training, TO gene, Genetic profiling.

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INTRODUCTION

As Ahmed, a promising young athlete, stared at his reflection in the gym's mirror, he felt a surge of determination mixed with anxiety. After months away from the track due to an ankle injury, the weight he had gained during the downtime now felt like an insurmountable obstacle. The once easy laps around the field now seemed daunting. This struggle is not unique to Ahmed; many people around the world use terms such as obesity, chubby, puffy, fleshy, and overweight to describe bioaccumulation in the body. These terms differ scientifically in their descriptions of this phenomenon (Al Daghri et al., 2014). This phenomenon is not limited to humans; it can also be observed in animal societies (Arendas et al., 2008). Obesity is a biological condition characterized by excess fat accumulation. This fat is rarely used as a source of energy due to reduced activity and individual tendencies to avoid movement, work, and environmental interaction (Andreasen et al., 2008 , Choi et al., 2005). The World Health Organization (WHO) considers obesity a major population health problem, describing it as a rapidly growing global epidemic of overweight people in many parts of the world (Claussnitzer et al., 2015).

A report by the Organization for Economic Co-operation and Development (OECD) indicates obesity rates ranging from 4% in Japan to 30% or more in the United States and Mexico (Farooqi, 2006). This phenomenon accounts for 1–3% of healthcare costs in most countries worldwide and 5–10% in the United States, amounting to approximately 25% of healthcare costs for a healthy individual. (The Economic Impact of Overweight & Obesity in 2020 and 2060 (2nd Edition).

In general, obesity has been associated with a medical condition requiring healthcare in most countries (Flynn et al., 2006). It is a social phenomenon resulting from overnutrition (Hiraike et al., 2021) and inactivity, as well as its association with the quality and quantity of food consumed. This differentiation can enhance the understanding of distinct drivers of obesity, paving the way for targeted interventions that address both genetic predispositions and lifestyle modifications.

Limiting the evaluation of this phenomenon to nutritional status is a weakness in scientific explanation, because the mechanisms of food (hunger and satiety) are subject to complex hormonal coordination and under the control of the central nervous system (Howard et al., 2008). These mechanisms operate under the influence of genetic factors in the normal state, and in many abnormal cases, obesity is unrelated to the nutritional process for various reasons, such as pathological, disease-related, medication-induced (Kim et al., 2016), or linked to psychological state and social prosperity (Leońska-Duniec et al., 2018). Obesity is a complex disease caused by a combination of genetic and environmental factors, and numerous studies have shown that genetic predisposition varies across ethnic groups (Manson et al., 1995).

The phenomenon of obesity has received widespread scientific attention since the late 20th century. Among the most important studies were those addressing the genetic basis of obesity, including the identification of specific genes and the mapping of the human genome (Mitchell et al., 2010, Morton et al., 2006). These studies looked at different groups of people like kids, women, and adults.

Besides the obvious environmental factors such as a fat-rich diet and sedentary lifestyle that cause obesity, genetic factors precipitate or make someone vulnerable to accumulating body fat. In this regard, one of the most scientifically validated is the Fat mass and obesity-associated (FTO) gene in its mutant forms like A allele which upregulates enzymes' expression among them alpha-ketoglutarate dependent dioxygenase changing energy metabolism into enhanced storage of fat (Neovius et al., 2009).

The FTO gene has recently turned out to become an area of increasing interest within the field of sports science, due to its potential implications on physical performance, body composition and response towards training and weight loss programs. Some researchers have identified that obese athletes may or may not benefit from training and nutritional programs based on their genetic makeup particularly genes related with metabolism and appetite regulation (Organization for Economic Co-operation and Development [OECD], 2012).

Athletes who return to training after a period of layoff due to any reason, health, injuries, or personal commitments provide an excellent model for genetic studies. Detraining can be considered as a 'stress test' for the effects of genotypes because it tests the ability of the body to maintain adaptations and performance in the absence of regular exercise stimuli.

Most commonly observed are losses in muscle mass accompanied by gains in fat mass together with decreases in aerobic capacity, strength, and endurance which effectively highlight the impacts of genetic predispositions. The knowledge about how much differences in the FTO gene affect these changes will guide more targeted interventions. Recent evidence shows that high-risk FTO variant carriers have reduced fat oxidation and energy conversion during exercise. This leads to worse training outcomes (Ponce-González et al., 2023). These individuals may also regain weight more easily after detraining, showing the need for individualized strategies.

Many studies have examined the effects of detraining on physiological variables. Based on these gaps, we aimed to analyse the effects of FTO gene polymorphisms on physical performance indicators and responsiveness to weight loss programs in obese athletes during a period of inactivity. The study seeks to aid genetically oriented sports and nutritional intervention program designs.

Aim of study

The present study has been designed with the following specific objectives: to determine the influence of FTO gene polymorphisms on physical performance parameters and effectiveness of weight loss programs in obese athletes after a period of training cessation, to find out the association between different variants of FTO gene with changes in body composition, aerobic capacity and muscle strength after a break in training.

1. Identify the connection between FTO gene variants and modifications in body composition, aerobic capacity, and muscle strength following a break in training.
2. Assess the influence of these genes on fat burning, energy efficiency, and predisposition for weight gain during and after organized training.
3. Establish scientifically proven personalized sports and nutritional strategies based on athletes' genotype to enhance weight-loss results as well as performance recovery.

This shall be the objective, therefore increasing knowledge on interactions between genes and exercise to support precision-based interventions concerning sports science as well as the management of obesity.
This study aims to investigate the influence of FTO gene polymorphisms on physical.

MATERIALS AND METHODS

FTO gene changes in relation to differences in physical performance and weight loss among obese athletes after training cessation were comparatively studied between May 2024 and October 2024, in Tikrit and Samarra/Iraq. Participants were selected by the most standardized method of selection procedures

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accompanied by baseline assessments before starting the actual training program or intervention (gene analysis). All assessments had been conducted at least two weeks prior to commencing any form of structured physical activity so as not to allow for acute effects resulting from previous exercises on measured parameters. The study is quasi-experimental because there has been no random assignment of subjects into different groups; hence it can also be classified under comparative studies.

Study participants

The research was carried out from May 2024 to October 2024. It covered both males and females with obese bodies who stopped training for not less than three months, collected from different sports centres in Tikrit and Samarra. Thirty participants were selected according to the WHO classification criteria of BMI for obesity. The comparisons made in the research design were only within the same sample between genotypes (AA, AT, TT), without any separate control group.

The inclusion criteria were:

- Age between 20–50 ± 2 years.
- No history of cardiovascular disease, diabetes, or genetic
- disorders unrelated to obesity.
- No use of weight-loss medications.

A structured questionnaire was used to collect demographic and training-related information from all participants.

The sample size (n = 30) was determined as the minimum required to detect genotype-related differences in physiological and anthropometric variables, with a statistical power of 0.80 and a significance level of $p \leq .05$, consistent with previous studies examining FTO polymorphisms in athletic populations. Effect sizes were calculated using eta squared (η^2) to determine the magnitude of genotype-related differences, with values interpreted according to established thresholds (small: 0.01, medium: 0.06, large: 0.14). Baseline and post-intervention anthropometric characteristics of participants according to FTO genotype are presented in Table 1.

Table 1. Baseline and post-intervention anthropometric characteristics of participants according to FTO genotype (mean ± SD).

Risk of developing health problems	BMI category (kg/m²)	Classification
Increased	18.5 and below	Slim
Least possible	18.5 – 24.9	Normal weight
Increased	25 – 29.9	Overweight
High	30 – 34.9	Class I obesity
Very high	35 – 39.9	Class II obesity
Excessive	40 and above	Class III obesity

Statistical analysis

Data were analysed using SPSS version 26.0. The normality of distribution was assessed using the Shapiro–Wilk test, and Levene's test was applied to confirm the homogeneity of variances. Differences between the three genotypes (AA, AT, TT) were evaluated using one-way ANOVA followed by Tukey's post hoc test. Pre- and post-training comparisons within each genotype group were determined using paired-sample t-tests.

Effect sizes were reported using partial eta-squared (η^2) to determine the magnitude of differences. Statistical significance was set at $p < .05$ for all tests.

Collection of personal and baseline data

A standardized questionnaire was used to gather:

- Age (years).
- Gender.
- Type of specialized sport prior to cessation.
- Duration of cessation from training (weeks/months).
- Duration of gradual return to training prior to the research program.

Baseline physiological and physical assessments

Before the training program, all participants underwent the following measurements:

- Anthropometric Measurements:
  - Weight (kg).
  - Height (cm).
  - Body Mass Index (BMI) is calculated as weight (kg) divided by height² (m²).
  - Body fat percentage using a body composition analyser (e.g., InBody).

Physical performance indicators

- Aerobic endurance: measured via maximum oxygen consumption (VO_{2max}) test.
- Muscular strength: assessed using handgrip dynamometry.
- Flexibility: assessed using the sit-and-reach test.
- Cardiac recovery rate: measured as heart rate recovery one minute after aerobic exercise.

Genetic analysis of FTO gene polymorphisms

Genotyping of the FTO rs9939609 polymorphism was performed using polymerase chain reaction (PCR) followed by allele-specific analysis. DNA was extracted from peripheral blood samples using a commercial extraction kit (Qiagen, Germany), and PCR amplification was conducted in a thermal cycler using the following conditions: initial denaturation at 95°C for 5 minutes, 35 cycles of 95°C for 30 seconds, 58°C for 30 seconds, and 72°C for 45 seconds, followed by a final extension at 72°C for 5 minutes.

Training program intervention (8–12 Weeks)

Grouped according to genotype, participants underwent a standardized training program as follows:

- Cardio workouts: brisk walking, stationary cycling, and light jogging.
- Strength training: free weights or resistance machines.
- Flexibility and balance training: dynamic and static stretching exercises.

The program ran three times weekly for a period between eight and twelve weeks with each session within sixty to seventy-five minutes. Participants, grouped according to genotype, underwent a standardized training program. In the first weeks, exercises were conducted at sixty to seventy-five percent of the maximum heart rate gradually increasing intensity in succeeding weeks as explicitly guided by individual enhancements.

Post-program measurements

Upon program completion, all baseline measurements were repeated:

- Anthropometric indicators (weight, BMI, body fat percentage).
- Physical performance indicators (VO_{2max}, strength, flexibility, recovery rate).

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- Comparison of pre- and post-intervention values among different genotype groups.

Ethical considerations

The study was approved by the Research Ethics Committee, College of Physical Education and Sports Sciences, University of Samarra, Iraq (Form Number: 4; Decision Date: September 16, 2025), and conforms to institutional ethical standards and the principles laid down in the Declaration of Helsinki. Written informed consent was obtained from all participants before their enrolment in the research that took place from May 2024 until October 2024.

RESULTS

The results registered improvements in the values of all physical performance indicators after the training intervention, depending on the three FTO genotypes (AA, AT, TT). Genotype distribution Genetic analysis showed genotype distribution among participants for polymorphism FTO (rs9939609) as follows:

- AA genotype: 10 participants (33.3%).
- AT genotype: 12 participants (40%).
- TT genotype: 8 participants (26.7%).

Table 2. Arithmetic means for weight and fat percentage.

Genotype	Fat % Before	Fat % After	Change (%)	Weight Before (kg)	Weight After (kg)	Change (kg)
AA	33.5 ± 2.4	31.8 ± 2.6	−1.7	84.2 ± 3.1	81.5 ± 3.4	−2.7
AT	32.1 ± 2.0	28.5 ± 1.9	−3.6	82.6 ± 2.9	78.4 ± 2.5	−4.2
TT	30.8 ± 1.7	26.0 ± 1.5	−4.8	80.1 ± 3.0	75.6 ± 2.8	−4.5

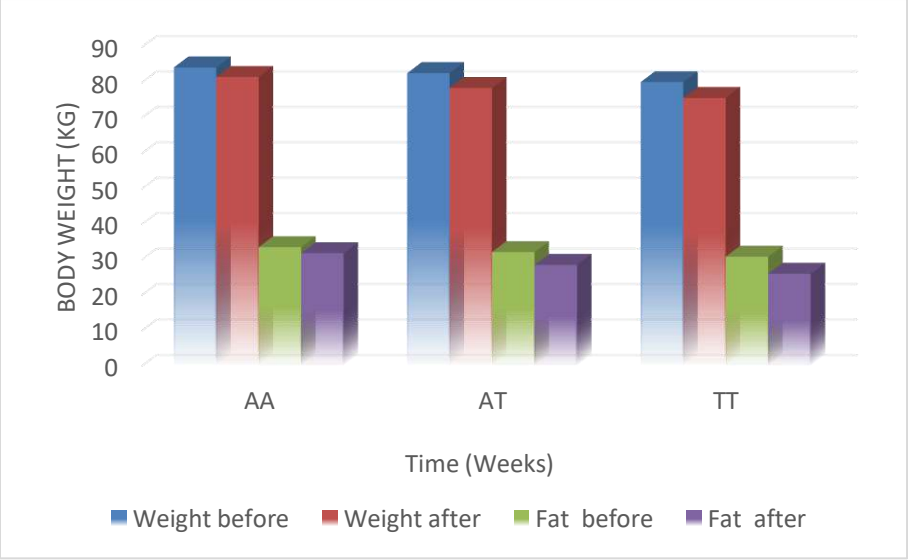


Figure 1. Changes in body weight and fat percentage across FTO genotypes before and after the intervention.

This pattern is consistent with reports in Arab populations where the A allele is relatively prevalent among individuals with obesity. In particular, studies involving Iraqi populations reveal a similar trend, highlighting the role of genetic predisposition in regional obesity rates. Such prevalence may reflect an underlying genetic predisposition to weight gain in the sampled population.

Changes in weight and fat percentage

Pre- and post-intervention values for weight and fat percentage are presented in Table 2 and illustrated in Figure 1.

- TT genotype participants achieved the greatest reductions, with decreases of −4.5 kg in body weight and −4.8% in body fat.
- AT genotype participants followed, with reductions of −4.2 kg and −3.6%, respectively.
- AA genotype participants showed the smallest changes (−2.7 kg and −1.7%).

The trend indicates that TT carriers exhibit the most favourable response to body composition interventions, whereas AA carriers display a comparatively resistant profile, potentially linked to allele-specific regulation of FTO expression and energy homeostasis (Rahimi & Symonds, 2025).

Physical performance enhancements

The effects of the intervention on VO_{2max}, muscle strength, flexibility, and recovery rate are presented in Figure 2 and summarized in Table 3.

Table 3. Post hoc comparisons.

Variables	Comparison	Mean Difference	SE	*p*-Value	Significance
Weight	AA vs AT	1.6	0.65	.023	$p < .05$
	AA vs TT	2.1	0.70	.010	$p < .05$
	AT vs TT	0.5	0.68	.450	Not significant
Fat Percentage	AA vs AT	1.4	0.55	.018	$p < .05$
	AA vs TT	2.3	0.60	.005	$p < .01$
	AT vs TT	0.9	0.58	.120	Not significant
VO_{2max}	AA vs AT	1.3	0.50	.030	$p < .05$
	AA vs TT	1.9	0.53	.008	$p < .01$
	AT vs TT	0.6	0.52	.380	Not significant
Muscle Strength	AA vs AT	1.1	0.58	.060	Not significant
	AA vs TT	2.4	0.62	.012	$p < .05$
	AT vs TT	1.3	0.60	.100	Not significant
Flexibility	AA vs AT	1.3	0.54	.080	Not significant
	AA vs TT	2.8	0.57	.005	$p < .01$
	AT vs TT	1.5	0.56	.090	Not significant
Recovery	AA vs AT	6.0	2.10	.040	$p < .05$
	AA vs TT	8.0	2.30	.020	$p < .05$
	AT vs TT	2.0	2.20	.300	Not significant

VO_{2max}

- TT genotype: +5.3 ml/kg/min.
- AT genotype: +4.4 ml/kg/min.
- AA genotype: +2.4 ml/kg/min.

Muscle strength (hand grip)

- TT genotype: +4.6 kg.
- AT genotype: +3.7 kg.
- AA genotype: +2.3 kg.

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Flexibility
- TT genotype: +3.5 cm.
- AT genotype: +2.7 cm.
- AA genotype: +1.9 cm.

Recovery Rate (decrease in heart rate one minute after exercise cessation)
- TT genotype: −12 bpm.
- AT genotype: −10 bpm.
- AA genotype: −8 bpm.

The results show a clear interaction between genotype and performance, with TT carriers showing greater improvements in both aerobic and strength training adaptations. AA carriers showed minimal improvements, mainly in aerobic endurance and cardiac recovery.

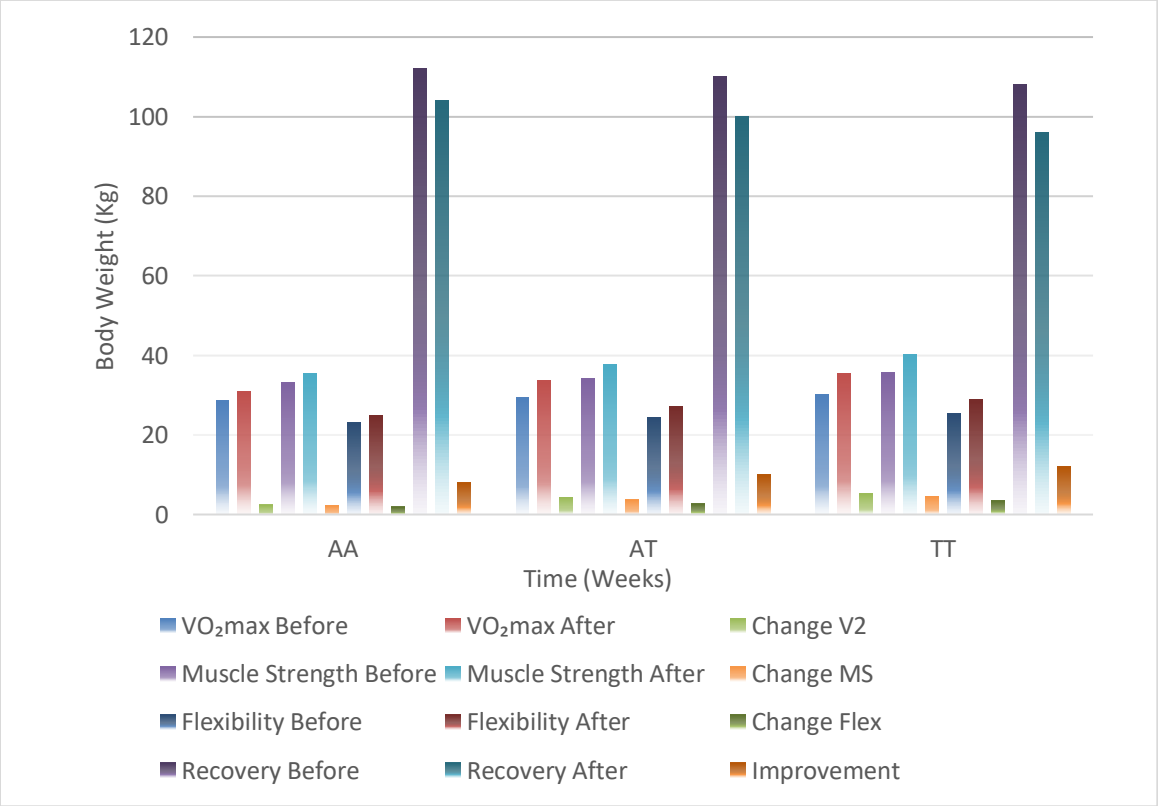


Figure 2. Pre- and post-intervention differences in VO_{2max}, muscle strength, flexibility and recovery rate across FTO genotypes.

Post hoc comparisons

Pairwise comparisons between genotypes were performed for all measured variables (Table 3).

Weight & fat percentage

Post-intervention weight in the AA group was observed to be significantly higher than both the AT (p = .023) and TT (p = .010) groups. Similarly, fat percentage remained significantly higher in AA participants compared

to AT (p = .018) and TT (p = .005). No significant differences were observed between AT and TT for these variables.

Aerobic capacity (VO_{2max})
The increase in VO_{2max} was much TT than AA (p = .008) and AT (p = .030). There was not AT and TT.

Muscle strength
TT carriers showed a significantly greater increase in muscle strength than AA (p = .012), while the differences between AA–AT and AT–TT were not statistically significant.

Flexibility

- TT carriers showed markedly greater improvements in flexibility than AA carriers (p = .005). No other genotype pairings reached statistical significance.
- Recovery Rate: Recovery rate improvement (lower heart rate after 1 minute) was significantly better in TT compared to AA (p = .020) and in AT compared to AA (p = .040). Differences between AT and TT were not significant.

Overall Interpretation: There were significant benefits to all genotypes but most TT, in a comparative analysis table of results on weight or fat lost, and VO_{2max} or muscle strength and flexibility gained or recovery rate improved. Least benefited was the AA genotype, thus making quite a strong case for the earlier supposed theory that probably it is the A allele which attenuates responsiveness to exercise- and diet-based interventions; possibly through its metabolic and appetite-regulating effects.

DISCUSSION

Variation in response to weight loss between genotypes

The results of this study showed that participants with the TT genotype recorded greater decreases in both body weight and body fat percentage followed by AT genotype while AA genotype carriers displayed outcomes which were least favourable hence suggesting a variability on responsiveness to intervention for loss of weight by genotypes where A allele may probably be associated with reduced signalling for satiety as well as poor regulation on energy (Morton et al., 2006 , Ponce-González et al., 2023).

Anthropometric indicators between AT and AA carriers were significantly different in favour of the TT group, consistently with much other literature, for example, a large meta-analysis review that included 30 studies comprising 46,976 subjects. Better weight loss results among people with the TT genotype involved in structured exercise and diet interventions were reported (Rankinen et al., 2010).

Improvements in physical performance indicators

There were increases in VO_{2max}, strength, flexibility and recovery time for all genotypes but the most TT carriers showed the highest magnitude of changes. This is partly consistent with results from the DREW trial which found genotypic differences related to weight loss but no significant differences in cardiorespiratory fitness improvements across groups (Mitchell et al., 2010 , Tsigos et al., 2008).

Exercise as a modifier of gene environment effects

Evidence from large-scale studies indicates that moderate physical activity can attenuate the negative effect of the FTO risk allele on body weight. For example, a Taiwanese cohort study (n = 20,906) reported that regular exercise significantly reduced the weight gain effect associated with FTO polymorphisms ($p \approx .03$)

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(Hiraike et al., 2021). These results align with our findings, which show that structured training programs reduced genetic disadvantage across all genotype groups.

Role of an allele in resistance to interventions

Previous research suggests that the A allele is associated with greater fat mass and reduced responsiveness to exercise-based interventions (Farooqi, 2006 , Walley et al., 2009). For instance, individuals with the AA genotype often fail to exhibit significant fat loss after resistance training. The present findings are consistent with this evidence, as the AA group in our cohort demonstrated smaller improvements across most outcome measures.

Metabolic adaptations during exercise

Our results also align with studies indicating that TT carriers have a higher fat oxidation capacity during exercise compared to AT and AA carriers, as well as differences in post-exercise appetite regulation (p = .004–.049) (Ponce-González et al., 2023) . This greater metabolic flexibility may explain the superior body composition and performance outcomes seen in the TT group.

Physical activity gene interaction

The broader literature supports the notion that moderate physical activity can reduce the negative metabolic effects of the A allele (Kim et al., 2016 , Yanagiya et al., 2007). Consistent with this, our data showed meaningful improvements in all genotype groups, although the magnitude of improvement was attenuated in A-allele carriers.

Summary interpretation

The results demonstrated and confirmed the previous assumption of a major role that FTO gene polymorphisms play in the responsiveness of obese athletes to weight loss and physical performance enhancement programs, particularly the A allele. TT carriers expressed more favourable outcomes, structured exercise interventions reported benefits for all genotypes. How personalized should post-detraining programs be? Answering this question could help us bridge genetic evidence to practical application: how personalized interventions could optimize exercise benefits? This fact brings to light an important message for policymakers or practitioners who are hesitant about prescribing exercises as part of a weight management program due to someone's "*unfavourable*" genetic profile.

Limitations

The sample size is relatively small, involving only one population where results might be generalizable and the intervention period was short to allow any long-term evaluation of adaptations based on genotypes. Other genetic factors except for the FTO polymorphism were not assessed; dietary intake was reported rather than controlled. Studies recommended to further validate and explore these findings should have larger cohorts with controlled nutrition over an extended follow-up period.

CONCLUSIONS

The findings of the study demonstrated a relationship between FTO gene polymorphisms and reduced response to weight loss programs as well as improvements in physical performance, mainly detailing the effects observed among participants with AA and AT genotypes . Those having TT genotype showed results much positively compared to their counterparts with AA genotype who registered results mildly progressive thus associating an allelic form probably responsible for inefficient fat metabolism(apparent lack control over appetite).

Results support the possibility of genetic screening as an added component in the planning process for training and weight management programs, hence partly personalizing training interventions to optimize results based on individual genotype profile. Well-planned aerobic and resistance exercise seems to overcome some metabolic handicaps found more frequently among A allele carriers.

Despite the differences related to genotype, all of them showed improvements that were measurable at the end of the training program. This again emphasizes exercise as an effective intervention towards improved body composition and physical performance across genetic backgrounds.

Future studies should be conducted on a larger and more varied sample to confirm the associations between genotypes and exercises discovered in this study. Long interventions assessing adaptations over a longer term should also be conducted. Hormonal and inflammatory markers ought to be included for better understanding of the biological pathways connecting FTO variants with metabolic as well as performance outcomes.

These guidelines may further develop scientifically exact prescription training through the adjustment of training techniques in attaining maximum weight loss, and also improvement of performance gains among various genotypes. Genetic screening is recommended for coaches and policymakers at large to make their interventions more effective, hence making a step toward results that are more individualized as well as successful both athletes and patients.

AUTHOR CONTRIBUTIONS

Saif Rasheed Ghanim: conceptualization of the study, study design, data collection, supervision of experimental procedures, statistical analysis, and drafting of the original manuscript. Ammar Faris Atiyah: participation in data collection, implementation of the training program, and assistance in data interpretation. Ahmed Mahmood Mahdi: laboratory work related to genetic analysis, data validation, and contribution to the methodology section. AlSeddiq Oday Latof: scientific consultation, critical revision of the manuscript, methodological guidance, and final approval of the manuscript for submission. All authors have read and approved the final version of the manuscript and agree with its submission and publication.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL APPROVAL

This study was reviewed and approved by the Research Ethics Committee of the College of Physical Education and Sports Sciences, University of Samarra, Iraq (Approval Form No. 4; Decision Date: 16 September 2025). All research procedures were conducted in accordance with institutional ethical standards and the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants prior to their inclusion in the study. Data collection was carried out between May 2024 and October 2024.

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ARTIFICIAL INTELLIGENCE AND SIMILARITY CHECK STATEMENT

The authors confirm that no generative artificial intelligence tools were used in the creation, fabrication, or manipulation of the scientific content, data, or results of this manuscript. Automated tools were used solely for language checking and proofreading purposes. A similarity check was conducted using Turnitin, and the overall similarity index was below 20%, in compliance with the journal's ethical and editorial requirements.

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ORIGINAL ARTICLE

Shorter sprints, greater gains? Effects of sprint duration on soccer physical performance

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ABSTRACT

Purpose: To examine the effect of sprint bout duration during speed-endurance training on soccer-specific performance. Methods: Sixteen male soccer players (18.0 ± 0.8 y; 179.9 ± 4.8 cm; 71.4 ± 6.6 kg) completed two training protocols for 4 weeks, twice weekly: 10-s sprints (SEP10; n = 8) or 20-s sprints (SEP20; n = 8). SEP10 involved 8–12 × 10-s all-out runs with 60-s rest; SEP20 involved 4–6 × 20-s all-out runs with 120-s rest. Before and after training, players performed 20- and 200-m sprints, a repeated-sprint ability (RSA) test, and the Yo-Yo intermittent recovery test level 2 (Yo-Yo IR2). Sprint time, blood lactate, and GPS data were collected during training sessions. Results: RSA total time decreased by 1.1% (SEP20) and 1.5% (SEP10; $p < .05$). Yo-Yo IR2 performance improved by 10% (SEP20) and 16% (SEP10; $p < .05$). Shorter sprint duration (10 vs. 20 s) elicited higher power output and lower blood lactate. Conclusion: Both 10- and 20-s sprint-based training improved high-intensity performance and RSA in soccer players, with 10-s sprints inducing more favourable physiological responses.

Keywords: Performance analysis, Speed-endurance training, Sprint duration, Soccer performance, Repeat sprint ability (RSA), Yo-Yo intermittent recovery test.

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INTRODUCTION

In elite soccer, the increasing number of matches limits the time available for physical conditioning during the competitive season. Training is often prioritized toward recovery and technical–tactical preparation rather than physical development (Anderson et al., 2016; Malone et al., 2015; Martín-García et al., 2018; Simonelli et al., 2025; Trecroci et al., 2019). Under these constraints, selecting the most effective training stimuli is crucial to maximize physiological adaptations and performance outcomes.

Speed-endurance training using repeated sprints (5–30 s) has emerged as a time-efficient strategy to enhance supramaximal performance (Bangsbo et al., 2009; Gibala et al., 2006; Iaia & Bangsbo, 2010; Iaia et al., 2009), repeated-sprint ability (RSA) (Iaia et al., 2015; Mohr & Krustrup, 2016), and high-intensity intermittent exercise in well-trained athletes (Iaia et al., 2008), even with reduced overall training volume (Bangsbo et al., 2009; Gunnarsson et al., 2012; Iaia & Bangsbo, 2010; Iaia et al., 2009). However, the wide range of possible training variables (e.g., intensity, recovery, exercise type, and work-to-rest ratio) can elicit distinct physiological responses. For example, speed-endurance production (SEP) training, characterized by ~20-s all-out sprints with long recoveries, has been shown to improve RSA and intermittent high-intensity performance (Castagna et al., 2017; Iaia et al., 2015; Mohr & Krustrup, 2016). Moreover, the efficacy of this training modality is possibly ascribed to the maintenance of high mechanical power (Iaia et al., 2015), and adaptations in glycolytic (MacDougall et al., 1998) and oxidative enzymes activity (Burgomaster et al., 2006; Burgomaster et al., 2005; Granata et al., 2017) as well as in pH regulation (Iaia et al., 2008) and ion transport (Bangsbo et al., 2009; Iaia et al., 2008).

While there is consensus that longer recovery intervals enhance soccer-related performance (Castagna et al., 2017; Iaia et al., 2015; Mohr & Krustrup, 2016), the effect of sprint duration remains less clear. Evidence indicates that both short (≤10 s) (Iaia et al., 2017) and longer (≥20 s) (Iaia et al., 2015) sprint bouts can improve performance, albeit through different metabolic pathways (Buchheit & Laursen, 2013a). Longer sprints increase anaerobic energy production and cardiopulmonary responses (Fiorenza et al., 2019), whereas shorter sprints elicit higher power output, reduced lactate accumulation, and less peripheral fatigue, potentially allowing faster recovery (Buchheit & Laursen, 2013a). Furthermore, short sprints have been associated with greater improvements in sprint times over 20–40 m (Iaia et al., 2017; Iaia et al., 2015; Mohr et al., 2007a).

Despite these observations, direct comparisons between short and long sprint durations in soccer players are lacking. Most studies have focused on aerobic outcomes (e.g., $\dot{V}O_{2max}$, endurance performance), with inconsistent results. Some report superior adaptations with longer sprints, while others show that reducing sprint duration to 10–20 s yields comparable improvements in both aerobic and anaerobic markers (Gillen et al., 2016; Gillen et al., 2014; Hazell et al., 2010; McKie et al., 2018; Nalcakan et al., 2018; Yamagishi & Babraj, 2017; Zelt et al., 2014).

Therefore, the present study aimed to (i) compare the physiological and mechanical responses to sprint training with different bout durations (10 vs. 20 s), and (ii) examine the subsequent effects on soccer-specific performance. Based on previous evidence (Iaia et al., 2017; Iaia et al., 2015; Mohr et al., 2007b), we hypothesized that shorter bouts (10 s) would improve repeated-sprint performance, whereas longer bouts (20 s) would provide a stronger stimulus for exhaustive high-intensity performance.

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METHODS

Participants

Sixteen young male soccer players from the same amateur team (age: 18.0 ± 0.8 y; height: 179.9 ± 4.8 cm; body mass: 71.4 ± 6.6 kg) were recruited. All participants had a minimum of 7 years of soccer training experience. Participants and their parents provided written informed consent after being fully briefed on potential risks and discomfort associated with the experimental procedures. The study was approved by the Ethical Committee of the University of Milan and conducted in accordance with the Declaration of Helsinki.

Experimental approach

A parallel, pre-to-post, two-group, work-matched longitudinal design was employed to examine the effects of two speed-endurance training protocols. Participants were matched based on baseline physical performance and randomly assigned to either the 20-s sprint protocol (SEP20; n = 8) or the 10-s sprint protocol (SEP10; n = 8). Randomization was based on performance scores derived from all baseline tests, with each participant assigned a score from 1 (lowest) to 16 (highest) for each test; the sum determined group allocation.

Data collection occurred during the final phase of the competitive season (April–May) and included a familiarization period, 1 week of baseline testing (Pre), a 4-week training intervention, and 1 week of post-testing (Post). Performance tests included: (i) aerobic fitness (Mognoni test), (ii) 20-m sprint, (iii) repeated-sprint ability (RSA) test, (iv) 200-m sprint, and (v) Yo-Yo Intermittent Recovery Test Level 2 (Yo-Yo IR2). During the 2nd and 8th training sessions, internal load was monitored via heart rate (HR), blood lactate ([La^-]), and session rating of perceived exertion (sRPE), while external load was tracked using GPS technology.

Training protocols

SEP10 consisted of 6–12 repetitions of 10-s all-out bouts (2 × 30-m shuttle runs) interspersed with 60-s of passive recovery. SEP20 comprised 3–6 repetitions of 20-s all-out bouts (3 × 40-m shuttle runs) with 120-s of passive recovery. Both protocols were matched for total work and performed twice weekly over 4 weeks (Figure 1).

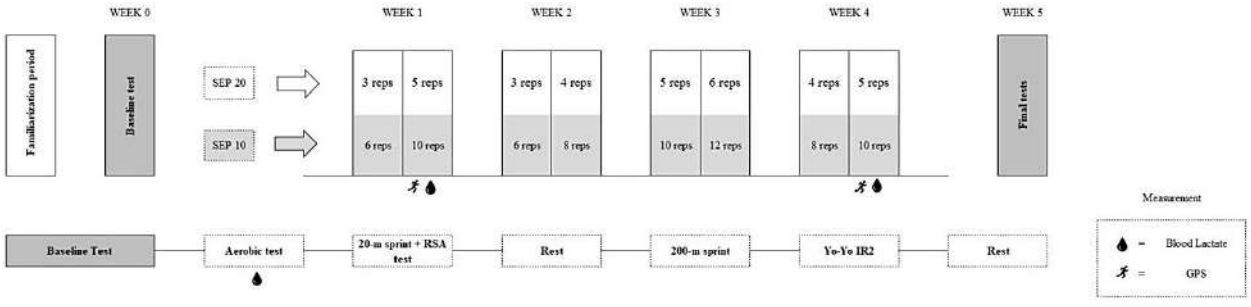


Figure 1. Overview of experimental days and training. Speed endurance production training 20 s of sprint (SEP 20), Speed endurance production training 10 s of sprint (SEP 10), Repeated sprint ability test (RSA), Yo-Yo intermittent recovery Test level 2 (Yo-Yo IR2), Repetitions (Reps).

Training monitoring

During the 2nd and final training sessions, blood samples were collected from the earlobe at specified points: before the 5th and after the 1st, 2nd, 3rd, and 5th bout in SEP20, and before the 10th and after the 1st, 4th,

6th, and 10th bout in SEP10. Lactate concentration ([La^-]) was analysed using a portable lactate analyser (Lactate Plus, Nova Biomedical, Waltham, MA, USA). Sprint times were recorded via photoelectric cells (Witty, Microgate, Bolzano, Italy).

GPS collection and analysis

External load was tracked using GPS units (10 Hz, 400 Hz tri-axial accelerometer; Playertek, Dundalk, Ireland) positioned between the shoulder blades and activated 15 min before training. Players wore the same unit throughout the study to minimize inter-device error. Parameters analysed included high-intensity distance (>19.8 km·h^{-1}), sprint distance (>25.1 km·h^{-1}), top speed, and number of accelerations/decelerations >3 m·s^{-2}. Energy cost (EC, J·kg^{-1}·m^{-1}) and average metabolic power (P Met aver W·kg^{-1}) were calculated, with average Pmet and distance above 20 W·kg^{-1} also reported.

Performance assessment

Testing was conducted on four separate days both pre- and post-intervention: Monday (MD-6), Mognoni aerobic fitness test; Tuesday (MD-5), 20-m sprint and RSA test; Thursday (MD-3), 200-m sprint; Friday (MD-2), Yo-Yo IR2. A rest day was provided on Wednesday (MD-4) and Saturday (MD-1). Participants were familiarized with all procedures before testing and refrained from strenuous exercise, alcohol, and caffeine for 24 h prior. Nutritional intake (~60% carbohydrate) was recorded and replicated during all test days.

Aerobic fitness test (Mognoni)

Submaximal run at 13.5 km·h^{-1} for 6 min on natural turf. [La^-] measured from earlobe immediately post-test (Sirtori, 1993).

20-m sprint test

Three maximal sprints with 150 s passive recovery between trials; best time used for analysis. Start from standing, 0.3 m before first gate (Iaia et al., 2015). Time was recorded using photoelectric cells (Witty, Microgate, Bolzano, Italy).

Repeated Sprint Ability (RSA) test

Following the 20-m sprint test (after 10 min of recovery) participants performed an RSA test consisting of 5 repetitions of 30-m all-out sprints interspersed by 25 s of passive recovery. Best sprint time (RSA_{best}) and total sprint time (RSA_t) for the five sprints (S_1, S_2, S_3, …) were determined. Also, to quantify fatigue during the RSA test, the percentage decrement score (RSA_{dec}) was calculated as follows (Girard et al., 2011):

$$RSAdec = \left[\frac{S_1 + S_2 + S_3 \cdots + S_{final}}{S_{best} \times number\ of\ sprints} - 1\right] \times 100 \quad (1)$$

200 m sprint test

An all-out run was performed over 200 m. Time recordings were obtained using photoelectric cells.

Yo-Yo IR2 test

The Yo-Yo Intermittent Recovery Test level-2 was performed. The test consists of 2 x 20-m shuttle runs at increasing speeds, interspersed with 10 s of active recovery, controlled by audio signals. The distance achieved was recorded when the participants were no longer able to maintain the required speed (Bangsbo et al., 2008).

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Statistical analyses

The normal distribution of each variable was examined by the Shapiro-Wilk's test. An unpaired t-test was used to assess between-group differences in the Pre-test measurements. Data were analysed using a two-factor repeated-measure ANOVA with one between factor (group: SEP 20 vs. SEP 10) and one within factor (time: Pre-vs Post). In case of significant interaction, a Bonferroni post-hoc test was employed to evaluate each comparison. The level of statistical significance was set for all analyses at $p < .05$. Moreover, Pre-post effect size was measured as suggested by Hedge (Wasserman, 1988). In addition to null-hypothesis testing, a statistical approach based on the magnitudes of change was also utilized (Hopkins et al., 2009). The corresponding quantitative chances of beneficial, unclear of harmful changes were evaluated as follows: < 25% *trivial*, 25-75%, *possibly*; 75-95%, *likely*; 95-99%, *very likely*; and > 99%, *almost certainly*. If the chance of obtaining greater and poorer differences was both >5%, the true difference was assessed as *unclear*. To perform each calculation and interpretation related to the magnitude-based inference approach, customized spreadsheets, available at https://www.sportsci.org/index.html, were utilized. Data are presented as means ± SD, whereas relative changes are presented as means ±90% confidence intervals.

RESULTS

Performance

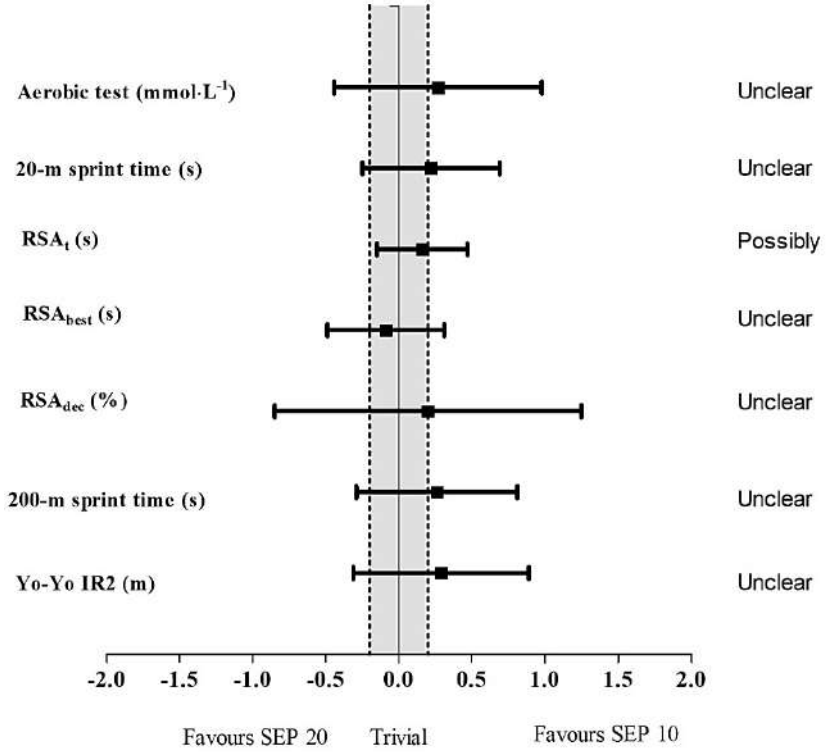
All performance measures showed no significant differences between groups at the pre-intervention stage ($p > .05$). Post-intervention, there were no significant changes in RSA_{dec}, 200-m sprint time, or blood lactate concentration at the end of the aerobic fitness test for either group ($p > .05$). The 20-m sprint time decreased by 0.8% and 1.8% following the training intervention, in SEP 20 and SEP 10, respectively ($F = 6,00$; $p < .05$). The RSA_t decreased by 1.1% and 1.5% following the training intervention, in SEP 20 and SEP 10, respectively ($F = 18,37$; $p < .05$). The RSA_{best} decrease by 1.2% and 1.5% following the training intervention, in SEP 10 and SEP 20, respectively ($p < .05$). The Yo-Yo IR2 performance improved by 10% and 16% in SEP 20 and SEP 10, respectively ($F = 12.92$; $p < .05$). No significant interaction was found after the intervention for all performance tests (Table 1).

Table 1. Changes in performance following speed endurance training consisting of different sprint durations.

	Performance test	Pre	Post	Effect Size Pre-Post	Within-group comparisons		
					Standardized differences (Cohen's d ±90% CI)	Percent changes of worse/trivial/better performance	Qualitative inferences
SEP 10	Aerobic Test (mmol·L^{-1})	7.4 ± 1.6	6.9 ± 1.8	0.11 Small	-0.34 ± 0.60	7/27/67	Unclear
	20-m sprint time (s)	3.11 ± 0.15	3.05 ± 0.12*	0.42 Small	-0.32 ± 0.32	1/25/74	Possibly
	RSA_{best} (s)	4.45 ± 0.19	4.40 ± 0.16*	0.27 Small	-0.24 ± 0.28	1/38/61	Possibly
	RSA_t (s)	23.2 ± 0.9	22.9 ± 0.8*	0.37 Small	-0.34 ± 0.23	0/14/86	Likely
	RSA_{dec} (%)	4.1 ± 1.6	4.2 ± 1.3	0.07 Trivial	0.12 ± 0.74	43/36/22	Unclear
	200-m sprint time (s)	28.0 ± 1,3	27.5 ± 1,2	0.30 Small	-0.28 ± 0.34	2/32/66	Possibly
	Yo-Yo IR2 (m)	370 ± 126	440 ± 111*	0.74 Moderate	0.51 ± 0.38	0/8/92	Likely
SEP 20	Aerobic Test (mmol·L^{-1})	8.5 ± 2.5	8.2 ± 1.7	0.28 Small	-0.03 ± 0.42	17/59/23	Unclear
	20-m sprint time (s)	3.13 ± 0.1	3.11 ± 0.11*	0.18 Trivial	-0.24 ± 0.25	1/39/60	Possibly
	RSA_{best} (s)	4.45 ± 0.16	4.39 ± 0.18*	0.33 Small	-0.36 ± 0.27	0/15/85	Likely
	RSA_t (s)	22.9 ± 0.8	22.7 ± 0.8*	0.35 Small	-0.23 ± 0.16	0/38/62	Possibly
	RSA_{dec} (%)	2.9 ± 0.7	3.3 ± 1.6	0.56 Moderate	0.53 ± 1.04	71/17/11	Unclear
	200-m sprint time (s)	28.0 ± 1.4	27.9 ± 1.0	0.08 Trivial	-0.05 ± 0.36	11/66/23	Unclear
	Yo-Yo IR2 (m)	410 ± 88	460 ± 90*	0.53 Moderate	0.49 ± 0.36	0/8/91	Likely

*Note. Speed endurance production for 10 s (SEP 10); Speed endurance production for 20 s (SEP 20); confidence interval (CI); Best sprint (RSA_{best}); Total sprint time (RSA_t); Percentage decrement score (RSA_{dec}); Yo-Yo intermittent recovery test level 2 (Yo-Yo IR2). *Significant differences pre-post ($p < .05$).*

Between-group changes are presented in Figure 2. Changes in RSA_t were possibly better in SEP 10 than those observed in SEP 20.



Note. Speed endurance production for 10 s (SEP 10); Speed endurance production for 20 s (SEP 20); Best sprint (RSAbest); Total sprint time (RSAt); Percentage decrement score (RSAdec); Yo-Yo intermittent recovery test level 2 (Yo-Yo IR2).

Figure 2. Standardize differences between SEP 10 and SEP 20.

External training load monitoring

During the 2nd training session, significant differences were found between SEP 10 and SEP 20 for Total Number of accelerations > 3 $m \cdot s^{-2}$ (20 ± 1 and 15 ± 1, respectively), Total Number of decelerations < -3 $m \cdot s^{-2}$ (18 ± 1 and 13 ± 1, respectively), and distance > 20 $W \cdot kg^{-1}$ (624 ± 13 m and 587 ± 13 m) ($p < .05$). No differences between groups were observed for Total time, Sprint Decrement, High-intensity distance, Sprint distance and Top speed, and P Met aver (Table 2).

During the last training session, a time effect was detected for Total time, Number of decelerations < - 3 $m \cdot s^{-2}$ and Distance >20 $W \cdot kg^{-1}$. Total time improved by 0.9% and 1.9% in SEP 20 and SEP 10, respectively ($F = 16.01$; $p < .05$). Also, Total Number of decelerations < - 3 $m \cdot s^{-2}$ decreased by 7.7% in SEP 20 and by 16,6% in SEP 10 ($F = 6.53$; $p < .05$). Additionally, Distance >20 $W \cdot kg^{-1}$ decreased in SEP 20 by 1.5% and in SEP 10 by 2.7% ($F = 4.85$; $p < .05$).

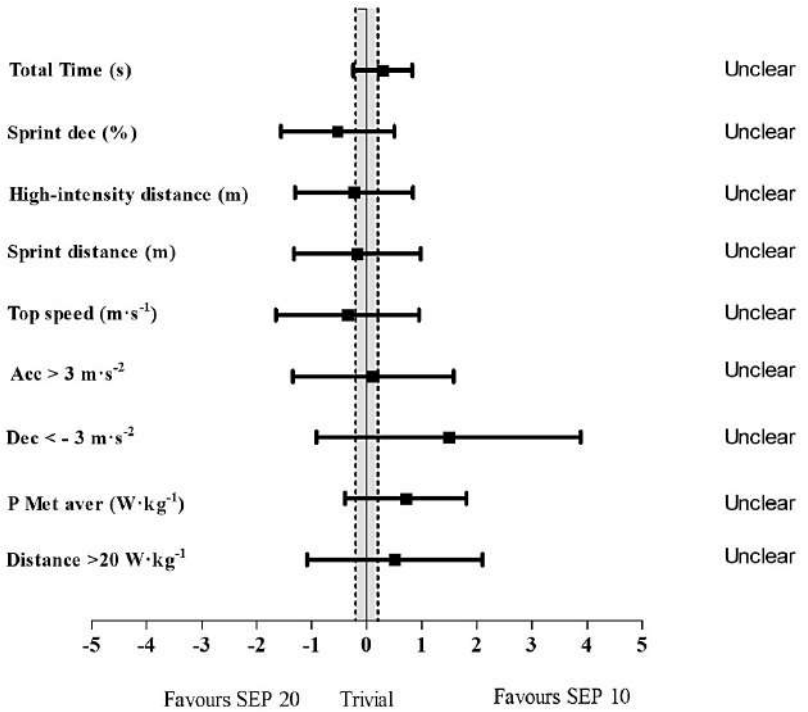
Between-group changes are presented in Figure 3. Differences in the changes of all external load parameters were unclear.

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Table 2. Training workload during the 2nd and the last training sessions for the different sprint endurance training groups.

External training load		2nd session	Last session	Within-group comparisons		
				Standardized Differences (Cohen's d ±90% CI)	Percent changes of worse/trivial/better performance	Qualitative inferences
SEP 10	Total Time (s)	104.5 ± 4.0	102.6 ± 3.0*	-0.44 ± 0.23	0/4/96	Very Likely
	Sprint dec (%)	4.9 ± 3.0	4.7 ± 2.0	0.02 ± 0.72	29/39/32	Unclear
	High-intensity distance (m)	280 ± 59	284 ± 43	0.10 ± 0.81	25/33/42	Unclear
	Sprint distance (m)	212 ± 83	190 ± 65	-0.10 ± 0.81	41/34/25	Unclear
	Top speed ($m \cdot s^{-1}$)	7.8 ± 0.4	7.9 ± 0.4	0.02 ± 1.04	35/27/37	Unclear
	Acc > 3 $m \cdot s^{-2}$	20 ± 1#	20 ± 1	-0.48 ± 1.02	69/19/12	Unclear
	Dec < - 3 $m \cdot s^{-2}$	18 ± 1#	15 ± 2*	-2.08 ± 1.89	95/2/3	Likely
	P Met aver ($W \cdot kg^{-1}$)	8.1± 0.5	8.1 ± 0.5	-0.02 ± 0.87	36/32/32	Unclear
	Distance >20 $W \cdot kg^{-1}$	624 ± 13#	607 ± 16*	-1.25 ± 1.44	89/6/5	Likely
SEP 20	Total Time (s)	103.8 ± 2.2	102.9 ± 3.1*	-0.38 ± 0.68	7/24/69	Unclear
	Sprint Dec (%)	4.9± 2.0	4.0 ± 2.0	-0.66 ± 0.7	3/11/86	Likely
	High-intensity distance (m)	297 ± 40	293 ± 51	-0.12 ± 0.58	40/43/17	Unclear
	Sprint distance (m)	175 ± 58	167 ± 79	-0.39 ± 0.87	65/23/12	Unclear
	Top speed ($m \cdot s^{-1}$)	8.0 ± 0.4	7.9 ± 0.5	-0.34 ± 0.72	64/26/10	Unclear
	Acc > 3 $m \cdot s^{-2}$	15 ± 1#	15 ± 1	-0.24 ± 1.08	53/24/23	Unclear
	Dec < - 3 $m \cdot s^{-2}$	13 ± 1#	12 ± 2*	-0.91 ± 1.69	77/10/13	Unclear
	P Met aver ($W \cdot kg^{-1}$)	8.0± 0.4	8.3 ± 0.5	0.75 ± 0.54	0/4/95	Very Likely
	Distance >20 $W \cdot kg^{-1}$	587 ± 13#	578 ± 17*	-0.65 ± 0.95	80/13/7	Unclear

*Note. Speed endurance production for 10 s (SEP 10); Speed endurance production for 20 s (SEP 20); confidence interval (CI); Total time, percent of sprint decrement (Sprint Dec); High-intensity distance (distance between 19.8 and 25.1 $km \cdot h^{-1}$); Sprint distance (>25.1 $km \cdot h^{-1}$); Top speed ($m \cdot s^{-2}$); number of accelerations >3 $m \cdot s^{-2}$ (Acc > 3 $m \cdot s^{-2}$); number of decelerations < 3 $m \cdot s^{-2}$ (Dec. -3 $m \cdot s^{-2}$); metabolic power average (P Met aver, $W \cdot kg^{-1}$). *Significant differences pre-post ($p < .05$). # Significant differences between groups during the 2nd training session ($p < .05$).*

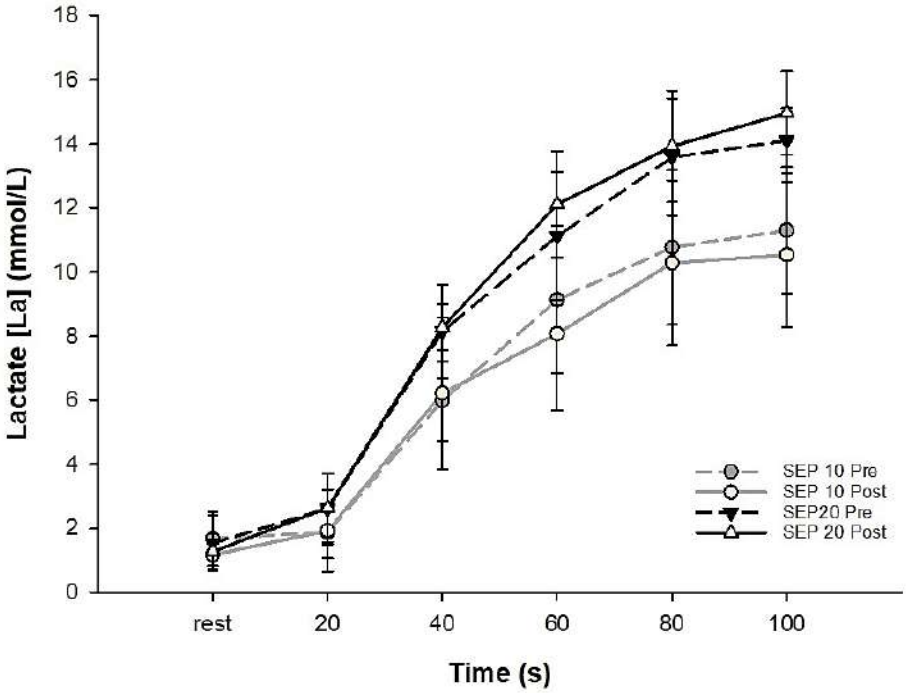


Note. Speed endurance production for 10 s (SEP 10); Speed endurance production for 20 s (SEP 20); Total time, percent of sprint decrement (Sprint Dec); High-intensity distance (distance between 19.8 and 25.1 $km \cdot h^{-1}$); Sprint distance (>25.1 $km \cdot h^{-1}$); Top speed ($m \cdot s^{-2}$); number of accelerations >3 $m \cdot s^{-2}$ (Acc > 3 $m \cdot s^{-2}$); number of decelerations < 3 $m \cdot s^{-2}$ (Dec . -3 $m \cdot s^{-2}$); metabolic power average (P Met aver, $W \cdot kg^{-1}$).

Figure 3. Standardize differences on external training load variables between SEP 10 and SEP 20.

Physiological responses

The assessment of blood lactate concentrations showed significant differences between-group ($p < .01$) (Figure 4). There were no time effects for changes in blood lactate concentration for either group from 2nd to last training. The blood lactate concentration increased during exercise in both groups: Rest<20-s<40-s<60-s<80-s = 100-s ($p < .05$).



Note. Speed endurance production for 10 s (SEP 10); Speed endurance production for 20 s (SEP 20).

Figure 4. The assessment of blood lactate concentrations during the 2nd and the last training sessions for the different sprint endurance training groups.

Heart rate

Heart rate measurements at the 2nd and last training session are shown in Table 3. Significant between-group differences were observed for $\%HR_{mean}$ and time spent over 85% of HR_{max} ($p < .05$) but not for $\%HR_{peak}$. There were also no pre-to-post differences the in any of the HR parameters ($\%HR_{mean}$, time spent over 85% of HR_{max}, and $\%HR_{peak}$).

Table 3. Heart rate parameters during the 2nd and the last training sessions for the different sprint endurance training groups.

Heart rate parameters	SEP 10		SEP 20		Interaction
	2nd session	Last session	2nd session	Last session	
%HRmean	87 ± 2#	86 ± 5	82 ± 4#	82 ± 5	$p = .12$
%HRpeak	96 ± 2	96 ± 3	96 ± 3	95 ± 3	$p = .66$
Time > 85% HRmax (s)	492 ± 94#	422 ± 188	276 ± 111#	293 ± 119	$p = .06$

Note. Speed endurance production for 10 s (SEP 10); Speed endurance production for 20 s (SEP 20); the percentage of heart rate means ($\%HR_{mean}$); the percentage of heart rate peak ($\%HR_{peak}$); time spent above 85% of heart rate max (Time > 85% HR_{max}).
Significant differences between groups in the 2-session measurements($p < .05$).

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DISCUSSION AND CONCLUSIONS

The main findings of the present study indicate that both speed-endurance production (SEP) training regimes significantly improved 20-m sprint, RSA_t, RSA_{best}, and Yo-Yo IR2 performance. To our knowledge, this is among the first studies to report improvements in sprint performance following SEP training. Previous studies typically reported significant speed gains only for sprint bouts shorter than 6 s. For instance, Iaia et al. (2017) observed improved sprint performance after 4 weeks of repeated short sprints (6 × 5 s, 30-s recovery), while Mohr et al. (2007) found improvements after 6 × 6-s sprints with 54-s passive recovery, but no changes after 6 × 30-s sprints (Iaia et al., 2015; Mohr et al., 2007b). Interestingly, similar enhancements in sprint performance were observed in both SEP10 and SEP20 despite differences in physiological responses, including heart rate, blood lactate concentration, and acceleration/deceleration profiles. These effects may be attributable to the all-out nature of the protocols and the recruitment of young amateur players, who may be less accustomed to maximal sprint efforts. The high neuromuscular demands of the protocols (Fiorenza et al., 2019) likely contributed to the observed improvements, highlighting their practical relevance for young players, especially considering the association between high-intensity phases and key moments of a match (Faude et al., 2012).

Another important finding was the significant increase in RSA_t in both groups (1.5% in SEP 10 and 1.1% in SEP 20, $p < .05$). The *possibly* greater effect of SEP 10 on RSA_t suggests that improvements in repeated sprint performance may be primarily related to the muscle's capacity to sustain forceful bouts. This aligns with previous evidence indicating that elevated power output and maintenance of high speed throughout repeated sprints are critical for enhancing repeated-sprint ability (Bishop et al., 2004; Iaia et al., 2017; Iaia et al., 2015). Both interventions also improved Yo-Yo IR2 performance, suggesting that the specific characteristics of each protocol (i.e. high-speed development and fatigue resistance) contribute positively to high-intensity intermittent exercise capacity.

Aerobic capacity, assessed via the Mognoni test, remained unchanged throughout the training period. It has been suggested that inducing maximal cardiovascular and peripheral aerobic adaptations requires >10–15 min per session above 85% Hr_{max} (Buchheit & Laursen, 2013b). In our study, participants spent less than 8 min above this threshold, indicating that repeated all-out efforts with long recoveries (work-to-rest ratio 1:6) are insufficient to further enhance aerobic fitness in already trained individuals. This observation is consistent with prior studies, which reported that SEP training primarily induces peripheral adaptations (e.g., muscle architectural remodelling (Gunnarsson et al., 2012; Iaia et al., 2009), changes in membrane transport proteins regulating pH(Gunnarsson et al., 2012; Iaia et al., 2008), and preservation of excitability (Bangsbo et al., 2009; Gunnarsson et al., 2012; Iaia et al., 2008)) rather than improvements in $\dot{V}O_{2max}$ (Bangsbo et al., 2009; Gunnarsson et al., 2012; Iaia et al., 2009; Iaia et al., 2008).

Despite no change in aerobic fitness, high-intensity intermittent capacity, as measured by Yo-Yo IR2 distance, increased by 10% and 16% in SEP 20 and SEP 10, respectively. These improvements are consistent with studies demonstrating enhanced fatigue resistance following SEP training (Iaia et al., 2015), although the magnitude is smaller than reported in recreational players (Mohr & Krustrup, 2016), reinforcing SEP as an effective strategy for enhancing high-intensity intermittent performance in soccer players. The similar Yo-Yo IR2 improvements between groups suggest that maintaining high mechanical output throughout repeated sprints is a key factor for enhancing high-intensity intermittent performance.

Lower end-exercise blood lactate concentration in SEP 10 compared with SEP 20 indicates that longer repeated all-out efforts are strongly associated with glycolytic anaerobic energy production, consistent with

previous research (Bogdanis et al., 1998; Mohr et al., 2007b). Surprisingly, there were no significant differences between groups for 200-m performance, although the differences observed in blood lactate concentration would suggest a different amount of anaerobic contribution between groups.

Some limitations of the present study should be acknowledged, including the short training duration (4 weeks), moderate sample size, participants' competitive level, and absence of a control group. Future studies should address these limitations, potentially incorporating longer interventions in elite youth players to corroborate these findings.

In conclusion, short-term SEP training improves aspects of high-intensity performance and repeated-sprint ability in soccer players. The high metabolic power and number of accelerations (>3 $m \cdot s^{-2}$), despite lower lactate accumulation, suggest that SEP 10 is particularly effective for enhancing soccer-related physical performance. The greater number of high-intensity accelerations and decelerations in SEP 10 compared with SEP 20 indicates potential benefits for improving change-of-direction ability, though this requires further investigation.

Practical applications

Understanding the characteristics of a training stimulus and its effects on performance enables coaches to optimize training delivery. Manipulating sprint duration can alter mechanical and physiological outputs, allowing for individualized training prescriptions based on player role and characteristics. The increased neuromuscular stimulus observed with SEP 10 indicates that short sprint bouts may induce positive adaptations in soccer-specific performance with lower neuromuscular strain at the end of exercise, making this approach particularly useful in short-term training periods (Fiorenza et al., 2019).

AUTHOR CONTRIBUTIONS

EP, DB and MA have given substantial contributions to the conception or the design of the manuscript. EP, AT, FZ and MS to acquisition, analysis and interpretation of the data. All authors have participated to drafting the manuscript, GA and DB revised it critically. All authors read and approved the final version of the manuscript.

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ORIGINAL ARTICLE

Factors related to shooting performance in 8–12-year-old basketball players

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ABSTRACT

This study aimed to investigate the relationship between shooting performances, specifically free throw (FT) and turn-around jump shot (TJS), and individual characteristics, physical performance, and proprioception in child basketball players. FT and TJS were evaluated with 10-shot trials. Individual data were collected via questionnaire. Lower limb explosive power was measured by the Sargent jump test (SJT), core endurance by the plank test, and shoulder, elbow, wrist proprioception by joint repositions error (JRE) tests. This cross-sectional study was conducted with 38 basketball players (age: 9.9 ± 1.5 years). FT and TJS correlated positively with SJT (ρ = .402, .388) and plank (ρ = .349, .342), respectively (p < .05). A significant positive correlation was found between FT and body height (ρ = .463), TJS and basketball experience (ρ = .352) (p < .05). Also, a negative correlation was found between plank and JRE-shoulder (ρ = - .431, p < .05). Shooting performance (FT and TJS) related to physical performance (lower limb explosive power and core muscles endurance). Improved FT performance was associated with increased body height, while TJS performance was related to longer experience. Understanding shared and distinct correlates of shooting skills can guide targeted assessment and training strategies.

Keywords: Performance analysis, Paediatrics, Free throw, Turn-around jump shot, Explosive strength, Core muscle endurance, Proprioception.

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INTRODUCTION

Participation in sports has been reported to support children's personal, social, and physical development, such as health, socialization, teamwork, self-esteem, stress management, and reduced screen time, with these benefits being enhanced by supportive coaching environments and parents who reinforce teachable moments at home (Neely & Holt, 2014; Peyer & Smith, 2022). Basketball, one of the most popular team sports among children, is a game in which the winner is determined by the total number of points scored. One of the primary methods of scoring involves various shooting techniques, such as free throws, jump shots, and turn-around jump shots. Shooting skills are a key determinant of scoring success in basketball.

The performance of various basketball shot types is related to individual factors including body height and basketball playing experience, along with physical performance indicators such as explosive muscle strength (Okazaki et al., 2015; Okazaki & Rodacki, 2018). When examining the physical performance of basketball players, elite athletes have been found to possess greater lower extremity muscle strength, achieve higher vertical jump heights, and demonstrate superior agility compared to their peers (Han et al., 2023). In the literature, while some studies report no significant relationship between free throw performance and lower extremity muscle strength, there is evidence indicating that lower extremity muscle strength, particularly in relation to shooting distance, can influence ball release velocity in the upper extremity during jump shots (Cabarkapa et al., 2022; Nakano et al., 2020). Unlike the standard jump shot, the turn-around jump shot involves the player starting with their back to the basket, then quickly turning to face the basket before jumping to execute the shot. After turning to face the basket, the player must quickly prepare their body to execute the shot. This study will examine the relationship between lower extremity explosive muscle strength and free throw shooting. This will both contribute to the literature's diverse findings and contribute new insights to the literature by examining the relationship between lower extremity explosive muscle strength and turn-around jump shots.

In basketball players, another frequently studied muscle group, distinct from lower extremity muscles, is the core musculature. Strong and enduring core muscles are important for maintaining lower extremity muscle function and sustaining athletic performance (Tazji et al., 2023). Furthermore, a significant relationship has been identified between core muscle endurance and postural stability in basketball players, which may positively influence their overall athletic performance (Cengizhan et al., 2019).

In competitive sports such as basketball, precise and coordinated body movements are critically important for success. Proprioception can be defined as the ability to determine the position and movement of body segments in space by integrating sensory signals received from mechanoreceptors (Han et al., 2016). Moreover, proprioceptive signals enable us to perceive the force and effort generated by our muscles, as well as the weight of the objects we lift (Héroux et al., 2022). In the literature, various studies have reported no significant relationship between elbow and wrist proprioception and free throw performance or standing free throw scores, while shoulder proprioception has been found to have a borderline significant association with free throw performance (Kaya et al., 2012; Sevrez & Bourdin, 2015).

Shooting is arguably the most decisive skill for scoring in basketball and, ultimately, for winning games. While free throw performance has been widely studied, research on the turn-around jump shot, a technically demanding and game-relevant skill, remains surprisingly scarce. To our knowledge, this is the first study to simultaneously and comparatively examine the factors associated with both free throw and turn-around jump shot performance. By addressing this gap, we aim to offer novel and meaningful insights that could inform both player development and training strategies in basketball. The aim of this study is to investigate the

relationships between different shooting techniques (free throw and turn-around jump shot) performance and individual characteristics (height, BMI, basketball experience, age), physical performance (lower extremity explosive muscle strength, core muscle endurance), and proprioception (shoulder, elbow, and wrist) in child basketball players.

MATERIAL AND METHODS

Study design

A cross-sectional study was conducted to investigate the relationships between free throw and turn-around jump shot performance and individual characteristics, physical performance, and proprioception in basketball players aged 8–12 years.

Participants

This study was conducted between May 15 and June 15, 2025, at the Pera Basketball Sports Club. Participants aged 8–12 years had been playing basketball regularly for at least one year and had current membership in a basketball club, regardless of duration. Individuals who had undergone any surgical procedures within the last six months or had any health conditions that could affect the assessments (particularly musculoskeletal disorders) were excluded from the study.

Prior to the study, ethical approval was obtained from the KTO Karatay University Ethics Committee (Date: May 8, 2025; Decision No: 2025/007). Before participation, both the participants and their parents were informed about the study, and written informed consent was obtained.

Sample size estimation

A priori power analysis was conducted using G*Power (version 3.1.9.7) to determine the minimum required sample size for detecting a significant correlation using a two-tailed test. The effect size ($\rho = .50$) was derived from a previous study that reported a moderate negative correlation between free-throw performance and elbow joint position sense (Sevrez & Bourdin, 2015). Power analysis ($\alpha = .05$, $1–\beta = .80$) indicated that at least 29 participants were needed to detect a significant correlation.

Procedures

In the study, participants' individual characteristics, shooting performance, lower extremity explosive muscle strength, jump height, proprioception, and core muscle strength were assessed.

Individual and descriptive characteristics

Individual and descriptive information such as age, gender, height, weight, body mass index, and duration of basketball experience (in sports club) of the individuals in the study sample were recorded using a demographic information form.

Assessment of shooting performance

Participants' performance in free throws and turn-around jump shots was assessed. In the turn-around jump shot, the player started with their back facing the basket, then turned to face the basket and performed the shot while jumping. Free throws were performed at 4.6 m and turn-around jump shots at 3 m from the basket. For each type of shot, participants first performed 3 practice trials, followed by 10 recorded attempts. Each successful shot was scored as 1 point, and unsuccessful shots were scored as 0 points.

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Assessment of lower extremity explosive muscle strength

Explosive lower extremity muscle strength was assessed using the Sargent jump test. In the initial measurement, the participant stands upright with feet fully contacting the ground. The dominant arm is extended overhead parallel to the wall, and the highest reachable point is marked. In the second measurement, the participant is instructed to jump vertically as high as possible and mark the wall with the dominant hand at the peak of the jump (do Amaral Vasconcellos et al., 2012; Dos Reis et al., 2024). The distance between the two marks is recorded as the jump height. The test is repeated three times, and the highest score is recorded. An increase in jump height indicates an improvement in explosive muscle strength.

Assessment of core muscle endurance

The plank test was used to assess core muscle endurance. In this test, participants are asked to place their hands and elbows on the mat, with elbows positioned directly under the shoulders, and raise themselves onto their toes. The objective is to maintain the plank position, keeping the spine and pelvis in a neutral alignment, for as long as possible. Prior to the test, participants were verbally informed, shown a demonstration, and guided through the correct position and relevant procedures when necessary. A stopwatch was started on the command "Start!" and stopped when the participant was unable to maintain a straight back position (deviation > 5 cm measured with a ruler), lowered onto the mat, or successfully completed the isometric hold for 3 minutes. The duration was recorded to the nearest second (Laurson et al., 2022).

Assessment of proprioception

Proprioception was assessed via joint reposition error (JRE) using a digital inclinometer. JRE measurements were performed on the dominant upper extremity. The joint to be assessed is first positioned at a predetermined angle, and the participant is asked to memorize this position. The joint is then returned to its starting position. With the participant's eyes closed, they are instructed to reposition the joint to the previously memorized angle (120° shoulder flexion, 100° elbow flexion, and 30° wrist extension). The absolute difference between the initial target angle and the angle achieved by the participant is recorded as the JRE. The test is repeated three times, and the best (minimum) value is recorded. A smaller JRE indicates better proprioceptive ability (Hillier et al., 2015; Jacobs et al., 2025).

Statistical analysis

The data in this study were analysed using IBM SPSS Statistics software. Categorical variables were presented as frequencies and percentages, while continuous numerical variables were reported as mean ± SD and median with interquartile range (IQR). The normality of continuous numerical data was assessed. For correlation analyses, Spearman's correlation test was used for variables that did not meet the assumptions of normal distribution. Correlation coefficients were interpreted as follows: values between .00 and ±.30 were considered negligible, ± .30 to ± .50 as weak, ± .50 to ± .70 as moderate, ± .70 to ± .90 as high, and ± .90 to ± 1.00 as very high correlations (Mukaka, 2012). The 95% confidence intervals for the Spearman correlation coefficients were estimated using the bootstrap method with 1000 resamples. The significance level of $p < .05$ was considered statistically significant.

RESULTS

The mean age of the participants was 10.03 ± 1.70 years, and the mean body mass index (BMI) was 20.04 ± 3.08. Other individual characteristics of the participants are presented in Table 1.

Table 1. Individual characteristics of participants.

	Mean ± SD	Median- IQR (25/75)	n (%)
Age (years)	9.92 ± 1.53	10.00- 8.75/12.00	-
BMI (kg/m²)	20.04 ± 3.08	19.97- 17.48/21.90	-
Height (cm)	143.79 ± 12.68	140.50- 133.50/154.50	-
Basketball experience[a] (years)	1.30 ± 1.38	0.67- 0.50/2.25	-
Gender			
Female	-		28 (73.7)
Male	-		10 (26.3)
Dominant hand			
Right	-		34 (89.5)
Left	-		4 (10.5)
Dominant foot			
Right	-		34 (89.5)
Left	-		4 (10.5)

Note. SD: Standard Deviation, IQR: Interquartile Range, REA, BMI: Body Mass Index, [a] As a Registered Member of a Sports Club.

The participants' free throw shooting performance averaged 2.55 ± 2.07, while the turn-around shot performance averaged 3.24 ± 1.88. Detailed numerical data on the participants' shooting performances, physical performance, and joint reposition error angles are presented in Table 2.

Table 2. Descriptive statistics of shooting performance, physical performance, and joint reposition errors.

	Mean ± SD	Median- IQR (25/75)
Free throw	2.55 ± 2.07	2.0- 1.00/4.00
Turn-around jump shot	3.24 ± 1.88	3.0- 2.00/4.00
Sargent jump (cm)	26.73 ± 8.72	24.00- 20.00/33.25
Plank (s)	67.73 ± 44.30	61.57- 33.13/97.52
JRE shoulder	10.35 ± 6.54	8.67- 4.83/14.00
JRE elbow	7.77 ± 4.75	7.00- 4.25/10.00
JRE wrist	6.54 ± 4.14	4.83- 2.92/9.83

Note. SD: Standard Deviation, IQR: Interquartile Range, JRE: Joint Reposition Error.

Correlation analyses were conducted to investigate the relationships between shooting performances and various participant characteristics. A weak positive correlation was found between participants' free throw and turn-around Jump Shot performances (ρ = .437, 95% CI [0.147, 0.681], p = .006). A weak positive correlation was observed between free throw performance and body height (ρ = .463, 95% CI [0.117, 0.712], p = .003). Turn-around jump shot performance showed a weak positive correlation with the duration of playing basketball as a registered member of a sports club (ρ = .352, 95% CI [0.049, 0.582], p = .030). No significant correlations were found between shooting performances and other descriptive statistics (p > .05) (Table 3).

Table 3. Correlations between shooting performance and descriptive statistics.

		ρ	95% CI	p-Value
Free throw	Age (years)	0.238	[-0.126, 0.542]	.15
Turn-around jump shot		0.194	[-0.133, 0.484]	.24
Free throw	BMI (kg/m²)	0.170	[-0.148, 0.467]	.31
Turnaround jump shot		-0.064	[-0.389, 0.260]	.70
Free throw	Height (cm)	0.463**	[0.117, 0.712]	.003
Turn-around jump shot		0.285	[-0.054, 0.545]	.08
Free throw	Basketball experience[a] (years)	0.216	[-0.113, 0.542]	.19
Turn-around jump shot		0.352*	[0.049, 0.582]	.03

*Note. [a] As a Registered Member of a Sports Club, ρ: Spearman's rho, CI: Confidence Interval, p** < .01, p* < .05.*

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Correlation analyses were conducted to investigate the relationships between shooting performances, physical performance tests, and reposition error angle values. A weak positive correlation was found between free throw performance and the Sargent Jump Test (ρ = .402, 95% CI [0.087, 0.666], p = .01), as well as between Turn-around jump shot performance and the Sargent Jump Test (ρ = .388, 95% CI [0.107, 0.611] p = .02). Similarly, both free throw and turn-around jump shot performances showed weak positive correlations with the Plank test (ρ = .349, 95% CI [0.026, 0.622] and ρ = .342, 95% CI [0.016, 0.627] respectively; p < .05). However, no significant correlations were observed between shooting performances and reposition error angle values (p > .05). Detailed information on the correlation results is presented in Table 4.

Table 4. Correlations between shooting performance, physical performance tests, and joint reposition error values.

		ρ	95% CI	p-Value
Free throw	Sargent jump (cm)	0.402*	[0.087, 0.666]	.01
Turn-around jump shot		0.388*	[0.107, 0.611]	.02
Free throw	Plank	0.349*	[0.026, 0.622]	.03
Turn-around jump shot		0.342*	[0.016, 0.627]	.04
Free throw	JRE-shoulder	0.012	[-0.355, 0.364]	.94
Turn-around jump shot		-0.151	[-0.432, 0.185]	.37
Free throw	JRE-elbow	0.166	[-0.159, 0.446]	.32
Turn-around jump shot		-0.019	[-0.355, 0.341	.91
Free throw	JRE-wrist	-0.047	[-0.407, 0.307]	.78
Turn-around jump shot		-0.166	[-0.472, 0.152]	.32

*Note. JRE: Joint Reposition Error, ρ: Spearman's rho, CI: Confidence Interval, p** < .01, p* < .05.*

Another result found because of the correlation analysis is the weak and negative relationship between the joint reposition error measured in the shoulder joint and the plank time (ρ = -.431, 95% CI [-0.677, -0.131] p = .007). This result was not initially included in the main tables, as it falls outside the primary scope of the study. However, given its potential importance, we report the correlation coefficient, confidence interval, and p-value here, and further discuss its implications in the Discussion section. Detailed pairwise correlation results are available in the supplementary material (Table S1, and Table S2).

Table S1. Pairwise correlations results between shooting performance and individual characteristics.

		Free throw	Turn-around jump shot	Age (years)	BMI (kg/m²)	Height (cm)
Turnaround shot	ρ	0.437**				
	p-Value	.006				
Age (years)	ρ	0.234	0.201			
	p-Value	.16	.23			
BMI (kg/m²)	ρ	0.170	-0.064	0.154		
	p-Value	.31	.70	.36		
Height (cm)	ρ	0.463**	0.285	0.867**	0.267	
	p-Value	.003	.08	.001	.10	
Basketball experience * (years)	ρ	0.216	0.352*	0.731**	-0.076	0.731**
	p-Value	.19	.03	.001	.65	.001

*Note. * As a Registered Member of a Sports Club, BMI: Body Mass Index, ρ: Spearman's rho, p** < .01, p* < .05.*

Table S2. Pairwise correlations results between shooting performance, physical performance tests, and joint reposition error values.

		Free throw	Turn-around jump shot	Sargent jump (cm)	Plank	JRE-shoulder	JRE-elbow
Turnaround shot	*ρ*	0.437**					
	p-Value	.006					
Sargent jump (cm)	*ρ*	0.402*	0.388*				
	p-Value	.01	.02				
Plank	*ρ*	0.349*	0.342*	0.530**			
	p-Value	.03	.04	.001			
JRE-shoulder	*ρ*	0.012	-0.151	-0.172	-0.431**		
	p-Value	.94	.37	.30	.007		
JRE- elbow	*ρ*	0.166	-0.019	-0.195	-0.081	0.084	
	p-Value	.32	.91	.24	.63	.62	
JRE- wrist	*ρ*	-0.047	-0.166	-0.213	-0.107	-0.252	-0.212
	p-Value	.78	.32	.20	.52	.13	.20

Note. JRE: Joint Reposition Error, ρ: Spearman's rho, p** < .01, p* < .05.

DISCUSSION

This study aimed to investigate factors that may be associated with free throw and turn-around jump shot performance, including individual characteristics, lower extremity explosive muscle strength, core muscle strength, and proprioception. To our knowledge, this is the first study to simultaneously and comparatively examine the factors associated with both free throw and turn-around jump shot performance. When individual variables were considered, the results of this study revealed a weak yet significant correlation between improved free throw performance and increased body height. Additionally, there was a significant relationship between improvement in turn-around jump shot performance and longer duration of playing basketball as a registered member of a sports club. No significant relationship was found between shooting performances and age or BMI values. Regarding the relationships between shooting performances, physical performance, and proprioception, the findings showed a significant association between increased free throw and turn-around jump shot performance and greater lower extremity explosive strength. Similarly, there was a significant relationship between shooting performance (both free throw and turn-around jump shot) and increased endurance of core muscles. However, no significant relationship was found between shooting performances and proprioception of the shoulder, elbow, or wrist joints.

In this study, a weak but significant relationship was found between improved free throw performance and body height. However, no significant relationship was found between turn-around jump shot performance and height. In a previous study, height was found to be associated with sport-specific skills in basketball players (Mikołajec et al., 2025). Increased release height, which is associated with greater body height, is a factor that positively influences shooting performance. (Okazaki & Rodacki, 2018). The relationship found in our study between increased free throw performance and greater height is consistent with the literature. However, no significant relationship was observed between turn-around jump shot performance and body height. In the turn-around jump shot technique, since the player initially faces away from the basket, accurate perception and alignment of the target during the turn are critical. At this point, other individual differences, such as varying levels of experience, may have diminished the advantage typically associated with greater height. Another finding of this study was that an increase in turn-around jump shot performance was associated with longer basketball playing experience, whereas no such relationship was found between free throw performance and duration of playing basketball. In a study conducted with elite basketball players,

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increasing experience over the years was found to be associated with higher free throw percentages and a greater number of assists. However, due to observed individual differences in other performance indicators, it was emphasized that individualized analytical approaches are needed to better understand player performance (Lorenzo et al., 2019). Given that the participants in this study had relatively short durations of professional basketball experience, the absence of a significant relationship between free throw performance and playing experience may be expected. Since the turn-around jump shot involves more components compared to a free throw, a significant relationship may have been detected despite the limited playing experience. We suggest that the association between experience and turn-around jump shot performance, but not with free throw performance, may be due to the more complex nature of the turn-around jump shot.

In this study, improvements in shooting technique performance were found to be associated with increases in lower extremity explosive muscle strength and core muscle performance. However, a previous study on this topic reported no significant relationship between lower extremity explosive strength and shooting performance (including free-throw, two-point, and three-point shooting) (Cabarkapa et al., 2022). It has been suggested that this result may be influenced by the participants' experience with basketball playing and resistance training, and that the participants may have already possessed sufficient lower extremity strength required for shooting. One study investigating the relationship between free throw performance and elbow and wrist proprioception in basketball players reported no significant correlation between free throw scores performed in a standing position and joint position sense (Gür et al., 2022; Nakano et al., 2020). It has also been noted that during shooting, different body segments work in synergy, and that imbalances in this intersegmental synergy may negatively affect shooting performance (Matsunaga & Oshikawa, 2022). A study on this subject demonstrated that fatigue in the lower back muscles can negatively affect jump performance and landing mechanics, thereby reducing shooting success in basketball players and altering lower extremity biomechanics (Lin et al., 2022).

Proprioception is another variable examined in this study that may be related to shooting performance. According to results of this study no significant relationship was found between shooting technique performance and proprioception values of the shoulder, elbow, and wrist. The literature presents varying findings on this topic. One study investigating the relationship between free throw performance and elbow and wrist proprioception in basketball players reported no significant correlation between free throw scores performing standing and joint position sense. However, significant correlations were found between free throw scores performed while seated and joint position sense (Sevrez & Bourdin, 2015). In another study conducted with professional basketball players, a borderline significant relationship was found between shoulder proprioception and free throw performance (Kaya et al., 2012). A study investigating the role of visual and proprioceptive information in movement demonstrated that the brain relies on visual information when planning movements, but in the absence of visual feedback during movement, it uses proprioceptive information to correct potential deviations or errors (Bagesteiro et al., 2006). In a different study, it was shown that when proprioceptive information was disrupted through tendon vibration, the accuracy and precision of arm movements were impaired even in the presence of visual information (Goodman & Tremblay, 2018). Studies investigating the relationship between proprioception and visual information in literature indicate that proprioception plays a regulatory role when visual feedback is absent, while also maintaining its importance even when visual feedback is present. However, it is important to note that the participants in this study were healthy individuals. In our study, since participants' visual information was not obstructed and there were no health issues that would completely impair the proprioceptive system (such as sensory nerve damage), no relationship may have been found between shooting performance and proprioception.

Other findings related to proprioception in our study include the association between increased plank duration and enhanced shoulder proprioception. The muscles around the shoulder, which are active during load transfer to the upper extremity, are important not only for stabilization but also for proprioception. However, the density of muscle spindles can vary depending on the mechanical properties and function of the muscle. Therefore, the quality of proprioception should be evaluated not only in terms of stabilization level but also together with the functional behaviour of the muscle (Kissane et al., 2022; Uhl et al., 2003). This relationship should therefore be interpreted with caution.

The limitation of this study is related to the assessment of proprioception. Although the joints in the upper extremity are in continuous and dynamic use during shooting performance, proprioception was evaluated using a single, static reference range of motion for each joint. This approach may not fully reflect the complex and functional nature of joint proprioception during actual performance. Although both upper extremities are used during shooting, proprioception was assessed only in the dominant upper extremity in this study. Therefore, this limitation should be considered when interpreting the proprioceptive outcomes of the study. Another limitation of this study is that different variables, which may be associated with shooting performances, such as arm length, visual attention, and upper extremity muscle strength, were not included in assessments in the study. Participants who had been playing basketball for more than one year were included in the study. However, in the analysis, basketball experience was defined as the duration after joining a sports club. We considered the time spent training under professional coaches to be a more accurate reflection of skill development. Nevertheless, from different perspectives, this approach could be considered a limitation of the study. The absence of sex-based subgroup analyses is another limitation of the present study. Since the participants were unevenly distributed (28 females and 10 males), comparisons between sexes could not be performed. Future research should consider examining sex-related differences to provide a more comprehensive understanding of these relationships.

CONCLUSIONS

The results of this study indicate that improvements both the free throw and the turn-around jump shot techniques in child basketball players are associated with increases in lower extremity explosive muscle strength and core muscle performance. Moreover, while the improvement in free throw performance was found to be associated with an increase in body height, the improvement in turn-around jump shot performance was associated with longer basketball experience. Thus, if the goal is to enhance shooting technique performance in child basketball players, assessments and exercise approaches targeting lower extremity explosive strength and core muscle endurance may be beneficial. In addition, body height and basketball playing experience should be taken into consideration.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation and data collection analysis were performed by L.N.G., and S.B.Ç. Analysis was performed by O.K. The first draft of the manuscript was written by O.K. and all authors commented on previous versions of the manuscript. All authors contributed by drafting the manuscript and/or critically revising it for important intellectual content. All authors read and approved of the final manuscript. All authors take responsibility for the work and will help resolve any issues about its accuracy or integrity.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS APPROVAL

Prior to the study, ethical approval was obtained from the KTO Karatay University Ethics Committee (Date: May 8, 2025; Decision No: 2025/007).

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ORIGINAL ARTICLE

Identification of the training environment and its relationship with talent development from the perspective of Brazilian athletics coaches

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ABSTRACT

Evidence from international studies shows indicates that environmental structures influence talent development (TD) and, consequently, the performance of elite athletes. To identify the training environment and its relationship with talent development from the perspective of Brazilian athletics coaches. Five athletics coaches with significant national and international results participated in in-depth semi-structured interviews. Data were analysed using content analysis supported by NVivo 12 Pro. A deductive thematic analysis with a communicational interpretative approach was adopted, and data credibility was ensured through participant validation after transcript review. A total of 151 Mini-units (MUs) were identified. Coaches understood the training environment as comprising structures directly related to training (71 units), including available and ideal infrastructure, the relationship between structure and performance outcomes, incentives for training, competitions, and continuing education. Structures beyond training (80 units) included multidisciplinary follow-up, financial support from guardians, social relationships, and cultural influences. In addition to aligning with existing literature, the findings highlight the relevance of social inequality, within which athletics development in Brazil occurs. From the coaches' perspective, the study demonstrates the multidimensional nature of the environment in athletic talent development. Despite persistent resource constraints, coaches' adaptability, resilience, and communication skills emerged as decisive factors in the talent development process.

Keywords: Performance analysis, Professional experience, Context, Retrospective research, Athletics.

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INTRODUCTION

The development of sporting talent, according to the Differentiated Model of Giftedness and Talent (DMGT) (Gagné, 2013), the Development Model of Sports Participation (Côté, 1999), Sports Policies Leading to Sporting Success (De Bosscher et al., 2006), and Bloom's work Developing Talent in Young People (1985), depends largely on contextual variables, particularly the environment that supports medium- and long-term training. These theoretical models emphasize that the environment comprises the physical facilities available in the club or city, as well as the political, social, and cultural context, and the immediate environment surroundings (e.g., parents, friends, coaches), all of which play crucial roles in the transformation from talent to expertise.

In countries such as Brazil, where sports infrastructure has historically been unevenly distributed among different disciplines, Mazzei et al. (2012) report that only soccer, volleyball, and archery have Olympic Sports Confederations with high-quality facilities and equipment. In athletics, this disparity is also evident geographically: the Southeast region concentrates a higher number of institutions, training facilities, national results, and accredited athletes (Caregnato et al., 2018). Therefore, Olympic sports coaches face ongoing challenges in ensuring adequate training opportunities for young talent.

Environmental limitations have been shown to directly affect competitive performance and athletes' long-term engagement, particularly in sports such as athletics. This reinforces the need for organized strategies to strengthen the country's development of sport system (Mazzei et al., 2012; Caregnato et al., 2018; Santos et al., 2020).

Although theoretical models of talent development (TD) have indicated for decades that talent does not emerge solely from individual aptitudes, but rather from the interaction between personal and environmental factors (Bloom, 1985; Gagné, 2013), there are still gaps in our understanding of how the environment manifests itself in contexts with limited resources. Training spaces, socioeconomic conditions, support from multidisciplinary teams, and community engagement have been considered decisive environments for athletes' successful trajectories toward high performance (Henriksen & Stambulova, 2023; Martindale & Mortimer, 2011). These components act as structures, factors, or catalysts that collectively facilitate positive reactions in the TD process.

Although talent emerges in favourable environmental conditions, for example, in families of musicians, many musicians are produced, there is, not least, the need for an internal basis of natural ability in the individual, which is why not all subjects in similar environmental conditions develop (Gagné, 2013; Guenther, 2015). Henriksen and Stambulova (2023) suggest a more holistic ecological perspective on athletic DT environments, which considers coaches, but also those responsible for athletes, as characters who influence this process.

The responsible parties can provide essential emotional and financial support for children to continue practicing (Côté, 1999; Ferreira & Moraes, 2012), but they may be viewed by athletes as obstacles (Elumaro et al., 2016) or as one of the main causes of early specialization (Chase & DiSanti, 2017). This positive support also comes from peers, friends, and/or training partners, who act as social motivators in maintaining sports practice (Taylor & Bruner 2012; Seanor et al., 2017).

Despite theoretical advances regarding the environment in sports TD, the following question arises: how does the training environment and its relationship with talent development occur from the perspective of

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Brazilian athletics coaches in contexts of social inequality? National studies indicate that Brazilian athletics achieves significant results even without ideal structures, suggesting the existence of adaptive and collaborative strategies that deserve to be investigated, especially from the perspective of the coaches responsible for this process (Caregnato, 2017; Elumaro et al., 2016). There are cases in which they act as guardians/parents or friends, as in studies on gymnastics (Costa & Nonomura, 2025) and athletes from various sports (Pankhurst & Collins, 2013). In other cases, coaches perform the functions of nutritionists and physical therapists, as in studies with athletes in table tennis, gymnastics, karate, and taekwondo (Gullu et al., 2020) and swimming (Raposo & Rosado 2025).

In addition to the multidimensionality of the environment mentioned above by theoretical models, it is also present in other studies. This niche also includes partnerships with other public or private institutions and access to sports facilities (Martindale & Mortimer, 2011), equipment and financial resources (Pankhurst & Collins, 2013, Costa et al., 2021b), professional monitoring (Mazzei et al., 2012), and the social skills of coaches (Cunha et al., 2010).

Given this scenario, the objective of this study was to identify the training environment and its relationship with talent development from the perspective of Brazilian athletics coaches. Considering the multidimensional nature of talent development, the hypothesis is that this training environment has more than one dimension and is not limited to the physical structure used by athletes.

MATERIALS AND METHODS

Study characteristics

This is a qualitative, descriptive, and retrospective study (Marconi & Lakatos, 2011). This approach allows us to interpret the meanings attributed by coaches to the structures that make up the training process for track and field athletes in Brazilian contexts.

The period was defined as 2012 to 2019, referring to two Olympic cycles. The Olympic cycles determine the organization of training planning, which is a reference in setting competitive goals. The observational design structure established here, even though it is a qualitative study, was characterized as nomothetic, with a static and unidimensional nature in terms of the data, and used only primary parameters, which, according to Anguera et al. (2011), allow for distinguishing between frequency, order, and duration.

Participants

Five athletics coaches (four men and one woman) participated, with an average age of 44.8 ± 6.0 years and 15.4 ± 6.7 years of experience in the sport, who worked in Mato Grosso, Brazil, between 2012 and 2019. All had formal ties with clubs or educational institutions and, as an inclusion criterion, had worked with young athletes who had achieved significant results in international competitions (Table 1), this factor being determined by the coach's effectiveness, according to Filgueira Perez (2016). At the time of the study, the state had 10 coaches, but three did not meet the inclusion criteria because they did not have significant results in international competitions. Of the seven coaches in the state, two refused to participate in the study, leaving 71.4% of the sample in relation to the population.

Instruments and procedures

A semi-structured in-depth interview technique was used, consisting of open-ended questions related to the training process and available structures. A previously established script was followed to assist in conducting the interview and understanding the facts (Manzini, 2012). The interview questions were based on the

theoretical dimensions established from the DMGT theoretical model (Gagné, 2013), which details the aspects that make up the structure necessary for the coach for the TD process.

Table 1. Profile of the coaches participating in the study.

Coach sex	Professional data Time/level IAAF	International results	1st or 2nd place	Year
C1 ♀	08 years Level I	Long jump	South American Youth Games (U18), CHI Youth Olympic Games, ARG South American U20 Athletics Championships, COL	2017-2019
C2 ♂	25 years Level II	3000 and 5000 m	South American U18 Athletics Championships, ARG South American U20 Athletics Championships, ARG	2012-2013
C3 ♂	18 years Level III	Javelin Throw, Triple Jump, 100 m and 200 m	Youth Olympic Festival, AUS South American U18 Athletics Championships, ARG South American Youth Games (U18), CHI World U18 Athletics Championships, KEN World U20 Athletics Championships, FIN South American U20 Athletics Championships, COL	2013-2019
C4 ♂	10 years Level II	200 m and 4x100 m	South American Youth Games, PER Youth Olympic Games Qualifier, COL South American U20 Athletics Championships, ECU	2013-2015
C5 ♂	16 years Level II	800 m, 1500 m, 3000 m and 10000 m	South American U18 Athletics Championships, ARG South American U20 Athletics Championships, ARG Youth Olympic Games Qualifier, COL South American Youth Games (U18), CHI Youth Olympic Games, ARG	2012-2019

Notes: ♀: Female; ♂: Male; CHI: Chile; ARG: Argentina; COL: Colombia; AUS: Australia; KEN: Kenya; FIN: Finland; PER: Peru; ECU: Ecuador.

The interviews were conducted individually and online, using Google Meet and Web Room applications, and recorded using the DU Recorder application for later analysis. The interviews were conducted by the researcher, who is a Level 1 athletics coach certified by the IAAF, with two years of experience in Mato Grosso state and participation in official competitions as a technical assistant.

The following themes, based on studies by Henriksen and Stambulova (2023), were used to structure the roadmap: club resources, coaches and their skills, training facilities, city infrastructure; and Elumaro et al. (2016), addressing: home, school, community, sports culture, and support for athletes.

The study followed the ethical precepts of research involving human subjects, with approval from the UFMT Health Research Ethics Committee under No. 245256190.0.0000.8124 (opinion No. 3,849,709).

Data analysis

The collected data were processed and analysed using Content Analysis (Bardin, 2016), and NVIVO 12 Pro software was used to manage and support this analytical process.

The focus of the study, in understanding the perspective of coaches, required concentration on qualitative aspects, in line with the examination of the meanings and underlying sense of verbal messages (Lara & Molina, 2011). The communicational interpretation adopted was that of deductive thematic analysis, following the phases proposed by Braun et al. (2016). After transcribing the interviews, the credibility of the data was established through a validation process by the participants, with the coaches confirming their original discourse.

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The analytical phase continued with familiarization with the content and subsequent coding, in which the raw data were categorized in NVIVO software. This process involved the creation of "*nodes*" through the selection of text units, called mini-units (MUs), grouped into categories, indicating the frequency of occurrence of the themes. After refining the categories and reviewing the statements, the results report was prepared.

RESULTS

The interviews showed that coaches' perceptions of sports talent development are related to the structural conditions of each context. The content analysis yielded a total of 151 MUs, distributed into two main categories, each with its respective themes (nodes), as shown in Figure 1.

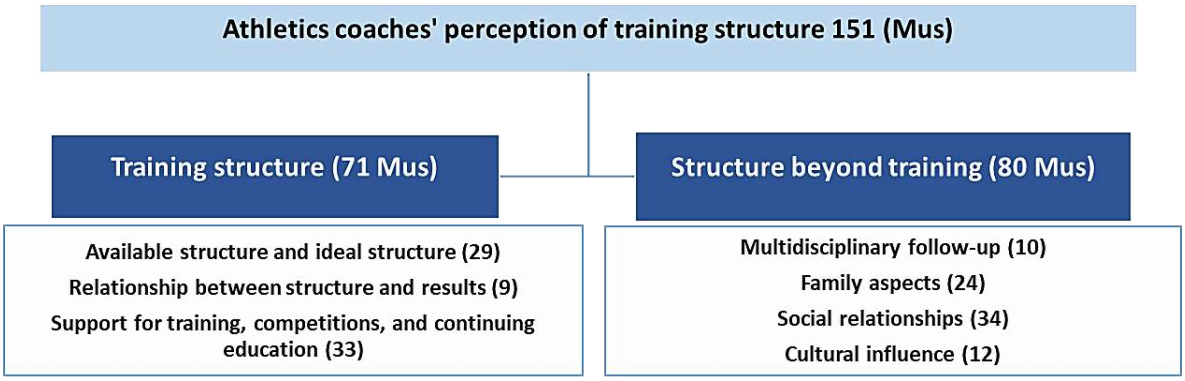


Figure 1. Categories and themes containing the mini-units (Mus) emerging from the content analysis of the interviews with the coaches.

From the emergence of these categories, it was identified that the promotion of sporting talent depends not only on the environmental structure, a concept contained in theoretical models of talent development, but also on contextual and human aspects that go beyond the sporting environment. The results indicated that coaches recognize the importance of structural conditions, whether physical, human, or social, as determinants for the performance and continuity of their athletes, revealing in their discourse both the limitations and adaptation strategies in the face of scarce resources, as well as the transformative potential of sport in the lives of young people and in the local sports culture.

The results are presented in two main sections according to the categories generated: environmental structures for training and structures beyond training.

Training structure

A. Available structure and ideal structure

Of the facilities available to the coaches, all stated that they had a dirt track and that this condition remains unchanged. As for improvements, there was a big difference between two coaches. Coach (C) 2 pointed out that his facility was very poor, working with adapted equipment, such as bamboo darts. However, he made great improvements, such as implements for various events, even a rubberized jumping track.

The C5 pointed out that even with the construction of the athletes' house, the facilities for the events still need improvement, as there are still no adequate environmental structures for training. Unlike the environmental

structures available, the coaches were unanimous in their opinion regarding the environmental structures that are still needed or that would be ideal.

> "*The synthetic track! What we needed to add, to improve our athletes' results*". (C1)
> "*Today, what is mainly missing here for us, which we didn't have in 2012 and still don't have here in 2020, I'm talking about 2019/2020, is the official track*". (C2)

In addition to improvements to the track, coaches reported aspects such as assistance from psychologists, physiologists, and physical therapists, as well as various physical aspects to create an ideal structure.

> *"(...) ideally, you would have all the facilities and support you need, a good track, a gym, a physical therapy lab for recovery, a pool, everything... and a psychologist, a doctor, good nutrition—all of that would be part of the physical structure, which would be ideal*". (C4)

On the other hand, many coaches said they no longer found themselves in precarious conditions. Most expressed their desire for improvements in their track conditions and the need to have more professionals working alongside them in the DT process. Thus, the direct relationship between improving infrastructure and promoting talent, as well as achieving good results, is clear.

B. Relationship between structure and results

There is a relationship between the efforts of coaches to obtain better environmental structures and the behavioural efforts of athletes to achieve results, to take advantage of these structures, and that financial resources permeate between these two points.

> "(...) *because when you leave a dirt track and compete on a synthetic track, it mainly changes for technical events such as the long jump, triple jump, and high jump, where each athlete has their own running mark (...) the track is faster, so your run ends up increasing and you are faster*". (C1)
> "*So, saying that structure will make an Olympic athlete is a lie. The first structure you need to become an Olympic athlete is human, it's the will, it's the desire. That's the first structure. If you don't have that first structure, any other structure is rubbish, it's throwing money away*". (C4)
> "(...) *because in the project, it is not enough to have resources, organization, and structure; if there are no results, it will not move forward, so it all comes down to results. If there are no results, you will not get investment in it; the city, state, or company will not want to finance it*". (C2)

C. Support for training, competitions, and continuing education

Support for training

For coaches to carry out their training sessions, a favourable situation was identified, given that three of them are paid for their exclusive work in athletics. Two others work voluntarily, as they are physical education teachers in elementary schools. However, even coaches who receive funding to work in athletics pointed out difficulties.

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> "(...) we can't complain that our Institute is sponsored by Energisa and Unimed, but we worked anyway because we love what we do, right? Because if we thought about it financially, we would have given up halfway through". (C1)

The volunteer coaches described receiving sporadic payments for the work they did with their athletes. Because the project involved children in vulnerable situations, they were also able to secure partnerships with public agencies.

> "*I received incentives for personal training from CBAt, a coaching grant linked to the athlete's results. If the athlete performed well, the coach also received a bonus, so yes, I did. In 2015, with Allifer and Isabela*". (C4)
> "*After that, we also had a partnership with the Ministry of Labor in 2018 and 2019, a resource for the athletes' house (...) so we have good partners here (also in the city), what we don't have is money, for example, a credit at the supermarket that the judge went there, bought the food, and delivered it to us*". (C5)

Unlike in the past, there are now coaches who dedicate themselves exclusively to coaching and receive other incentives, ranging from trips to competitions, festivals, sports equipment, among others, funded by the local government and agricultural cooperatives.

> "*So, since then, there has been a change in management and today there is much better support, even though parents still don't get involved in the finances of their children who participate in the athletics team here. The city government finances all events, all trips, food, accommodation, including airfare, everything*". (C2)

Belonging to this theme of promoting training, athletic scholarships are also an important form of support, and coaches were asked whether their athletes received this assistance (Table 2). As a result, some athletes received it, which was a way to motivate and keep them practicing and within the TD process.

Table 2. Conditions for athletes receiving the Athlete Grant.

Coaches	Athletes who receive financial assistance
C1	"*They receive it, Lissandra herself (...) has the International scholarship*".
C2	"*So, talented athletes get athletic scholarships quite easily (...). So athletes do have financial incentives*".
C3	"*We have about 20 athletes who benefit from the federal and state athletic scholarship program*".
C4	"*Federal athlete scholarship, all federal, none received state*".
C5	"*Yes. Today, Francielly receives 900 reais per month, Evandro receives 900 reais, Duda receives 400 reais per month, and Lucas Pinho receives 1,800 reais from an international scholarship because he was the South American champion*".

Among the scholarship recipients mentioned, there are three different levels of scholarships: state, national, and international. However, it is known that this reality changes every year, depending directly on the results of competitions. In addition, the expenses incurred by coaches in taking their athletes to compete are also a way of keeping them in sport, given the recognized importance of financial support in promoting talent.

Support for competitions

The following topic deals with how each coach organizes themselves to take athletes to competitions. Most describe having good conditions thanks to municipal support, with full or partial assistance and partnerships

with other institutions. These came from companies in the city through tax incentive laws and assistance from the army.

> "(...) *thanks to the support we had from the municipality, which was the municipal sports incentive law, I would create a project, calculate the costs of competitions and events, and then a company would sponsor that project*". (C4)
> "(...) *for competitions within the state, we have a partnership with the army bus service. When competitions are outside the state, such as the Brazilian Championship, each athlete pays for their own travel expenses, and we can provide food and accommodation within a military area*". (C1)

There is also disparity in financial terms. While some coaches have the full support of the municipality and have more than ten athletes who receive government support, others work on a voluntary basis and have fewer than five athletes receiving athletic scholarships. This status persisted throughout the period investigated, since coaches who have a better support network within the environmental structures for training also have more athletes with athletic scholarships, maintaining better conditions to work on their TD projects in athletics.

Support for continuing education
The coaches were unanimous in reporting that they had received incentives from athletics organizations, including the CBAt and the Mato Grosso Athletics Federation (MTAF), for their technical training. However, there are some courses offered in other states that still require participants to pay part of the expenses.

> "*For this course, the IAAF pays for your travel and accommodation, so they have their whole system there, the IAAF pays for everything while you're on the course. And when there are these clinics, the Confederation (CBAt) provides accommodation and meals, but you have to get your own travel there, which is usually to São Paulo*". (C3)
> "*The CBAt always offers these courses, but the travel expenses from your city to Bragança Paulista, where the CBAt Training Center is located today, are out of your own pocket. The times I went, I paid for it out of my own pocket, and there you have accommodation and meals*". (C1)

Athletics organizations are concerned with training their coaches and are aware of their economic conditions. To ensure that this happens more frequently, they collaborate by offering courses, sometimes even paying for travel expenses to maintain or improve the quality of MT coaches.

Considering all the items presented, it was noted that the training facilities had a heterogeneity of available elements, since some subjects had to deal with precarious conditions and others had good conditions from the outset. The facilities described above as good did not undergo major changes from 2012 to 2019, and in the most precarious facilities, there were some improvements justified by the work of the coaches with their athletes.

Structures beyond training

A. Multidisciplinary follow-up

All coaches reported receiving multidisciplinary services (Table 3), even if they were working with a single athlete, as in the case of C1 with the physical therapist. Over the years, partnerships in the projects have

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come from the private sector and have been acquired through the dissemination of the results achieved by the project.

Table 3. Multidisciplinary support provided to athletes.

Coaches	Multidisciplinary follow-up and other details	Through
C1	Physical therapist (one athlete) and psychologist (2015 for all athletes)	Partnership
C2	Physical therapist (focus on injuries for everyone) and psychologist (minority of athletes)	Municipality
C3	Physical therapist (for all athletes)	Municipality
C4	Physical therapist (2015 and 2016 for all athletes)	Partnership
C5	Physical therapist, doctors, and dentist (for all athletes)	Partnership

The initiative is still modest, with the exception of C5, which, despite having a training structure that is still precarious, received more significant multidisciplinary support.

B. Family aspects

The financial participation of family members/guardians is non-existent, as stated by three coaches, but was mentioned by the other coaches. This fact may be linked to the socioeconomic status of the parents, which, as pointed out by most coaches, is precarious. Table 4 shows the details of this information.

Table 4. Support, financial situation, and housing conditions of athletes' parents.

Coaches	Financial support from guardians	Housing conditions
C1	*"(...) parents are good partners*"	"*About 80% have good housing conditions*"
C2	"*In early 2012, the family was the 'sponsor,' right? (...) Today, parents don't get involved in their children's finances*"	"*In very poor conditions. And it was very small, very humble indeed*"
C3	"*Some families were very involved (...), there were more who supported it*"	"*Most lived with their grandparents in simpler neighbourhoods*"
C4	"*No, actually, I tried to spare the family as much as possible*"	"*Most live in more peripheral neighbourhoods, some in houses donated by the government, others still in wooden houses*"
C5	"*It's zero! Zero, nothing*."	"*Most of them are boys from the suburbs, all surviving on minimum income*"

Most live with their parents or grandparents (C3), but in precarious conditions, in very small houses located on the outskirts of town and living on minimum wage incomes. Considering this financial situation, most of these athletes belong to a disadvantaged group in society.

C. Social relationships

This subtopic consists of questions regarding relationships between athletes, between athletes and their families, and between coaches and their athletes. Regarding relationships between athletes, all coaches described their quality as good, as shown in the following excerpts.

> "*Look, thank God there is a very good camaraderie among them, especially because we defend this social aspect of behaviour. I have never had any issues with my athletes that are beyond our control*". (C5)
> "*There were a few arguments and such, but I always managed to get around that. I never had any behavioural problems with them, especially in competitions*". (C4)

Regarding the relationship between athletes and their families, four coaches pointed out that it was not always easy, but that it changes over time. C2 provides an overview that was also mentioned by the other coaches.

> "(...) *There are those who are good children and those who are not so good, there are those who have good parents and those who have not so good parents, and we as coaches end up influencing the relationship between parents and children. We visit the family to see how the child is doing, when there are adverse situations at school that the parents are sometimes unaware of, promoting this socialization between the family*". (C2)

The promotion of socialization with the family was also present in the descriptions of other coaches, who make athletics an important tool in bringing families closer together and valuing them. When athletes are not solidly committed to practicing sports, the absence of the family is a determining factor in the abandonment of many of them.

Regarding the relationship between coaches and athletes, different descriptions emerged about how they were treated. Among them, there was a report of a change in attitude perceived by one coach as beneficial to the growth of the project.

> "*Very good, I'm strict. Discipline causes some stress, you know that, but I've always maintained a lot of respect and they respect me... when I walk down the street, if they see me coming, they sit up straight because the teacher is coming*". (C3)
> "*I've always been very playful, and I also work on the professional side of training. I've always talked a lot and listened to them a lot in all aspects, you know?*". (C4)

Based on the reports, the athletes get along well with each other, but the same cannot be said for their relationships with their families. However, one of the highlights of participating in MT athletics projects was the promotion of socialization with the family, with most coaches valuing their involvement in talent promotion activities, as this support becomes another reason for athletes to remain in the process.

D. Cultural influence

To conclude the subcategory of structures beyond training, coaches responded to whether the work they did influenced the city's sports culture.

> "*We are highly respected here in the municipality, you know, the people, the community, the press, society really respects athletics, they know how important athletics is for children's socialization, changing their lifestyle and behaviour*". (C3)
> "*Here we still have a little bit of publicity for athletes in the local media. They are recognized at school, in the neighbourhood, and in a way, other athletes who have even become Brazilian champions have looked up to those who were appearing. This made the sport a little more popular in the city, so much so that I ended up with more than 100 students (...)*." (C4)

It should be noted that cultural influence can be a way to strengthen the sport and promote it in the city, as well as its benefits to local practitioners. These aspects could become a means for coaches to obtain more investment for the structures necessary for athletics, promoting higher quality TD.

DISCUSSION

The present study aimed to identify the training environment and its relationship with talent development from the perspective of Brazilian athletics coaches. The hypothesis was that the training environment had more

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than one dimension and was not limited to the physical structure used by athletes. The results revealed two dimensions or categories of the training environment, namely the training structure (71 MUs) and the structure beyond training (80 MUs), which in turn were subdivided into three and four subcategories, respectively, accounting for a high number of MUs identified in the coaches' discourse.

The findings reinforce that the process of developing athletic talent is multidimensional and depends as much on spatial and material structures as it does on the social and institutional networks surrounding the athlete. This understanding is consistent with ecological models of talent development (Henriksen et al., 2010; Henriksen & Stambulova 2023), which highlight the interaction between material resources, human relationships, and sports culture as determinants of long-term success.

Although coaches point out that good facilities and equipment can provide safety and motivate athletes to achieve better results, the lack thereof obviously hinders this process, but does not prevent it from happening. Other studies in athletics corroborate this result and indicate that athletes and coaches alike suffer from a lack of financial support and access to the facilities necessary for effective development (Elumaro et al., 2016; Santos et al., 2020, Costa et al., 2021a). In contrast, there is a need for coaches to be in an environment conducive to the production and development of athletes (Wiman et al., 2010), and many clubs are successful in athletics because they offer a suitable environment and good opportunities for coaches and their respective athletes (Henriksen et al., 2010).

To address the dynamics necessary for both (coach and athlete), Henriksen and Stambulova (2023 p.06), when examining empirical case studies of successful environments in various sports and countries, highlight the important role of health and well-being as an essential resource for the performance and personal development not only of athletes, but also draw the attention of researchers and professionals to "*investigate and promote healthy environments for coaches, managers, colleagues, parents, and sports psychology consultants who influence athletes*". These authors complement the importance of not placing athletic performance above all else but rather seeking balance in the athletic environment.

The athletics coaches investigated demonstrated an active role in overcoming structural limitations, adopting creative strategies to enable training even in contexts of material deprivation. This stance reinforces what the literature points out about the multifunctional role of the coach, who, in addition to being responsible for technical planning, also acts as a manager, social mediator, and values trainer, as confirmed by the studies by Caregnato (2017) and Elumaro et al. (2016) in athletics, and Ramos et al. (2025) and Taylor and Bruner (2012) in soccer. Furthermore, according to a scoping review on talent in volleyball, De Oliveira (2024) states that coaches have a high capacity to detect talented athletes, as they can identify potential characteristics that test batteries cannot measure.

As athletes' performance levels rise, coaches' skills and efforts also increase to compensate for the lack of environmental structures in promoting talent. The coach is part of the DT not only in training, but also in creating an environment for success through dialogue between people in the athlete's context (specialists, teachers, clubs, families, and athletes), with the aim of ensuring that everyone is on the same page and that activities are coordinated, as mentioned in the soccer studies by Storm et al. (2025) and Ramos et al. (2025).

When considering the category of training facilities, two distinct groups were observed: coaches who had good facilities from the outset, and those who had to develop strategies to operate even without basic materials. Most coaches belong to this second group, and, despite the limitations, they achieved gradual improvements between 2012 and 2019, mainly with the support of city governments and partnerships, such

as the construction of the "*athletes' house*," which represented one of the improvements in training conditions and highlights the importance of the participation of various sectors in strengthening the sport. Thus, it is reiterated that nations that invest more in sport can provide more opportunities for athletes to train in ideal circumstances, such as building a strong organizational structure (De Bosscher et al., 2006) with a long-term view (Zhang & Wei, 2025).

These findings are consistent with Caregnato (2017), who analysed partnerships between the Ministry of Sports and the CBAt aimed at creating the National Athletics Training Network, with significant investments between 2011 and 2019. A club in Mato Grosso mentioned in this study, belonging to the group with the best structural conditions, illustrates how infrastructure and sporting results are strongly related, as it has the largest number of athletes receiving scholarships, confirming the relevance of environmental structures for the promotion of sporting talent.

As for the ideal structure, coaches highlight the need for synthetic tracks, well-equipped gyms, multidisciplinary monitoring, and psychological support. However, coaches emphasized that such conditions only become effective when accompanied by effort, commitment, and engagement from athletes and coaches. Mazzei et al. (2012) reinforce that, in Brazil, only a few sports, such as soccer, volleyball, and archery, have complete and integrated structures. In other sports, the lack of resources requires greater human and pedagogical effort from coaches, which is confirmed in the context of athletics in Mato Grosso. Furthermore, parents are not always helpful in this process of engaging athletes, as their behaviour can have a negative influence, putting pressure on athletes instead of encouraging them (Ramos et al., 2025, Zhang & Wei, 2025).

As for training incentives, most coaches receive specific remuneration for their work in athletics, although some work on a voluntary basis. This reality contrasts with that of other sports such as basketball, where many professionals need to take on multiple jobs to ensure their livelihood (Reis et al., 2016). Henriksen et al. (2010) observed a similar situation in Sweden, where volunteer athletics coaches have excellent infrastructure conditions, the opposite of the Brazilian reality, where a scarcity of resources forces coaches to seek and sustain their own means of working.

In the case of athletes, only a minority receive this financial assistance from the Bolsa Atleta program, with the most significant support for athletics concentrated in the Southeast and South regions, with the Midwest in second-to-last place (Anunciação et al., 2017). This scenario reinforces the vulnerability of sports projects in the Midwest and limits the smooth development of new talent, requiring coaches to make greater efforts to retain and motivate athletes.

Support for competitions proved to be more consistent, as most coaches reported receiving partial or full support from municipal agencies and institutional partnerships, such as local companies and assistance from the Army. In addition to the motivational factor, participation in competitions represents a gateway to financial incentive programs and, consequently, to the continuity of the process of developing talent in sport, since financial incentives are one of the reasons for starting and continuing in athletics, according to Costa et al. (2021b). According to Caregnato (2017) and Martindale & Mortimer (2011), competitive experience, combined with a favourable training environment, is one of the main factors for permanence and athletic evolution.

On the subject of continuing education, all coaches reported receiving encouragement and support from athletics organizations (CBAt and FAMT), especially in technical courses. These actions are related to the

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Agnelo-Piva Law (No. 10,264/2001), which allocates resources from the Brazilian Olympic Committee to Olympic sports confederations, promoting professional qualification (Almeida & Marchi Junior, 2011). These training courses strengthen the role of the coach as an agent of change in the sporting environment. The findings of Boeck et al. (2024) reinforce the need for these incentives for continuing education, as in the coaching career, the pursuit of continuous knowledge demonstrates a commitment to training and, consequently, the development of athletes as competitors.

In structures beyond training, multidisciplinary support is limited. All coaches reported receiving physical therapy services, but most through partnerships. Only one of the coaches reported having a full team. This scenario reflects the national reality pointed out by Caregnato (2017), in which coaches accumulate technical, administrative, and pedagogical functions, often without specialized support for the development and/or promotion of sporting talent.

Still on the subject of multidisciplinary support, Raposo & Rosado (2025), in their quest to identify the most important factors in professional training and coach efficiency, concluded that "*multidisciplinary support involving professionals from areas such as medicine, biomechanics, physical therapy, nutrition, psychology, and rigorous management of the training and competition process*" are decisive factors for success in high-performance swimming. This result reinforces the need for a broad environmental structure, in addition to the physical environment, to remain among the international sporting elite.

In terms of family background, it was found that most athletes belong to low-income families, live in peripheral areas, and have poor housing conditions. In this context, athletics emerges as a tool for inclusion, social mobility, and better living conditions for athletes in MT. These findings corroborate those of Santos et al. (2020), who identified athletics as a path to personal and social advancement for young athletes from lower socioeconomic backgrounds, as identified in one of the reports: "*Athletics changed my story, and because of it, today I am a teacher, a respected citizen.*" The improvement in the relationship between athletes and their families, promoted through the practice of athletics, was highlighted as one of the most positive impacts of the projects analysed (Souza et al., 2024).

Cultural influence also proved to be relevant in this study. Coaches reported that the results achieved by athletes and the visibility obtained in local and national media contributed to strengthening regional sports culture and inspiring new generations. Studies in various sports, such as those by Almeida & Marchi Junior (2011), and the literature review by Santana, Costa & Purificação (2024) reinforce that media coverage is a key element in consolidating sport as a social and educational practice. In addition, Moraes et al. (2021) advocate the use of community spaces as a strategy for social integration and encouraging deliberate sports practice. Finally, returning to the findings of Henriksen et al. (2010), it is observed that sports environments with a strong organizational culture and cooperative values tend to produce more engaged athletes and more lasting projects. Thus, in the Brazilian context, especially in athletics in Mato Grosso, the strengthening of sporting talent depends on an integrated ecological approach, articulating infrastructure, social support, sporting culture, and continuous training of coaches.

The limitations of this research include the fact that it was conducted during the pandemic, which we understand contributed to the refusal of two invited coaches to participate. In addition, completing all interviews took considerable time, as we depended on the availability of the participants. Further research with coaches from different sports within the state, as well as with athletics coaches in other Brazilian states, may help compare data and generate broader national evidence on this topic. This study advances our

understanding of how athletic talent develops to reach relevant national and international performance, even in contexts characterized by various forms of precariousness.

CONCLUSION

The study highlighted, from the coaches' perspective, the multidimensional nature of what is understood as the environment in the development of athletic talent. Despite working in contexts marked by social inequality, the coaches' narratives identified both the available and ideal environmental structures, the relationship between structure and performance outcomes, incentives for training, competitions, and continuing education, multidisciplinary follow-up, financial support from guardians, social relationships, and cultural influences. Although resource scarcity is a recurring challenge, the adaptability, resilience, and communication skills of athletics coaches proved to be decisive factors in ensuring the continuity and quality of the developmental process.

The analyses revealed that spatial structure and sports equipment alone do not guarantee talent development; rather, they become meaningful when combined with the coaches' commitment, athletes' motivation, and the support of social and institutional networks. Thus, the training environment must be understood broadly, encompassing physical, human, and cultural dimensions. The findings also indicate that financial support and local partnerships are crucial for the sustainability of projects, and that family and community engagement strengthens young athletes' connection to the sport and expands its social impact. Coaches act as mediators between the social context and the sporting environment, achieving significant national and international outcomes. This demonstrates that talent is indeed being developed within these contexts, while also contributing to transforming athletics into a space for human development and social inclusion.

AUTHOR CONTRIBUTIONS

RB: methodology, data curation, data analysis, and writing of the original draft; TM: methodology, writing of the original draft, and writing, review, and editing; DC-M: writing of the original draft; SD: writing of the original draft; AP: writing of the original draft; SR: methodology, data analysis, and writing of the original draft; LA: methodology, data curation, data analysis, and writing of the original draft, as well as writing, review, and editing.

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ORIGINAL ARTICLE

The effect of upper body plyometric training program on young women volleyball players in their usual training program

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ABSTRACT

The study was to find out the effect of upper body plyometric training program on young women volleyball player's hand grip strength and upper body explosive power in their usual training program. For this study, twenty-four female volleyball players were selected as the participants and they randomly allocated to either experimental group or control group. The experimental group had 8 weeks of training program along with their usual training and control group had not special training. Training effects were analysed by independent t-tests. The significance level was set at .05. Notable improvements in HG and UBES were recorded in post values of between the experimental and control group. [HG: t (11) = -4.020, p < .001], [UBES: t (11) = -3.213, p = .004]. Conversely no significant improvements in HG and UBES were recorded in pre values of between the experimental and control group. [HG: t (11) = -0.954, p = .350), UBES: t (11) = 0.439, p = .665] in performance of both variables. The study concluded that upper body plyometric training program can effective modality for enhancing hand grip strength and upper body explosive power on young women volleyball players.

Keywords: Performance analysis, Upper body plyometric training, Hand grip strength, Upper body explosive strength, Volleyball players.

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INTRODUCTION

The sport of volleyball involves a great deal of physical activity, such that the players must possess physical fitness to shine in the game (Kasur et al., 2015; Marques et al., 2009; Sheppard et al., 2009). Rapid, forceful actions like serving, spiking, blocking, and setting require the shoulders, arms, and hands to be heavily involved as players are expected to perform them most of the time (Marques, et al. 2009). Continuous and repetitive movements constitute the characteristics of the game, thus exerting considerable pressure on different muscle groups (Chelly et al., 2009). To fulfil such requirements, athletes have to produce the maximum force repeatedly with physical efficiency during the match. With the competitiveness and speed at which the game is played, particularly in youth and elite levels, physical fitness becomes the utmost priority (Sheppard et al., 2009). In this regard, the upper body strength and explosive power have become a crucial factor in successful performance in attacking and defensive behaviours. In addition to it, a physically fit athlete can maintain strenuous activity without premature exhaustion, which gives any participant a tremendous competitive advantage (Gabbett, 2016). With the ever-growing competitive standards, there is a greater rise in demand for players who are technically competent and also have better physical relatedness. Volleyball requires greater upper body strength, explosiveness, and gripping strength due to the physical exertion requirements of the sport, especially in athletes in the developmental stage (Marques et al., 2008).

Volleyball is a game that involves coordinated muscle movements, especially among the arms, shoulders, chest, and forearms, so that athletes can coordinate forceful strikes with balls that cause repeated contacts, but remain in control and precise (Chou et al., 2025). On the other side, a strong grip is essential in managing the ball in receiving, setting, and spiking, and in the overall effort in striking and blocking (Camacho-Villa et al., 2024). Increased grip capabilities also help to avoid injuries related to the wrist and forearms and contribute to stability in the joints. Grip strength is unlikely to be a main emphasis of a volleyball conditioning program, even though it is important (Wiliński et al., 2022).

Compared to their traditional strength training protocols that mostly focus on enhancing the overall muscular strength, the traditional strength training may be unsuitable to meet the sport-specific explosive demands of volleyball. The more dynamic plyometric training or upper-body plyometric training (UBPT) aims to increase neuromuscular efficiency and power production and reactive strength by facilitating stretch-shortening cycles (SSC) (Garcia-Carrillo et al., 2023). Uniting the upper body plyometric training can also indirectly reflect on the better grip strength, as it targets the forearm muscles that focus on producing the same explosive pushing and throwing. In addition, plyometric exercises above the waist not only improve the power production capacity but also lead to better proprioception, joint stability, and movement economy in play (Wang & Xu, 2025).

Although the benefits of the plyometric training on lower-body performance of players in volleyball were reported in the past, little is known of the isolated effects of upper-body plyometric training on specifically named measures of hand grip strength and explosive power in upper-body performance. The results could help facilitate the implementation of sport-specific conditioning and educate coaches and trainers about the strategies enhancing volleyball performance optimization. However, there is few studies have examined the plyometric training affects grip strength and overall upper body explosive power in the field of volleyball. Addressing this gap could provide valuable insight into the performance enhancement. Therefore, the purpose of this study to find out the effect of upper body plyometric training program on young women volleyball player's hand grip strength and upper body explosive power in their usual training program. The findings may provide valuable insights into the effectiveness of UBES on these variables to inform coaches,

strength and conditioning professionals, and athletes about the need to maximize performance with the help of holistic methods of training.

MATERIALS AND METHODS

Participants

Twenty four female volleyball players from SRM Institute of Science and Technology, Kattankulathur, Chennai were selected as the participants for the study. The investigator informed benefits and risk of the study. Injured or illness players not selected for the study and all the participants had 5 years volleyball training background. Informed consent was collected from all the participants. They were randomly allocated to either experimental group or control group with 12 participants each group.

Experimental design and procedure

This study was a longitudinal training experiment; the experimental group had 8 weeks of upper body plyometric training program along with their usual training and control group had not special training. Pre and post testing completed before and after training program.

Training program

The participants had two training sessions per week, and duration was 90 minutes. The participants in experimental group completed the upper body plyometric exercises. All the participants have got detailed instruction about how to perform exercise properly before starting the training program.

Table 1. Training program of 8 weeks upper body plyometric training.

Week	Warm Up	Exercises	Sets	Reps	Rest(Min)	Warm Down
1-2	Dynamic	Medicine ball chest pass	3	10	1	Limbering down exercises, static stretching
3-4	stretching,	Plyometric pus-up	3	15	1	
5-6	Rotatory	Two hand over head throw	4	10	1	
	movements,	Two hand side to side throw				
7-8	Mobility	Single arm throw	4	15	1	
	exercises	Power drop				

The training program starts with 10 minutes of warm up period which includes dynamic stretching, rotatory movements, and mobility exercises. After the warming up session, the participants were a performed plyometric exercise which includes six exercises and after finishing starts with warm down exercises. Detailed training schedule presented in the Table 1.

Criterion measures

Pre and post tests were conducted before and after an eight week training program. Hand grip strength (HG) and upper body explosive strength (UBES) were measured by hand grip dynamometer and Medicine ball throw test (Genç, & Dağlıoğlu, 2021; Kim et al., 2022; Turgut et al., 2019).

Statistical analysis

In this study, several statistical methods were employed to analyse the data. The Shapiro-Wilk test indicated that the data were normally distributed ($p > .05$); therefore, parametric tests were employed in this study. After confirming normality Independent t test were used to assess the effect within the group. The significance level was set at .05 level. SPSS software was used for analysis.

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RESULTS

The baseline characteristics of the experimental group and control group including age, height, and weight were compared before the training (Table 2). The results indicated no statistical difference (p > .05) in baseline characteristics. These results demonstrate that the two groups were similar at the baseline, meaning that the difference that takes place thereafter can be ascribed to the training program and not to the existing differences.

Table 2. Results of independent t test for identifying Base line group difference of experimental and control group on selected variables.

Group	Mean ± SD		*p*-Value
	EG	CG	
Age	20.583 ± 1.50	21.083 ± 1.832	.473
Hieght	171.25 ± 10.61	168.917 ± 9.08	.569
Weight	61.083 ± 7.16	59.083 ± 6.748	.489

Note. EG = Experimental group, CG = Control group, Data are presented as Mean ± SD, Level of significance = .05.

Table 3. Independent t test between pre values of experimental and control groups.

Variables	Mean ± SD		Mean difference	95% CI for mean differences		t	*p*-Value	Effect size d
	EG Pre	CG Pre		Lower	Upper			
UBES	3.304 ± 0.564	3.096 ± 0.504	-0.208	-0.661	0.244	-0.954	.350	-0.390
HG	29.442 ± 4.927	30.150 ± 2.638	0.708	-2.638	4.054	0.439	.665	0.179

Note. Note: HG = Hand grip strength, UBES = Upper body explosive strength, EG = Experimental group, CG = Control group, Level of significance = .05.

The Table 3 compares the pre-test performance of the Experimental Group (EG) and Control Group (CG) on two variables: Upper Body Explosive Strength (UBES) and Hand Grip Strength (HG). It shows that there were no significant differences in both UBES (p-value of .350 > .05) and HG (p-value of .665 > .05) between the experimental and control group during Baseline, confirming that both groups were comparable before the intervention.

Table 4 presents the post-test comparison between the Experimental Group (EG) and Control Group (CG) for Upper Body Explosive Strength (UBES) and Hand Grip Strength (HG).

Table 4. Independent t test for post values between EG and CG.

Variables	Mean ± SD		Mean difference	95% CI for mean differences		t	*p*-Value	Cohen's d
	EG Post	CG Post		Lower	Upper			
UBES	3.975 ± 0.580	3.104 ± 0.476	-0.871	-1.320	-0.422	-4.020	<.001	-1.641
HG	34.133 ± 3.257	30.250 ± 2.630	-3.883	-6.390	-1.377	-3.213	.004	-1.312

Note. HG = Hand grip strength, UBES = Upper body explosive strength, EG = Experimental group, CG = Control group, Level of significance = .05.

For UBES, the EG (3.975 ± 0.580 m) showed a considerably higher mean score compared to the CG (3.104 ± 0.476 m). The mean difference was –0.871, with a 95% confidence interval ranging from –1.320 to –0.422, which does not include zero. The t-value (–4.020) with a p-value < .001 indicates a highly significant difference in favour of the experimental group. The effect size (Cohen's d = –1.641) suggests a very large effect, highlighting a strong impact of the intervention on UBES.

For HG, the EG (34.133 ± 3.257 kg) also recorded higher mean values compared to the CG (30.250 ± 2.630 kg). The mean difference was –3.883, with a 95% confidence interval between –6.390 and –1.377. The t-value (–3.213) with a *p*-value of .004 (<.01) shows a statistically significant difference favouring the experimental group. The effect size (Cohen's d = –1.312) indicates a large effect, confirming a meaningful improvement in hand grip strength for the EG compared to the CG.

The independent t -test results reveal that the experimental group showed significantly greater improvements than the control group in both upper body explosive strength and hand grip strength, with large effect sizes. This indicates that the intervention was highly effective.

DISCUSSION

The study was found out the effect of upper body plyometric training program on young women volleyball player's hand grip strength and upper body explosive power in their usual training program. The findings of the study indicate that upper body plyometric training program significantly improved both hand grip strength and upper body explosive power compared to the control group after the intervention. These observations emphasize the effectiveness of upper body plyometric training in improving hand grip strength and upper body explosive power.

The results of the present study are in line with earlier observations; plyometric training has always proven to be an effective tool in improving sport-specific physical qualities in various sports (Ramirez-Campillo et al., 2022). Our study results are consistent with the previous studies, for instance, experiments with handball players (Yanti et al., 2024), ball badminton players (Sawant, 2023), and volleyball players (Pereira et al., 2015) have shown that not only upper body performance, such as throwing strength but also lower body performance, such as vertical jump and extremity power were significantly enhanced through plyometric exercises. Even a short-term intervention on a 4-week upper extremity program involving wheelchair athletes (PASHA et al., 2024) resulted in enhanced trunk balance and fitness. And longer intervention, such as a 12-week program in soccer players (Siby et al., 2025) resulted in overall improvements in agility, speed, explosive power, leg and core strength. All of these studies cumulatively prove that plyometric training improves explosive and functional capacitive tasks related to competitive sport.

Plyometric training has become one of the most effective modalities in terms of the simultaneous acquisition of game-specific abilities, as well as various physical qualities in a wide range of sports (Zhou et al., 2024). Plyometric training in the upper body of volleyball players during a sports season has been shown to dramatically enhance the speed of a spike (Valadés Cerrato et al., 2018) and another study affirmed that plyometric training in the upper body also enhances the performance-relevant skills in serving among female volleyball players (Uzor et al., 2023), showing a direct transfer of plyometric training into a performance-relevant technique. In addition to skill improvement, plyometrics also addresses the various aspects of athletic capacity: a 10-week intervention in young handball female athletes led to significant gains in handgrip strength, back extensor strength, medicine ball throw, sprint performance, change of direction and vertical jump ability (Hammami et al., 2020). This and similar findings explore that plyometric training is not only specific to the refinement of game-specific actions crucial to the success of sports, such as volleyball, but also produces wide-ranging multidimensional benefits among athletes across different competitive environments.

Plyometric training is effective in improving physical capacities as well as game-specific performance in a variety of sports (Ramirez-Campillo et al., 2023). Our study results are reliable with previous studies, as an

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example, plyometric training of upper limbs among young male tennis players resulted in significant improvements of muscle strength, power, and serve velocity (Wang & Xu, 2025), whereas a combination of ten exercises of throwers with plyometric weight training resulted in significant increases of throwing distance, as well as the strength of the hand grip in shot put athletes (Ramkumar et al., 2024). In the same line of thought, upper-body plyometric exercise produced significant gains in maximal strength, medicine ball throw, sport-specific throwing performance, and the volume of upper-limb muscle among youth and young adults (Garcia-Carrillo et al., 2023). These results are further supported by laboratory data, which indicates that manipulating the mass of medicine balls during plyometric throwing exercises is effective in increasing the release momentum of the ball and upper-limb power output, thus providing a valid biomechanical explanation of safe load progression (Riemann et al., 2019). Taken together, these results not only develops the essential physical qualities but also transfer directly to game-specific skills, so that plyometric training acts as a dual role as a physical conditioner and technical performance enhancer.

Meta-analytical data support the use of plyometric training in the development of overall physical qualities and sport-specific abilities with a high level of evidence. A meta-analysis of 11 studies with 302 respondents reported great enhancements in countermovement and squat jumps, change-of-direction, sprint ability, throwing skills, jumping throw, penalty throw, repeated sprint ability, upper-limb peak power and bilateral handgrip strength in handball players (Hang et al., 2025). To add to this, a meta-analysis of 15 moderate-to-high-quality studies that included 523 athletes aged 12-22.4 years in total and used a combination of upper- and lower-limb plyometric interventions, confirmed that such interventions produced significant muscle-power, sprint-speed, strength, agility, and flexibility improvements (Deng et al., 2022). In addition to performance enhancement, plyometric exercise has also been identified as a vital rehabilitation device, which mediates recovery with return to sport by enhancing the stretch-shortening cycle, neuromuscular coordination, and explosive power (Davies et al., 2015). Combined, these meta-analytical results support strong evidence that plyometric training, when done systematically, not only enhances physical fitness parameters but also reinstates sport-specific preparedness, minimizes risks of injury, and necessitates safe and confident re-entry into competitive play. Thus, in this study indicates the favourable effect of upper body plyometric training on hand grip strength and upper body explosive power. So, our study suggests that upper body plyometric training is an effective and practical intervention for enhancing grip strength and upper body explosive power. UBPT an attractive for coaches, strength and conditioning professionals, and athletes to force- enhance volleyball skills like blocking, spiking, serving, and passing which depend on both grip and upper-body speed. Grip strength and upper body explosive power improvements may also help to better joint stability and less fatigue from repeated and quick movements, which could reduce the risk of overuse injuries.

The study showed positive outcomes, but there has few limitations. The size of the sample was small, that can limit the generalizability of results. Moreover, the present study concentrated on variables such as hand grip strength and upper body explosive power, future research could employ more variables and new method of measurements. It is recommended that future research should suggested to use longer training periods, compare with other training modalities, and investigating physical and performance variables.

CONCLUSIONS

Results of the presented study suggest that upper body plyometric training program can effective modality for enhancing hand grip strength and upper body explosive power. essential for volleyball, like rapid and continuous limb movement and force production. The findings add to the literature by showing evidence of benefit on performance that due to the plyometric training in women athletes.

AUTHOR CONTRIBUTIONS

Conceptualization, JD and SJAC; methodology, JD SJAC, and GR; investigation, JD, FS, SKV; resource, JD, GR, FS; data curation, JD and TS; writing, JD, GR; writing review and editing, JD, SKV; supervision, JD AND SJAC.

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ORIGINAL ARTICLE

The body of the traceur: Linking morphology and performance in parkour

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ABSTRACT

Parkour involves overcoming environmental obstacles through running, jumping, climbing, and vaulting, placing high physical demands on practitioners. Although the discipline accommodates diverse body types, anthropometric traits, body composition, and somatotype may influence performance. Previous research has mainly reported basic indicators such as height, body mass, and BMI, leaving gaps in morphological profiling and its relationship with fitness outcomes. This study aimed to characterize the anthropometric profile, body composition, and somatotype of male parkour practitioners and to analyse their associations with standardized physical fitness tests. Twenty-four Spanish male traceurs (23.7 ± 5.6 years; 11.3 ± 4.0 years of experience) were assessed. A predominance of mesomorphy was observed, particularly in more experienced athletes. Significant correlations were found between lower fat mass and superior jump performance (SLJ, CMJ+, 3HPJ; ρ = –0.56 to –0.72, p = .004–.03), between greater leg length and faster sprint times (40 m; ρ = –0.61, p = .02), and between limb girths and improved change-of-direction ability (T-Test; ρ = –0.53 to –0.67, p = .01–.04). These findings underscore the relevance of muscularity and limb proportions for explosive and efficient performance, providing novel reference data for athletes, coaches, and researchers in parkour.

Keywords: Performance analysis, L' art du deplacement, Anthropometrics, Somatotype, Physical conditioning.

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INTRODUCTION

L'Art du Déplacement (i.e.: the art of movement, ADD), commonly referred to as parkour derives from the French term *parcours* ("*course*" or "*route*") and was originally developed in the late 1980s by the group known as the Yamakasi in the suburbs of Paris (Angel, 2011; Sampayo, 2020). From its beginnings in the backstreets of Évry and Lisses, the practice has spread worldwide, evolving into both a form of physical training and a cultural movement. Its practitioners, known as traceurs, progress through environments by overcoming obstacles using their own physical qualities, such as running speed, flexibility, strength, and jumping ability, without the aid of equipment. Movements are performed under conditions of high physical demand, requiring adaptation of the practitioner's abilities to the structural challenges of the environment. The foundational repertoire of movements, vaults, jumps, climbs, and landings, draws heavily from the running and jumping components of sports such as athletics and gymnastics. As a result, many of the physical requirements for success in parkour are shared with these sports, allowing traceurs to navigate demanding environments without reliance on external apparatus (Grosprêtre, Ufland, & Jecker, 2018). Thus, physical conditioning has been a central component of ADD since its inception. This is reflected in the very name Yamakasi, often mistaken as Japanese but actually derived from Lingala, meaning "*strong body, strong spirit, strong person*" (Coline, 2009; Sampayo, 2020; Torchia, 2021). Far from being merely a legacy of the discipline's origins, the emphasis on conditioning remains evident today: recent findings indicate that approximately 73% of traceurs (i.e., parkour practitioners) engage in dedicated conditioning sessions at least once per week (Elizondo-Donado et al., 2025). Beyond structured training, the discipline itself places substantial physical demands on traceurs, requiring the development of jumping capacity, balance, spatial awareness, and impact absorption capacities to move through complex environments and challenge themselves with demanding jumps. In this context, Croft and Bertram (2017) argued that athletes with greater explosive strength were able to tolerate precision landings from higher drop heights before transitioning to rolls. This suggests that enhanced muscular strength not only facilitates the generation of large forces during take-off but also improves the eccentric control required to absorb high-impact landings. In other words, by developing their jumping capacity, parkour practitioners may increase the threshold at which they can safely perform precision landings. This consistent training focus, combined with the considerable physical demands required to perform in parkour, suggests that the body composition and structural characteristics of traceurs may present distinctive features.

While parkour can be practiced by individuals with diverse physical conditions and body types, the anthropometric profile, body composition, and somatotype of practitioners may play a particularly relevant role in performance. These characteristics can influence key physical capacities such as jump capacity, change of direction ability, and sprinting ability, all of which are critical for negotiating demanding movements efficiently and safely (Pagnon, Faity, Maldonado, Daout, & Grosprêtre, 2022). Evidence from sports science highlights that some body types, such as those defined by height, mass, or body shape, are better suited for athletic disciplines (Santos et al., 2014). Nevertheless, it is also recognized that long-term practice can progressively reshape the neuromuscular system, fostering adaptations aligned with the specific demands of the sport (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Cormie, McGuigan, & Newton, 2011; Markovic & Mikulic, 2010; Taube, Leukel, & Gollhofer, 2012). In parkour, few studies have systematically examined these variables. To date, research on the morphology of traceurs has focused mainly on basic indicators such as height and weight, and the subsequent BMI (Dvořák, Baláš, & Martin, 2018; Leite et al., 2011; Maldonado, Bailly, Souères, & Watier, 2019; Seyhan, 2019b; Solano Chamorro, 2016), with a few studies providing more detailed data on body composition and somatotype. Existing findings indicate that traceurs generally exhibit greater body mass compared to climbers, likely reflecting the discipline's explosive nature and its potential role in promoting a shift toward fast-twitch muscle fibres,

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particularly in the lower body (Marchetti et al., 2012). Furthermore, differences in somatotype have been observed depending on expertise, with experienced traceurs showing significantly lower ectomorphy and higher mesomorphy than both beginners and gymnasts (Abellán-Aynés & Alacid, 2016; Seyhan, 2019a). Mesomorphy, which emphasizes muscularity and structural robustness, appears more pronounced in advanced practitioners, while ectomorphy, reflecting leanness and linearity, is less prevalent (Pagnon et al., 2022). The present study seeks to address these gaps by applying standardized protocols to assess anthropometry and body composition in traceurs, offering a more comprehensive description of their morphological profile and its potential implications for performance.

Few studies have examined the relationship between body composition and physical performance in parkour, leaving open questions about how anthropometric traits translate into functional capabilities. In other sports, however, this link has been studied in depth. For example, in CrossFit®, greater muscle mass has been positively correlated with strength outcomes (Menargues-Ramírez, Sospedra, Holway, Hurtado-Sánchez, & Martínez-Sanz, 2022), while in gymnastics, body build and somatotype have been shown to influence both specialization and performance level (Sterkowicz-Przybycień et al., 2019). Similarly, sprinters with greater fat-free mass and mesomorphic traits tend to achieve better results in speed and power events (Barbieri et al., 2017). These findings underline the value of exploring whether anthropometric characteristics can determine or at least influence physical test performance. In parkour, Croft and Bertram (2017) provided initial evidence that body mass and limb length may condition landing strategies, yet the relationship between anthropometry and standardized performance tests remains largely unexplored. Addressing this gap, the present study not only characterizes the anthropometric profile, body composition, and somatotype of traceurs but also examines their association with performance in specific physical tests: standing long jump (SLJ), countermovement jump with arm swing (CMJ+), triple horizontal plyometric jump (3HPJ), 5 climb-ups for time (5CUFT), 40 m sprint (Sp40), and change of direction T-Test. Such an approach provides a more holistic understanding of how morphological and functional characteristics interact to support parkour-specific performance.

The present study aims to: (1) describe detailed anthropometric characteristics, body composition, and somatotype; (2) evaluate performance outcomes in a set of physical fitness tests relevant to parkour; and (3) analyse the correlations between anthropometry, body composition, somatotype, and physical performance in order to identify how morphological traits influence functional capacities. By addressing these aims, this research seeks to provide reference data of practical value for practitioners, coaches, and researchers, offering insights into the physical profile that contributes to parkour performance and safety.

MATERIAL AND METHODS

Participants

The study included 24 Spanish Caucasian male traceurs, with a mean age of 23.7 ± 5.6 years and an average parkour experience of 11.3 ± 4.0 years. Participants were recruited via local WhatsApp training groups. The inclusion criteria for this study were at least 3 years of experience, current regular practice of parkour, ADD, or freerunning, and voluntary agreement to participate. Due to injuries and other minor inconvenience 9 traceurs withdrew from the physical condition testing phase, resulting in 15 male traceurs (23.7 ± 4.08 years old and 10.35 ± 3.40 years of experience) that participated both in the anthropometric measuring and physical condition tests. Participation was voluntary, with all participants providing informed consent, and anonymity was maintained throughout the study. The research adhered to the ethical principles outlined in the Declaration of Helsinki (2024) and was approved by the Ethical Committee of The University of the Basque

Country (UPV/EHU, CEISH, code: M10_2023_112). Participants were informed of their right to withdraw from the study at any time without consequence.

Procedure

This cross-sectional study evaluated the physical performance, anthropometric characteristics, adiposity, muscularity, bone distribution, somatotype and health indexes of traceurs using a combination of standardized functional tests and complete anthropometric assessment. The first phase involved anthropometric measurements, with participants scheduled individually over the course of one week in 45-minute time slots according to their availability. The second phase consisted of the physical performance tests, which were carried out during a single weekend session with all participants present. Both phases took place in March 2024. To evaluate physical performance, participants first completed a standardized guided warm-up (Grosprêtre & Lepers, 2016) designed to enhance readiness and minimize injury risk. The warm-up included 2 minutes of on-the-spot jogging to raise heart rate, followed by 30 seconds each of dynamic knee raises and calf raises to activate the lower limbs, and concluded with 5–10 submaximal jumps to engage the neuromuscular system and simulate the explosive actions required in the tests. Afterward, participants performed a battery of standardized field tests in the following order: five timed climb-ups (5CUFT), T-Test for change of direction ability, 40-meter sprint (Sp40), countermovement jump with arm swing (CMJ+), standing long jump (SLJ), and triple horizontal plyometric jump (3HPJ). Each test was conducted three times with at least 90 seconds of rest between attempts, and the best performance was selected for analysis. All tests were completed within a single session.

Measures

Anthropometric measures, body composition and somatotype

In this study basic anthropometric measurements, skinfolds, girths, lengths, heights and breadths were measured, and 5 component anatomical fractionation, adiposity, muscularity, bone distribution, health indexes and somatotype were calculated. All measurements adhered to the International Society for the Advancement of Kinanthropometry protocol (ISAK, 2016) and were conducted by a Level 2-certified anthropometrist, maintaining technical error of measurement within ≤5% for skinfolds and ≤1% for all other variables. Participants were assessed wearing minimal clothing, with all measurements taken on the right side of the body in duplicate, and the average value used for analysis. Standing height was measured to the nearest millimetre using a SECA 220 stadiometer with participants aligned to the Frankfort plane, and body mass was recorded to the nearest 0.1 kg using a calibrated medical scale. Additional basic anthropometric variables included sitting height and arm span. Skinfold thickness was assessed to the nearest millimetre at eight sites (triceps, biceps, subscapular, abdominal, suprailiac, iliac crest, thigh, and calf) using a Slimguide calliper with 0.5 mm precision, and the sums of six and eight skinfolds were computed to estimate subcutaneous fat. Girth measurements, taken with a Cescorf metal tape accurate to 1 mm, included head, neck, relaxed and flexed arm, forearm, wrist, chest, waist, hips, upper thigh (1 cm below the gluteal fold), mid-thigh, calf, and ankle, with corrected values for flexed arm and calf circumferences calculated using the formula: corrected perimeter = perimeter − (π × skinfold thickness). Bone lengths and segment measurements including: acromiale–radiale, radiale–stylion, midstylion–dactylion, iliospinale height, trochanterion height, trochanterion–tibiale laterale, lateral tibial height, tibiale mediale–sphyrion tibiale, and foot length; were recorded with a Cescorf segmometer to the nearest millimetre, as were skeletal breadths including biacromial, biiliocristal, transverse chest, antero-posterior chest and abdominal depths, humerus, bistyloid, femur, and bimalleolar breadths with a Cescorf pachymeter. Body composition was assessed using ISAK and GREC guidelines (Norton, 2019). The five-component model of Kerr (1991) was used to provide a detailed estimation of adipose, muscle, bone, skin, and residual masses, offering a more comprehensive

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view of tissue distribution. In addition, the Carter–Heath method (1990) was applied to determine somatotype. Body mass index (BMI) and Waist/Hip index were subsequently calculated as well.

Physical performance

Countermovement Jump with Arm Swing (CMJ+): The CMJ+ (Acero, Sánchez, & Fernández-Del-Olmo, 2012; Gutiérrez-Dávila, Amaro, Garrido, & Rojas, 2014; Hara, Shibayama, Takeshita, Hay, & Fukashiro, 2008; McInnis & Donahue, 2024), also known as the Abalakov jump, allows participants to use arm movement to maximize vertical jump height. Traceurs started from a standing position and were free to use their arms to enhance lift-off. The jump began with a rapid descent into a self-selected countermovement depth, followed by an explosive extension of the knees and ankles, ensuring both safety and performance consistency. Participants were instructed to maintain an extended posture upon landing, and trials were repeated to ensure reliability. Jump height was measured using a laser system (Optojump Next, Microgate, Bolzano, Italy; Glatthorn et al., 2011). This test captures the contribution of upper-limb kinetics to vertical jump, providing insight into whole-body coordination during explosive movements.

Change of direction T-Test (T-Test): The T-Test evaluated multidirectional change-of-direction speed (Pauole, Madole, Garhammer, Lacourse, & Rozenek, 2000; Semenick, 1990; Sheppard, Dawes, Jeffreys, Spiteri, & Nimphius, 2014), an essential ability for navigating complex urban environments in parkour. The setup used four 30-cm cones arranged in a T-shape. Participants started at cone A, sprinted 10 m forward to cone B, shuffled 5 m left to cone C, shuffled 10 m right to cone D, then returned 5 m left to cone B, before backpedalling to cone A. At each turn, participants touched the top of the cone with their hand for precision, right hand for cones B and D, left hand for cone C. Timing gates (Witty, Microgate, Bolzano, Italy) positioned at hip height (1 m) recorded trial durations, starting and stopping as participants crossed the gate. Participants completed three trials with at least 90 seconds of passive rest between each, and the fastest time was used for analysis. This test simulates the sudden directional shifts typical of real-world parkour, providing high ecological validity for evaluating change of direction in such contexts (Strafford, Davids, North, & Stone, 2021).

Standing long jump (SLJ): Also known as horizontal jump or broad jump (Marin-Jimenez et al., 2024; Markovic & Mikulic, 2010; Rahman, 2021; Saint-Maurice, Laurson, Kaj, & Csányi, 2015; Thomas et al., 2020), was conducted to measure horizontal leg jumping capacity and coordination. Participants began with both feet parallel behind a marked starting line and were instructed to flex their knees and use arm swings to generate momentum. The goal was to leap forward as far as possible, maintaining two-footed take-off and landing. Distances were measured from the take-offline to the closest landing mark, usually the heel, with measurements taken to the nearest centimetre using a tape affixed to the floor. Trials were discarded if participants fell forward or backward, compromising landing integrity.

Triple Horizontal Plyometric Jump (3HPJ): The 3HPJ consisted of a modified version of the triple hop test (Davey et al., 2021; Hamilton, Shultz, Schmitz, & Perrin, 2008; Söyler et al., 2024), in which three consecutive horizontal broad jumps performed in a continuous, explosive sequence (Wood, 2005). Starting from a standing position, participants jumped forward as far as possible and immediately transitioned into the next jump, repeating the movement twice more. This test emphasizes lower-body power, coordination, and reactive strength, making it suitable for assessing horizontal propulsion and overall athletic explosiveness. Distances were measured from the take-offline to the closest landing point, typically the heel, using a tape affixed to the floor and recorded to the nearest centimetre. Trials were discarded if participants fell forward or backward, compromising landing integrity. Each participant completed three attempts, with the best distance used for analysis.

40-Meter Sprint Test (Sp40): To assess linear sprinting speed and acceleration, participants performed a modified 40-meter sprint with a 5-meter run-up (Altmann, Ringhof, Neumann, Woll, & Rumpf, 2019; Highton, Lamb, Twist, & Nicholas, 2012; Kolsky, Williams, Lorenzen, & Kemp, 2010; Nesser, Latin, Berg, & Prentice, 1996). This design reflects real-world parkour scenarios, where athletes typically accelerate before executing specific movements. Participants started 5 meters behind the first electronic timing gate (Microgate, Bolzano, Italy) and were instructed to accelerate naturally without altering mechanics. Timing started automatically as the athlete crossed the first gate and stopped at the 40-meter finish line, crossing the second gate. Each participant performed up to three maximal sprints, with at least 90 seconds of rest between attempts, and the fastest time was recorded for analysis. The test evaluates explosive acceleration, a key factor for efficient movement in dynamic environments.

Parkour-Specific Test: 5 Climb-Ups for Time (5CUFT): The 5CUFT was used to evaluate upper-body power and movement efficiency (Ford & Musholt, 2016), assessing participants' ability to repeatedly transition from a wall-hanging position to the top of a vertical obstacle. The test utilized a vertical wall without over grips or footholds. Participants started each repetition in a full-arm hang, with hands shoulder-width apart and feet at pelvic height in a staggered stance. On command, they initiated the climb using their preferred technique, aiming to place both feet clearly on the top surface of the wall; full standing was not required. Between repetitions, participants dropped back into a full hang with arms fully extended. Any failed repetition, such as incomplete arm extension at the bottom or insufficient foot contact on top, was disqualified. Timing was assessed via video analysis (1080p, 60 fps) in Kinovea (Version 0.9.5) (Charmant, 2021), starting from the first frame in which elbows, knees, or hips changed angles and ending when both feet contacted the top on the fifth successful repetition. Participants were instructed to maintain consistent technique, emphasizing rhythm, joint alignment, and coordination to optimize efficiency and minimize exertion. Verbal cues were provided to reinforce technical standards.

Statistical analysis

Descriptive statistics, including mean (M), standard deviation (SD), minimum (MIN), and maximum (MAX), were calculated to summarize sample characteristics and performance outcomes. In addition, anthropometric measurement, body composition, and somatotype data were also expressed in percentiles. Sample based internal percentiles were calculated in Excel using the adequate formula. Normality of the data was assessed using the Shapiro-Wilk test, and homogeneity of variances was examined with Levene's test. Relationships between variables were explored using Spearman's Rho for non-parametric data. Correlation strength was classified as trivial (<0.10), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), or nearly perfect (>0.90) (Hopkins, 2002). All analyses were performed with Statistical Package for Social Science for Windows (SPSS, version 26, IBM Corp., Armonk, N.Y., USA), with the significance threshold set at $p < .05$.

RESULTS

Anthropometry profile measurements

Table 1 presents the results of the anthropometric characteristics of all participants. The data include mean and standard deviation, as well as percentiles (minimum, 25th, 50th, 75th, and maximum) for a wide range of measurements.

Body composition variables and indexes

Table 2 provides a detailed overview of body composition, and associated indexes for the participants. Results are expressed in means, standard deviations, and percentiles (minimum, 25th, 50th, 75th, and maximum).

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Table 1. Results of anthropometric measurements from all participants (n = 24).

	M	SD	0p	25p	50p	75p	100p
Basic measurements							
Body Mass (kg)	73.3	10.1	55.4	65.8	73.3	79.8	95.3
Stretch Stature (cm)	175.6	8.3	154.0	172.0	175.2	182.5	189.5
Sitting Height (cm)	81.7	18.8	42.4	70.4	91.4	93.5	102.5
Arm span (cm)	178.4	9.0	159.4	173.0	178.8	185.3	192.5
Skinfolds							
Triceps skinfold (mm)	6.3	1.7	3.0	5.0	6.5	8.0	9.0
Subscapular skinfold (mm)	8.3	2.3	5.0	7.0	7.5	9.5	15.0
Biceps skinfold (mm)	2.6	0.6	2.0	2.0	2.5	3.0	4.0
Iliac crest skinfold (mm)	10.5	3.2	6.5	7.8	9.3	13.3	17.0
Supraspinale skinfold (mm)	6.4	2.0	3.0	5.0	6.3	7.8	11.0
Abdominal skinfold (mm)	9.6	3.8	4.5	7.0	8.5	11.9	18.3
Thigh skinfold (mm)	11.0	3.3	5.5	9.3	10.4	13.3	17.8
Calf skinfold (mm)	5.8	1.7	3.0	4.5	5.6	7.0	10.0
Girths							
Head girth (cm)	55.9	1.5	53.3	55.1	55.8	57.1	58.7
Neck girth (cm)	36.2	1.4	33.5	35.1	36.3	37.2	38.4
Arm relaxed girth (cm)	31.0	2.8	25.7	28.2	30.7	33.1	36.6
Arm flexed and tensed girth (cm)	33.1	2.9	27.9	30.7	32.9	35.0	38.9
Forearm girth (cm)	27.2	1.6	24.4	25.9	27.2	28.1	31.5
Wrist girth (cm)	16.1	0.8	14.2	15.5	16.1	16.7	17.5
Chest girth (cm)	95.2	6.9	79.8	91.5	93.6	99.6	110.5
Waist girth (cm)	79.0	4.9	68.5	74.6	79.9	82.6	88.8
Hips girth (cm)	95.3	5.3	85.0	91.4	94.8	98.7	105.5
Thigh 1cm gluteal girth (cm)	56.8	4.3	50.1	53.2	55.9	59.3	67.8
Thigh middle girth (cm)	53.0	3.7	47.8	49.6	52.0	55.4	63.4
Calf girth (cm)	36.1	1.8	33.1	34.8	35.7	37.3	41.0
Ankle girth (cm)	21.7	1.2	19.5	20.9	21.7	22.6	23.5
Lengths and heights							
Acromiale Radiale length (cm)	34.3	2.0	30.0	32.9	34.5	36.2	36.7
Radiale-stylion length (cm)	26.2	1.5	23.0	25.4	26.5	27.1	29.0
Midstylion-dactylion length (cm)	19.5	1.2	16.4	18.6	20.0	20.2	21.5
Iliospinale height (cm)	106.1	5.2	95.9	103.5	105.8	109.7	115.9
Trochanterion height (cm)	94.5	6.4	81.7	89.8	94.2	98.7	107.9
Trochanterion-tibiale laterale length (cm)	47.4	4.2	39.9	44.3	47.5	50.7	56.4
Lateral tibial height (cm)	46.3	4.5	28.6	45.1	47.0	49.0	53.0
Foot length (cm)	26.4	1.6	21.8	25.9	26.5	27.1	28.7
Tibiale mediale-sphyrion tibiale length (cm)	40.1	2.3	35.4	38.9	40.3	42.2	43.2
Breadths							
Biacromial breadth (cm)	40.7	2.2	37.7	38.3	40.7	42.2	45.1
Antero-posterior abdominal depth (cm)	19.2	1.9	15.0	18.2	19.0	20.5	22.7
Biilocristal breadth (cm)	27.1	1.8	23.5	26.0	27.0	28.1	31.2
Transverse chest breadth (cm)	30.2	2.5	25.7	28.5	29.5	31.5	36.4
Antero-posterior chest depth (cm)	19.0	2.0	13.8	18.4	19.2	19.8	23.7
Humerus breadth (cm)	6.9	0.4	6.2	6.6	6.8	7.3	7.8
Bi-styloid breadth (cm)	5.7	0.3	5.0	5.5	5.7	6.0	6.3
Femur breadth (cm)	9.6	0.5	8.5	9.3	9.7	10.0	10.5
Bimalleolar breadth (cm)	7.3	0.6	6.1	7.0	7.4	7.6	8.5

Note: M = mean; SD = standard deviation; 0p = minimum value (0th percentile); 25p = 25th percentile; 50p = median (50th percentile); 75p = 75th percentile; 100p = maximum value (100th percentile).

Table 2. Descriptive statistics of body composition and somatotype variables and indexes (n = 24).

Variable	M	SD	0p	25p	50p	75p	100p
Five component anatomical fractionation							
Adipose mass (kg)	15.2	2.9	10.1	13.1	15.0	17.2	22.2
Muscular mass (kg)	36.5	6.0	26.0	33.0	35.7	41.0	50.0
Bone mass (kg)	8.6	1.3	6.6	7.5	8.7	9.7	11.1
Adipose mass (Kerr, 1991) (kg)	15.2	2.9	10.1	13.1	15.0	17.2	22.2
Muscle mass (Lee, 2000) (kg)	33.1	4.0	26.5	30.4	32.3	35.0	44.2
Bone mass (Rocha, 1974) (kg)	11.8	1.6	8.8	10.9	11.5	13.1	14.7
Skin mass (kg)	4.1	0.3	3.5	3.8	4.1	4.4	4.6
Residual mass (kg)	8.2	2.2	3.6	6.7	8.4	9.9	11.5
Kg difference brute mass with 5 components model	-3.1	2.9	-9.4	-5.7	-2.9	-0.6	1.1
Adiposity							
Adipose muscle index (Kerr/Lee)	0.5	0.1	0.4	0.4	0.5	0.5	0.6
Adipose muscle index (Kerr/Kerr)	0.4	0.1	0.3	0.4	0.4	0.5	0.6
Superior fat distribution	31.2	3.3	26.3	28.6	30.2	33.6	39.7
Abdominal fat distribution	33.4	4.6	23.9	31.0	33.0	36.3	42.2
Lower Fat Distribution	35.5	5.0	26.8	32.5	34.8	39.4	44.3
Sum 6 skinfolds (mm)	47.5	12.6	28.5	36.4	47.3	57.4	76.1
Sum 8 skinfolds (mm)	60.6	15.8	37.0	46.2	60.0	72.1	94.9
Muscularity							
Muscle Bone index (Lee/Rocha)	3.5	0.9	2.4	2.8	3.2	4.1	6.2
Muscle distribution in Upper Limb (%)	24.1	0.6	22.8	23.8	24.1	24.5	25.3
Muscle distribution in Trunk (%)	39.8	0.9	38.2	39.2	39.8	40.4	42.1
Muscle distribution in Lower limb (%)	36.1	0.8	34.4	35.5	36.2	36.5	37.7
Bone distribution							
Conicity index	1.1	0.0	1.1	1.1	1.1	1.1	1.2
Relative arm span (cm)	101.6	2.3	97.1	99.6	101.9	103.2	106.6
Cormic index	46.4	10.3	25.0	39.7	52.0	53.5	54.2
Forearm-Arm index	76.7	4.7	66.1	73.2	76.9	79.8	87.4
Leg-Thigh index	85.0	4.8	73.6	81.9	83.8	89.6	93.3
Acromio-iliac index	66.7	3.3	60.4	64.5	66.0	68.5	72.8
Intermembral index	75.4	2.7	69.2	73.8	75.3	76.8	81.6
Health indexes							
BMI (kg/m^2)	23.7	1.9	21.0	21.9	23.6	25.4	28.6
Waist/hip index	0.8	0.0	0.8	0.8	0.8	0.8	0.9

Note. M = mean; SD = standard deviation; 0p = minimum value (0th percentile); 25p = 25th percentile; 50p = median (50th percentile); 75p = 75th percentile; 100p = maximum value (100th percentile), BMI = Body Mass Index.

Somatotype and somatochart

The participants displayed a predominantly mesomorphic profile (5.0 ± 0.9), with the median (4.9) confirming this tendency and values ranging between 3.5 and 7.1. Endomorphy remained low (2.0 ± 0.6; median = 1.9), whereas ectomorphy showed the greatest variability (2.2 ± 0.8; range: 0.6–4.1), indicating the presence of leaner individuals (25th percentile = 1.7) within an otherwise balanced morphology. The somatochart illustrates the distribution of individual somatotypes, capturing the relative contributions of fatness (endomorphy), muscularity (mesomorphy), and linearity (ectomorphy) to the participants' body build. This triangular representation facilitates comparisons across individuals or groups and helps highlight predominant morphological patterns in the sample. The mean somatotype and the distribution of participants are shown in Figure 1.

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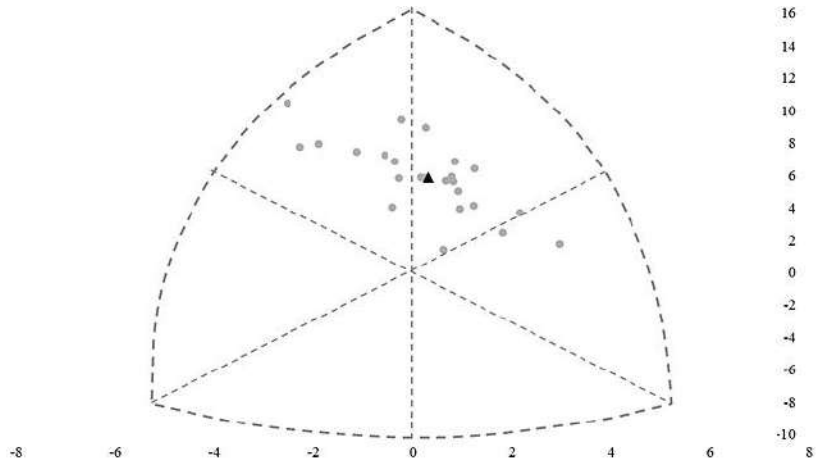


Figure 1. Participant's individual and mean somatotype values represented in a somatochart. Legend: ● = participants, ▲ = mean.

Physical performance tests

Table 3 reports the descriptive statistics of the physical performance assessments. Data are shown as means, standard deviations, and the observed minimum and maximum values.

Table 3. Results of physical performance tests (n = 15).

	M	SD	MIN	MAX
Vertical jump				
CMJ+ (cm)	56.0	8.7	37.1	72.3
Horizontal jump				
SLJ (cm)	272.8	18.8	225.0	296.0
3HPJ (cm)	851.1	61.7	723.0	961.0
Change of direction				
T-Test (s)	10.8	0.5	10.0	11.7
Sprint				
Sp40m (s)	5.1	0.2	4.8	5.5
Parkour specific test				
5 CUFT (s)	15.0	3.1	11.0	21.3

Note. CMJ+ = Countermovement Jump with arm swing, SLJ = Standing long Jump, 3HPJ = Triple horizontal plyometric jump, Sp40 = 40-meter sprint, 5CUFT = 5 climb ups for time, M = mean; SD = standard deviation; MIN = minimum value; MAX = maximum value.

Anthropometry and physical conditioning tests relationship

Correlation analyses highlighted sprinting ability (Sp40) as the test most consistently linked with anthropometric measures. Faster sprint times were strongly associated with lower calf skinfold thickness (ρ = –0.828, $p < .001$) (Figure 2H), biceps skinfold (ρ = –0.668, $p = .009$) (Figure 2G), thigh skinfold (ρ = –0.566, $p = .035$) (Figure 2I), and triceps skinfold (ρ = –0.549, $p = .042$). Sprint performance was also inversely related to adipose–muscle indexes (ρ = –0.639 to –0.547, $p < .05$) (Figure 2D), while positively associated with iliac spine height (ρ = 0.622, $p = .018$) (Figure 2F) and muscle distribution in the trunk (ρ = 0.550, $p = .042$) (Figure 2E). Jump performance revealed additional associations: the standing long jump (SLJ) correlated positively with arm span (ρ = 0.616, $p = .019$) (Figure 2B), acromiale–radiale length (ρ = 0.667, $p = .009$) (Figure 2A)), and foot length (ρ = 0.566, $p = .035$) (Figure 2C), but negatively with anterior–posterior chest depth (ρ = –0.539, $p = .047$). Similarly, the triple horizontal plyometric jump (3HPJ) related positively to acromiale–radiale

length (ρ = 0.567, *p* = .035) and negatively to chest depth (ρ = –0.576, *p* = .031). CMJ+ showed a negative association with the acromio–iliac index (ρ = –0.544, *p* = .044). No significant associations emerged for the T-Test or 5CUFT and anthropometric variables or body composition indexes.

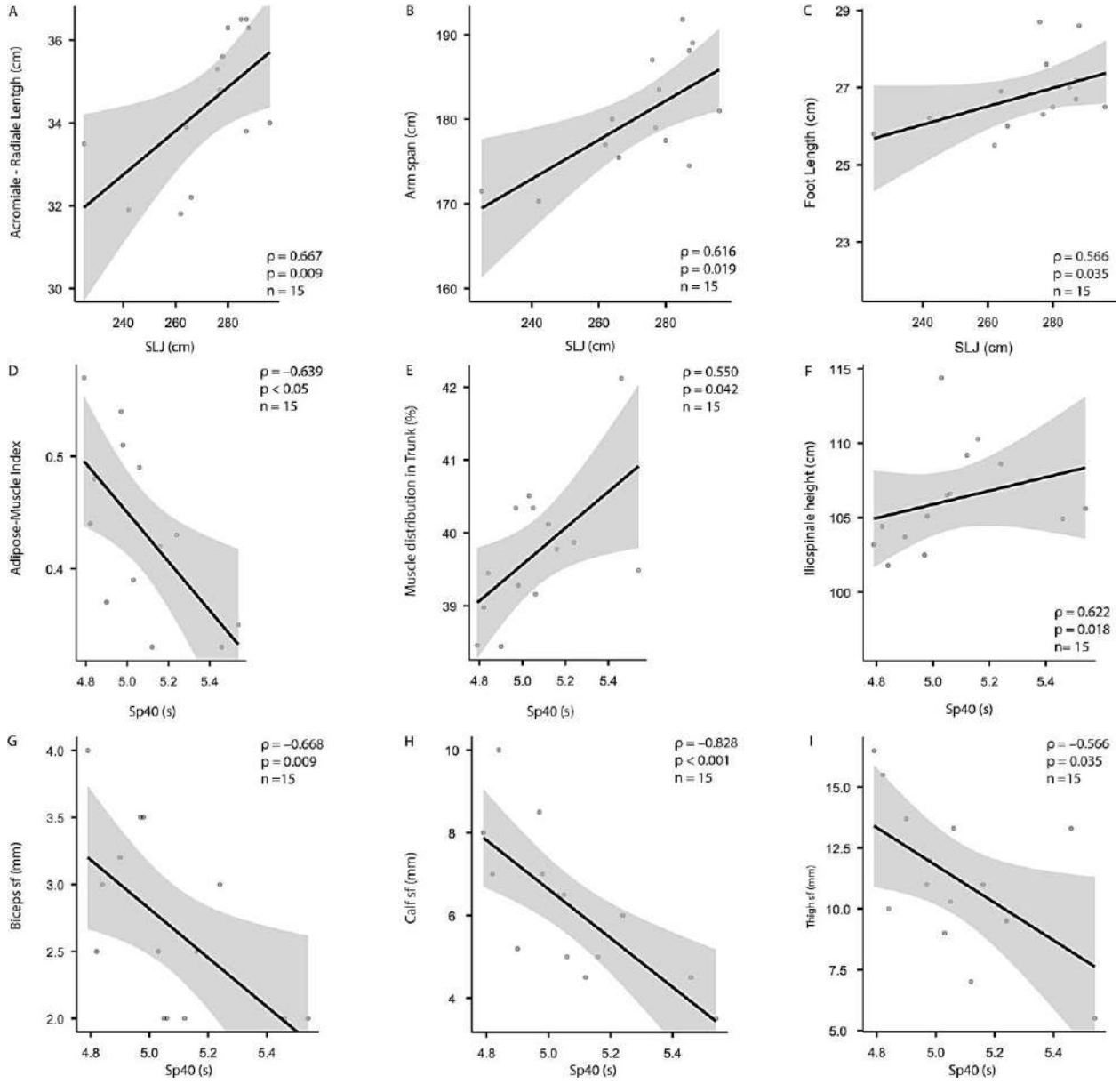


Figure 2. Spearman's rho correlation plots for Standing Long Jump (SLJ) and (A) Acromio-radiale length, (B) Am span and (C) foot length, 40m sprint (Sp40) and (D) Adipose-Muscle Index (E) Muscle distribution in trunk (%), (F) iliospinale height, (G) biceps skinfold, (H) calf skinfold and (I) thigh skinfold.

DISCUSSION

The principal objectives of this study were to conduct a detailed characterization of the anthropometric profile, body composition, and somatotype of male traceurs, and to assess the relationships between these morphological characteristics and performance in a battery of parkour-relevant physical fitness tests. This

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research is justified by the scarcity of comprehensive anthropometric studies in parkour, with even fewer attempting to link this detailed morphology directly to physical performance outcomes. The novel contribution of this work lies in its integrated approach, employing a rigorous anthropometric protocol and correlation analysis to move beyond mere description towards a functional understanding of the parkour athlete's body. The most interesting results centre on the strong and consistent correlations identified. Specifically, Sp40 exhibited the most pronounced relationships, being strongly inversely correlated with calf skinfold thickness ($\rho = –0.828$, $p < .001$) and other limb skinfolds and positively associated with trunk muscle distribution. Furthermore, horizontal jumping capacity (SLJ, 3HPJ) was significantly linked to segmental lengths, such as arm span ($\rho = 0616$, $p = .019$) and acromiale-radiale length ($\rho = 0.667$, $p = .009$), highlighting the role of leverage and body proportions in generating strength.

The analysis of body composition and somatotype is fundamental in sports science (Canda, 2012; Menargues-Ramírez et al., 2022), as it helps to define the "*morphological model*" of an athlete, which in parkour is crucial for overcoming the demanding physical challenges of the discipline. The anthropometric and body composition results of the present sample reveal a predominantly mesomorphic somatotype (5.0–2.0–2.2), with low endomorphy and moderate ectomorphy. This profile is consistent and slightly above previous findings in parkour, where mesomorphy has been repeatedly reported as the dominant component, as in Seyhan's (2019a) intervention (4.09–2.7–3.39). Interestingly, when comparing these results to Abellán-Aynes' (2016), the current sample is closer to the high performing group (5.3–1.7–2.5) than the lower performing group (4.7–2.0–2.7). The reasons underlying these results remain unknown as Abelán-Aynés' sample was similar in age (21.1 ± 2.5 years old), stature (177.3 ± 6.4 cm) and body mass (70.6 ± 9 kg) but not experience (5.6 ± 2.3 years of practice compared to the 11.3 ± 4 years of the current sample). The low levels of adiposity observed in the current sample (sum of 6 skinfolds, Σ6sf = 47.5 mm; Σ8sf = 60.6 mm) are also comparable to those reported in earlier studies, where traceurs consistently displayed values indicative of low body fat, such as Σ6sf = 40 – 53 mm and Σ8sf = 54 – 67 mm (Abellán-Aynés & Alacid, 2016; Seyhan, 2019a) or low fat percentages 7.5 – 14.05% (Abellán-Aynés & Alacid, 2016; Seyhan, 2019a; Solano Chamorro, 2016). These fat mass percentages should be interpreted with caution and not to be mixed with the current study's adipose mass results as the latter refers to the whole tissue. Beyond basic descriptors such as body mass, height, or BMI, which have been the main focus in prior research (Dvořák et al., 2018; Leite et al., 2011; Seyhan, 2019b), this report's analysis incorporated a five-component model, allowing a more detailed exploration of muscle, bone, adipose , skin, and residual mass. In this regard, results highlight a relatively balanced muscular distribution across trunk and limbs. Indices such as the muscle–bone ratio (3.5 ± 0.9) and adipose–muscle ratio (0.4–0.5) further reinforce the image of a morphology optimized for power-demanding activities. Compared to athletes in other sports, traceurs in our study exhibit similarities with explosive-oriented disciplines such as sprinting and gymnastics, where mesomorphy and low adiposity are also predominant (Barbieri et al., 2017; Menargues-Ramírez et al., 2022; Seyhan, 2019a). However, the variability in ectomorphy values suggests that parkour may involve a wider range of body shapes, reflecting both the heterogeneity of practitioners and the adaptability of the discipline. The practical implication is clear: parkour performance is supported by a body type that prioritizes muscularity and leanness over sheer mass or linearity. Consequently, conditioning programs should be designed to enhance functional strength and power while managing adiposity, optimizing the power-to-weight ratio for efficient movement and impact tolerance.

Physical conditioning is a central aspect of parkour (Grosprêtre et al., 2018), and the performance outcomes observed in this study support its relevance, demonstrating that traceurs develop high levels of explosive strength, speed, and overall athleticism. The CMJ+ results (56.0 ± 8.7 cm) surpass values previously reported in parkour populations (47.7–50.1 cm; Abellán-Aynés & Alacid, 2016; Grosprêtre & Lepers, 2016;

Strafford, Davids, Stone, & Antony, 2020), reflecting the ecological validity of including arm swing, which better simulates real-world parkour movements. Similarly, standing long jump (SLJ) performance averaged 272.8 ± 18.8 cm, consistent with or exceeding prior parkour studies (198–283 cm; (Abellán-Aynés & Alacid, 2016; Padulo et al., 2019) and comparable to team-sport athletes such as soccer, basketball, and rugby players (204–238 cm; Becker & Smith, 2015; Markovic, 2007; Porter, Anton, Wikoff, & Ostrowski, 2013). Triple horizontal plyometric jump (3HPJ) values (851.1 ± 61.7 cm) place practitioners near the lower range of elite track-and-field athletes, highlighting the substantial lower-limb explosiveness cultivated through long-term practice (Wood, 2019). Sprint capacity (Sp40 = 5.1 ± 0.2 s) also demonstrates significant neuromuscular efficiency, aligning with performance benchmarks in sprint-dominant sports such as football, lacrosse, and baseball (5.23–6.51 s; Kolsky et al., 2010; Nesser et al., 1996). Change-of-direction ability, assessed via the T-Test (10.8 ± 0.5 s), falls within ranges reported for parkour (9.33–10.90 s; Strafford et al., 2021) and is comparable to semi-professional basketball players (9.52–10.90 s; Morrison et al., 2022), though slightly slower than professional cohorts. This discrepancy likely reflects the specific movement patterns of parkour, where rapid lateral displacements are less frequent than in basketball, emphasizing the importance of sport-specific testing. The integration of parkour-specific assessments alongside conventional tests provides a more holistic perspective on functional performance, demonstrating that the discipline not only develops specialized motor skills but also cultivates transferable physical capacities applicable across athletic contexts. The collective evidence from this and previous works solidifies the notion that parkour practice cultivates an exceptional physical profile, particularly in domains of maximal strength, plyometric ability, and sprint acceleration. For coaches and athletes, this underscores the non-negotiable nature of a structured conditioning regimen that systematically develops jumping capacity, sprint speed, and strength, as these qualities form the foundational physical platform upon which technical parkour skills are built and safely executed.

Understanding the relationship between an athlete's inherent body structure and their physical capacity allows for better talent identification and training individualization. While this link is well-established in many sports, it remains significantly under-researched in parkour. The present study highlights specific relationships between anthropometric characteristics and physical performance in parkour. Sp40 was the variable most consistently associated with anthropometric traits. Faster sprint times were strongly linked to lower skinfold thicknesses in the calf (ρ = –0.828), biceps (ρ = –0.668), thigh (ρ = –0.566), and triceps (ρ = –0.549), as well as lower adipose–muscle indexes (ρ = –0.639 to –0.547). These findings align with studies in sprint and power-oriented athletes, where reduced subcutaneous fat and higher relative muscle mass facilitate more efficient force generation and minimize inertial resistance during high-velocity movements (Barbieri et al., 2017; Menargues-Ramírez et al., 2022). Additionally, positive associations with iliospinale height (ρ = 0.622) and trunk muscle distribution (ρ = 0.550) suggest that both segmental leverage and core muscularity contribute to sprinting efficiency in traceurs. Jump performance also demonstrated relevant correlations with anthropometry. SLJ distance positively related to arm span (ρ = 0.616), acromiale–radiale length (ρ = 0.667), and foot length (ρ = 0.566), while negatively associating with anterior–posterior chest depth (ρ = –0.539). Interestingly, when standing long jump (SLJ) performance was normalized by foot length (SLJ / foot length), participants achieved an average of 10.3 ± 0.9 "*feet*" of jump distance. Notably, this unit has practical relevance within the parkour community, as traceurs often estimate jumping distances using their own feet as a self-referential and intuitive measurement tool during training. This normalization therefore not only facilitates inter-individual comparison but also reflects an ecologically valid metric rooted in the discipline's practice culture. Comparable normalization strategies have previously been proposed using other anthropometric parameters, such as height or weight (Jarnig, van Poppel, & Kerbl, 2025; Nakai, Usumoto, & Takeshita, 2024; Rojas-reyes, Aedo-muñoz, Prat-Iuri, José, & Miarka, 2020). Although no significant associations were identified in the present study, calculating a jump-to-height ratio yielded an average of 1.56

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± 0.12, with low variability among participants. These findings suggest that, beyond absolute measures, relative indices, particularly those aligned with practitioners' own experiential references, may offer more meaningful insights for training prescription and goal setting. Furthermore, 3HPJ performance correlated positively with acromiale–radiale length (ρ = 0.567) and negatively with chest depth (ρ = –0.576). These associations reinforce the importance of limb length and structural geometry in optimizing horizontal and vertical propulsion, echoing observations in gymnasts, jumpers, and sprinters, where longer limbs and favourable lever ratios enhance explosive performance (Seyhan, 2019b; Ziv & Lidor, 2010). CMJ+ showed a negative correlation with the acromio–iliac index (ρ = –0.544), indicating that a relatively broader trunk may slightly limit vertical jumping height, potentially due to increased body mass distribution. Interestingly, no significant correlations were observed for the T-Test or 5CUFT with anthropometric variables, suggesting that change-of-direction ability and parkour-specific upper-body tasks may be more influenced by skill, coordination, and technique rather than pure morphology. This highlights the multidimensional nature of parkour performance, where certain capacities are heavily dependent on neuromuscular control and environmental adaptability rather than solely on structural characteristics. Collectively, these results underscore that while body composition and anthropometry significantly influence power- and speed-related tasks, functional skill acquisition remains a crucial determinant of performance in complex, parkour-specific movements, a pattern consistent with findings in gymnastics, climbing, and other agility-demanding disciplines (Croft & Bertram, 2017; Sterkowicz-Przybycień et al., 2019). Furthermore, the Conicity Index (1.1 ± 0.0), which assesses the shift from a cylindrical body shape to a double-cone, aligns with the physiological profile of athletes in sports where a high power-to-weight ratio is critical. Our sample exhibited a mean Relative Arm Span of 101.6%, indicating a "*positive ape index*" where the arm span is greater than stature. This morphological feature is a classic advantage as it may provide a longer lever for swinging movements, improve reach for wall-runs and arm jumps, and aid in climbing. The analysis of segmental indices offers even more granular insights.

The high Leg-Thigh Index (85.0) indicates a long tibia relative to the femur. This proportion is often considered advantageous for jumping and running, as the long lower leg increases the effective lever for the calf muscles, potentially allowing for greater force production at the ankle during take-off, a feature common in jumpers and sprinters (Kwon & Kim, 2025; Tomita et al., 2020). These findings provide an evidence-based rationale for training focus. Traceurs seeking to improve sprint and jump performance may benefit from conditioning that optimizes power-to-weight ratio, with particular attention to managing limb adiposity. Furthermore, coaches can use anthropometric profiling to identify innate strengths. For example, an athlete with a positive ape index and long lower legs might be coached to leverage their reach and leverage in precision jumps and explosive take-offs. Ultimately, the results confirm that while certain morphological traits provide a physical advantage, excelling in the technically complex and adaptable discipline of parkour requires dedicated skill practice that goes beyond optimizing morphology alone.

This study is not without its limitations. The cross-sectional design and modest sample size (n = 24 for anthropometry, n = 15 for performance) limit the generalizability of the findings and prevent the establishment of causal relationships. Additionally, while the physical tests selected are well-justified, these may not fully capture the complex, dynamic, and context-dependent nature of real-world parkour movements. The inclusion of more ecologically valid, obstacle-based assessments could provide additional insight into the translation of anthropometric traits into functional parkour skill. Future research should aim to recruit larger and more diverse cohorts, including female practitioners and athletes of varying skill levels, and employ longitudinal designs to track how morphological and performance changes co-evolve with structured training.

CONCLUSIONS

In conclusion, this research provides a comprehensive and detailed anthropometric portrait of the male traceur, establishing a profile dominated by mesomorphy, low adiposity, and a powerful musculoskeletal structure. The novel analysis of correlations demonstrates that performance in foundational tasks like sprinting and jumping is significantly influenced by specific morphological traits, particularly low limb skinfolds and advantageous segmental lengths. These findings offer valuable evidence-based insights for traceurs and coaches, highlighting that while parkour is celebrated for its inclusivity, high-level performance in its most power-demanding actions is associated with a distinct and optimized physical constitution. This knowledge can inform more targeted training and talent development strategies within the discipline.

AUTHOR CONTRIBUTIONS

Andoni Elizondo-Donado contributed to the conceptualization and design of the study, participant recruitment, data collection, statistical analysis, interpretation of the results, and drafting of the manuscript. He also coordinated the research process and approved the final version submitted for publication. Josune Rodríguez-Negro contributed to the study design, supervised data collection procedures, supported data interpretation, and critically revised the manuscript. She approved the final version of the manuscript. Javier Yanci contributed to the methodological design, supervised the analytical procedures, assisted in the interpretation of results, and critically revised the manuscript. He approved the final version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

The scientific knowledge among participants in swimming lifeguard courses

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ABSTRACT

The purpose was to measure the scientific knowledge outcome of the participants in the swimming lifeguard courses, as well as to identify the differences in the knowledge outcome between the lifeguards according to the variables (age, gender, scientific qualification). The study sample consisted of the participants in swimming lifeguard courses, which numbered (30) lifeguard. Method: The researcher used the descriptive approach used cognitive tests for lifeguards to measure the cognitive outcome of them, the cognitive test consisted of (25) questions included the following dimensions :(tasks and duties of the lifeguard, causes and manifestations of drowning, organization, and management of the rescue process, first aid. Results: the cognitive outcome of lifeguard's courses is at a weak level and for all areas of study, the results also indicated that there are statistically significant differences for the cognitive outcome among the lifeguards, in favour of females, also, it was found that there were no statistically significant differences of the knowledge outcome among the lifeguards. Conclusion: The researcher recommends focusing on the theoretical aspect in the lifeguard courses held by the Youth Leadership Development Centre.

Keywords: Physical education, Swimming, Lifeguards, Rescue, Knowledge outcome.

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INTRODUCTION

Practicing of various sports is one of the areas that must be known to its practitioners with a sufficient amount of diverse knowledge related to their field of sports for excellence and creativity, as the players have this knowledge through the experiences they are exposed to and friction with various sources of knowledge, which is thus reflected on their performance and personality and gain confidence in themselves and distinguish them from others in the same field.

Hatamleh (2002) stated that mathematical knowledge may help the individual to quickly learn various motor skills as well as increase the ability to face situations that the player is exposed to during the practice of a particular activity, and it also increases his ability to answer the various questions that stand in his way during work so that he can through the stock of information available to him to face the problems he faces in a positive way.

The profession of water rescue is one of the important and basic jobs in the field of swimming, as the spread of swimming pools in clubs, schools and youth centres has led to an increase in the need for qualifying lifeguards to maintain the safety and lives of practitioners of swimming in the water flats (Abaza et al., 2020).

The rescue courses held by the Youth Leadership Development Centre are specialized and distinctive courses whose members who successfully pass the skill and knowledge tests are granted a rescue license that qualifies them to work as lifeguards in swimming pools and water flats to preserve the lives of swimming practitioners.

Orabi et al. (2008) believe that water rescue is the interaction between the situation in which the distress of water begins to be seen or heard to respond in speeding up dealing with this situation in a proper manner that results in ridding the distressed or drowned person of danger that may lead to the loss of his life. The Youth Leadership Development Centre (2002) defined a lifeguard as a licensed person charged with maintaining the safety of people in swimming places or campuses that fall under its responsibility.

Al-Nammouri (2007) mentioned the need to raise the level of workers in the field of water rescue skilfully and physically to maintain the safety and lives of the pioneers of water flats through specialized courses to improve the cognitive, physical and skill qualities and all the necessary requirements for the water rescue profession to prepare a generation of lifeguards with an appropriate knowledge to carry out the tasks and responsibilities entrusted to them.

This is confirmed by Schwebel, et al, (2007), where he pointed out that the training of lifeguards and the advancement of their level of knowledge is the basic guarantee to maintain the safety and lives of water flats goers, so it must include training in various cognitive areas, whether physical, psychological, skill or other.

The profession of water rescue is one of the very important job in societies in general, especially those in which there are many swimming pools and water flats and many individuals frequent these places to practice swimming activity within the conditions of public safety that preserve their lives during swimming, so it was necessary for people who work in the water rescue profession to enjoy a great deal of physical and skill capabilities to do their duty to the fullest.

Abaza et al. (2020) have reported that there is a clear weakness in the cognitive field of water rescue workers in areas related to rescue careers.

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The researcher believes that the water rescuer can reach advanced levels and high achievement if he learns, trains, discovers, practices, and master's everything necessary during the performance of work, whether in the physical, skilful, legal, and cognitive aspect, so that he has a large amount of information and knowledge related to swimming activity in water flats.

Due to the importance of sports knowledge for all workers in the field of water rescue in order to reach a high level of mastery and safety for swimming practitioners so that they feel that they are practicing their favourite sport free of danger and injuries that occur during the competition, and through the work of the researcher as a trainer in water rescue courses, the idea of this research came through which the researcher hopes to measure the knowledge of the participants in the water rescue courses and to identify the extent of weakness and shortcomings in any aspect to be addressed to reach the rescuers to prestigious levels of scientific knowledge in the field of rescue and reduce as much as possible the errors that occur during the practice of swimming activity in swimming pools.

Objectives of the study

- to identify the knowledge outcomes of the participants in the water rescue courses according to the following dimensions: (tasks and duties of the lifeguard, causes and manifestations of drowning, organization and management of the rescue operation, first aid).
- to Identify the differences between the lifeguards according to the following variables (age, gender, educational qualification).

The study questions

- What is the knowledge of the participants in the rescue courses according to the study dimensions.
- What is the difference in the knowledge outcomes between the lifeguards.

Abaza and others (2020) conducted a study aimed at developing scientific foundations for lifeguard preparation and training programs. The researchers used the descriptive survey approach on a sample of (25) water rescuers, the results indicated the need to develop lifeguard preparation programs to raise their physical and skill level.

Khairat (2019) conducted a study aimed at using the generative model on the cognitive outcome in some skills related to water rescue in swimming. The sample consisted of (20) students of the swimming course at the Faculty of Physical Education for Girls at Zagazig University, the results indicated that the experimental group has a large scientific knowledge in the field of water rescue compared to the control group.

Abdul Ghani (2014) also conducted a study aimed at designing a profile that includes aspects (skill, physical and morphological) for workers in the field of water rescue. The researcher used the descriptive approach in the survey method on the study sample consisting of (220) lifeguards, the results indicated the need to raise the skill and physical level of the rescuers.

Hatamleh and Mahyar (2006) conducted a study aimed at measuring the cognitive outcome of the Jordanian team swimmers for various categories. The study sampled (40) swimmers. The researchers used the questionnaire as a study tool to collect data, the results of the study indicated that swimmers have more knowledge of general laws than precise laws.

METHODS

The researcher used the descriptive approach in the style of survey studies for its suitability to the nature of the study.

Study group

(30) lifeguards from the water rescue courses of the Youth Leadership Development Centre in Jordan.

Table 1. Distribution of the study.

Variable	Level	Number	Ratio
Qualification	Bachelor	21	70%
	Diploma	6	20 %
	High school and below	3	3 %
Age	18-23	2	6.7 %
	24-29	23	76 %
	30 over	5	16.7 %
Gender	Male	21	70 %
	female	9	30 %
Total		**30**	**100 %**

Independent variables: (educational qualification, age, gender). Dependent variable: (level of cognitive outcome of lifeguards).

Data collection tools

The researcher adopted the cognitive test for rescuers prepared by (Orabi et al., 2008), which consisted of two sections: the first section included the information and personal data of the rescuers in terms of: (academic qualification, age, gender). The second section included (25) questions measuring the scientific knowledge of lifeguards. The sincerity of (6) experts in the field of swimming and rescue arbitrators approved the cognitive test of the lifeguards.

The researcher relied on the interpretation of the results obtained on the percentages to estimate the opinions and responses of the study sample according to the opinion of the arbitrators in addition to the method adopted in some studies such as the Alwazeer (2000), which are as follows:

- From 80% and above to be high.
- From 70% to 79% is good.
- From 60% to 69% are above average.
- From 50% to 59% is average.
- From 49% and below you are weak.

Table 2. The test stability coefficient calculated by internal consistency method using the Cronbach alpha equation for each axis, and the overall test stability.

No	Variable	Paragraph nº	Cronbach alpha equation
1	Tasks and duties of the lifeguards	5	0.689
2	Organization and management of the rescue operation	6	0.747
3	First aid	6	0.809
4	Causes and manifestations of drowning	8	0.730
Knowledge outcome as a whole		**25**	**0.862**

As indicated in the previous table, the overall test stability coefficient was (0.862). which is acceptable value indicating the stability of the study tool.

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RESULTS

The results related to the first question: *"What is the knowledge of the participants in the rescue courses according to the study "?*

Table 3. Arithmetic averages, standard deviations, and percentages of study dimensions in descending order.

No	Dimension candidates	Dimension order	Arithmetic mean	Standard deviation	Percentage of successful	Evaluation level
1	Tasks and duties of the lifeguard	1	0.433	0.33	43.3 %	Weak
3	Organization and management of the rescue operation	2	0.422	0.31	42.2 %	Weak
4	First aid	3	0.379	0.32	37.9 %	Weak
2	Causes and manifestations of drowning	4	0.367	0.27	36.7 %	Weak
Total			**0.397**	**0.22**	**39.7 %**	**Weak**

It is clear from Table 3 that the total average of the cognitive outcome of the participants in the rescue courses was (0.397) with a standard deviation (0.22) and a weak level, and the percentage of successful in the questions on the test was (39.7%). The tasks and duties of the lifeguard, it ranked first, and in second place organizing and managing the rescue operation, then first aid, and finally came the causes and manifestations of drowning. and a weak level for all.

Regarding individual dimensions

To present the results in detail, as in Tables (4-7):

The first dimension: tasks and duties of the lifeguard

Table 4. Arithmetic averages, standard deviations, and percentage of correct answers to the dimension (tasks and duties of the lifeguard).

Rank	Question Number	Question	Arithmetic Mean	Standard Deviation	Percentage of Successful Candidates	Assessment Level
1	1	Check the percentage of chemicals daily in the pool	0.467	0.51	46.7 %	Weak
2	4	If the drowned person dies, the law prosecutes the lifeguard more severely if	0.467	0.51	46.7 %	Weak
3	5	Before starting the first aid procedure the lifeguard must	0.467	0.51	46.7 %	Weak
4	3	The lifeguard must decide after	0.400	0.50	0.40 %	Weak
5	2	One of the duties of a lifeguard	0.367	0.49	36.7 %	Weak
Total			**0.433**	**0.33**	**43.3 %**	**Weak**

It is clear from Table 4 that the total arithmetic mean of the dimension of the tasks and duties of the lifeguard is (0.433) with a standard deviation (0.33), and that the number of correct answers amounted to (43.3%) of the total number with weak level.

The second dimension: causes and manifestations of drowning

It is clear from Table 5 that the total arithmetic mean of the dimension of the causes and manifestations of drowning is (0.367) with a standard deviation (0.27), and that the number of correct answers amounted to (36.7%) of the total number.

Table 5. Arithmetic averages, standard deviations, and the percentage of correct answers to the dimension (causes and manifestations of drowning).

Rank	Question Number	Question	Arithmetic Mean	Standard Deviation	Percentage of Successful Candidates	Assessment Level
1	2	The movement of the arms of a stressed swimmer	0.500	0.51	50.0 %	Acceptable
2	6	When the drowned person begins to swallow water, he	0.400	0.50	40.0 %	Weak
3	4	One of the reasons that lead to the drowning of swimmers	0.367	0.49	36.7 %	Weak
4	5	When you have muscle cramps while swimming	0.367	0.49	36.7 %	Weak
5	3	The position of the body of the irritated drowned person	0.300	0.47	30.0 %	Weak
6	1	From the behaviours of the irritable drowned	0.267	0.45	26.7 %	Weak
Total			**0.367**	**0.27**	**36.7 %**	**Weak**

Regarding paragraph (2), the researcher believes that any abnormal movement carried out by the swimmer with the arms should not be overlooked by the lifeguard, as it may be a distress signal or a request for help, so the lifeguard must follow it to ensure that it is a natural movement and for this reason the lifeguard's responses to this paragraph were relatively correct.

The third dimension: organizing and managing the rescue operation

Table 6. Arithmetic averages, standard deviations, and percentage of correct answers for the dimension (organizing and managing the rescue operation).

Rank	Question Number	Question	Arithmetic Mean	Standard Deviation	Percentage of Successful Candidates	Assessment Level
1	3	Means of preventing drowning	0.533	0.51	53.3 %	Acceptable
2	4	You can help the drowned from outside the pool by	0.467	0.51	46.7 %	Weak
3	5	The importance of rescue lies in	0.467	0.51	46.7 %	Weak
4	1	The right place to throw the rope or lifeline for the drowned.	0.400	0.50	40.0 %	Weak
5	6	Which of the following statements is true?	0.367	0.49	36.7 %	Weak
6	2	One of the security and safety factors that must be considered in the swimming pool	0.300	0.47	30.0 %	Weak
Total			**0.422**	**0.31**	**42.2 %**	**Weak**

It is clear from Table 6 that the total arithmetic means of the dimension of organizing and managing the rescue operation is (0.422) with a standard deviation (0.31), and that the number of correct answers amounted to (42.2%) of the total number.

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Fourth dimension: first aid

Table 7. Arithmetic averages, standard deviations, and correct answer ratio for the dimension (first aid).

Rank	Question Number	Question	Arithmetic Mean	Standard Deviation	Percentage of Successful Candidates	Assessment Level
1	1	When calling an ambulance, you must give information related to.	0.500	0.51	50 %	Acceptable
2	8	If yellow water comes out with blood from the ear of the drowned, this means	0.500	0.51	50 %	Acceptable
3	2	The first work on the lifeguard to do after taking out the drowned	0.400	0.50	40 %	Acceptable
4	6	The method of cardiopulmonary resuscitation of a drowned person while lying down is called a	0.400	0.50	40 %	Acceptable
5	4	Procedures to remove obstructions from the airway if the drowned person is conscious	0.367	0.49	36.7 %	Weak
6	5	The nose is closed during artificial respiration to	0.367	0.49	36.7 %	Weak
7	3	the first stage for the injured swimmer from	0.267	0.45	26.7 %	Weak
8	7	What is meant by the term (C.P.R)	0.233	0.43	23.3 %	Weak
Total			**0.379**	**0.32**	**37.9 %**	**Weak**

It is clear from Table 7 that the total arithmetic mean of the first aid dimension is (0.379) with a standard deviation of (0.32), and that the number of correct answers amounted to (37.9%) of the total number.

The results related to the second question**:** *"Is there a statistically significant difference between the lifeguards according to the study variables?"*

Table 8. Arithmetic averages and standard deviations of cognitive outcome among lifeguards.

Variable	Level	Number	Average	Deviation
Gender	Male	21	0.32	0.17
	Female	9	0.59	0.24
Qualification	Secondary	3	0.12	0.04
	Diploma	6	0.27	0.16
	Bachelor	21	0.47	0.21
Age	18 - 23	2	0.14	0.03
	24 - 29	23	0.41	0.22
	Over 30	5	0.46	0.25
Total		**30**	**0.40**	**0.22**

It is noted from Table 8 that there are apparent differences between the arithmetic averages of the cognitive outcome among the lifeguards according to the study variables, and to verify the significance of the apparent differences, a triple variance analysis performed for their responses, as in Table 9.

Table 9. Results of three-way ANOVA analysis of cognitive outcome among lifeguards according to study variables.

Source of variance	Sum of squares	Degrees of freedom	Mean of squares	Value of F	Level of significance
Gender	0.336	1	0.34	12.0	.002*
Qualification	0.111	2	0.06	2.0	.159
Age	0.003	2	0.00	0.05	.953
Error	0.672	24	0.03		
Total	1.456	29			

*Note. * Statistically significant at the level (α = .05).*

The results of Table 9 indicate that there are statistically significant differences at the level of (α = .05) in the arithmetic averages of the cognitive outcome among the rescuers as a whole according to gender, based on the calculated (F) value of (12.0), and at the level of significance (.002), and in favour of females, also there were no statistically significant differences at the level of (α = .05) in the arithmetic averages of the cognitive outcome between the lifeguards as a whole according to the two study variables based on the calculated (F) values of (2.0, 0.05) respectively, and with a significance level of (.159, .953) respectively.

To find out whether there were differences or not in the dimensions of the scale regarding the study variables, the arithmetic averages and standard deviations calculated according to those variables, as shown in Table 10.

Table 10. Arithmetic averages of cognitive outcome among lifeguards according to study variables.

Variable	Level	Statistical	V 1	V 2	V 3	V 4
Gender	Male	No	21	21	21	21
		Average	0.33	0.29	0.29	0.34
		Stander deviation	0.29	0.22	0.23	0.30
	Female	No	9	9	9	9
		Average	0.67	0.45	0.72	0.47
		Stander deviation	0.30	0.32	0.29	0.34
Qualification	Secondary	No	3	3	3	3
		Average	0.07	0.22	0.22	0.00
		Stander deviation	0.12	0.10	0.10	0.00
	Diploma	No	6	6	6	6
		Average	0.27	0.19	0.36	0.27
		Stander deviation	0.39	0.16	0.27	0.26
	Bachelor	No	21	21	21	21
		Average	0.53	0.44	0.47	0.46
		Stander deviation	0.28	0.29	0.34	0.31
Age	18-23	No	2	2	2	2
		Average	0.10	0.25	0.25	0.00
		Stander deviation	0.14	0.12	0.12	0.00
	24-29	No	23	23	23	23
		Average	0.43	0.39	0.43	0.38
		Stander deviation	0.32	0.30	0.32	0.30
	Over 30	No	5	5	5	5
		Average	0.56	0.30	0.43	0.53
		Stander deviation	0.36	0.14	0.35	0.35
Total		No	30	30	30	30
		Average	0.43	0.37	0.42	0.38
		Stander deviation	0.33	0.27	0.31	0.32

Note. V 1 (Tasks and duties of the rescuer), V2: (Causes and manifestations of drowning), V3: (Organization and management of the rescue operation), V4: (First aid).

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The results of Table 10 indicate that there are apparent differences between the arithmetic averages of the dimensions of the cognitive outcome of the participants in the rescue courses according to the following dimensions (tasks and duties of the lifeguard, causes and manifestations of drowning, organization and management of the rescue operation, first aid) according to the study variables (gender, educational qualification and age), and to verify the significance of the apparent differences, a multiple variance analysis (MANOVA) was performed for their responses, as in Table 11.

Table 11. Results of Multiple Variance Analysis (MANOVA) for the cognitive outcome among lifeguards according to the study variables.

Source of variance	Dimensions	Sum of squares	Degrees of freedom	Mean of squares	Value of F	Level of significance
Gender	V 1	0.47	1	0.47	6.10	.02*
	V 2	0.24	1	0.24	3.88	.06
	V 3	1.17	1	1.17	18.55	.00*
	V 4	0.04	1	0.04	0.48	.50
Qualification	V 1	0.22	2	0.11	1.45	.26
	V 2	0.14	2	0.07	1.11	.35
	V 3	0.04	2	0.02	0.34	.71
	V 4	0.23	2	0.11	1.27	.30
Age	V 1	0.02	2	0.01	0.12	.89
	V 2	0.07	2	0.04	0.57	.57
	V 3	0.03	2	0.02	0.27	.77
	V 4	0.05	2	0.03	0.29	.75
Error	V 1	1.83	24	0.08		
	V 2	1.50	24	0.06		
	V 3	1.51	24	0.06		
	V 4	2.13	24	0.09		
Total	V 1	3.13	29			
	V 2	2.13	29			
	V 3	2.87	29			
	V 4	2.89	29			

*Note. V 1 (Tasks and duties of the rescuer), V2: (Causes and manifestations of drowning), V3: (Organization and management of the rescue operation), V4: (First aid). * Statistically significant at the level (α = .05).*

The results of Table 11 indicate the following:

- Regarding (gender variable), there were statistically significant differences in the two dimensions (tasks and duties of the lifeguard, organizing and management of the rescue operation), while there were no statistically significant differences in the two dimensions (causes and manifestations of drowning, first aid).
- Regarding the variable (academic qualification), there were no statistically significant differences in all dimensions (tasks and duties of the lifeguard, causes and manifestations of drowning, organizing and management of the rescue operation, first aid).
- Regarding the age variable, there were no statistically significant differences in all dimensions (tasks and duties of the lifeguard, causes and manifestations of drowning, organizing and management of the rescue operation, first aid).

DISCUSSION

The researcher believes that workers in the field of water rescue must enjoy a large scientific knowledge outcome in various fields related to the variables of the study in order to perform their duties better, either the

results of the current study has violated the expectations of the researcher and their scientific knowledge was at a weak level, and the results of the current study agreed with the study of both (Abdul Ghani, 2014) and the study (Abaza and others, 2020) in terms of the need to develop lifeguard preparation programs and include various aspects of knowledge related to the water rescue profession. From the point of view of the researcher, this result indicates a clear weakness in the cognitive aspect of the participants in the lifeguards courses, and perhaps the reason is that the focus in these courses is on the practical side more than the theoretical thinking of those in charge of implementing these courses that the lifeguard needs practical skills during the duties entrusted to him more than knowledge of theoretical information.

The results of the current study agreed with the study of Abaza (2020) and the study of Abdul Ghani (2014), where both studies indicated the need to develop programs to prepare lifeguards to raise their level in the field of rescue.

The researcher believes that paragraph (1) Table 3 related to the examination of the proportion of chemicals on a daily basis in the pool is one of the axioms for the lifeguard as he must examine the proportion of chemicals on a daily basis in the pool to ensure their suitability for the proper specifications, which ensure that swimmers enjoy swimming without fear of exposure to the transmission of infection or germs to them during swimming, as well as paragraph (4) knowledge the lifeguard penalties imposed by law if it is proven that the cause of death was negligence of the hem is one of the things that concern the lifeguard and must Know.

As for paragraph (2) Table 4, it does not concern the lifeguard much, as obtaining the job as soon as possible to work as a lifeguard and obtaining a monthly income makes him sign the employment contract without reading the duties or tasks required of him carefully.

As for paragraph (2) Table 5, which is related to the behaviours of the irritated drowned, it may have obtained the lowest arithmetic average due to the lifeguard's inability to distinguish between drowning cases and its different stages, whether the stage of the exhausted or irritated drowning.

The researcher believes that paragraphs (3), (4), (1) Table 6 got the highest percentage of correct answers because he believes that these procedures are the basic and followed when a case of drowning in the pool is suspected and all lifeguards should do them in terms of the means carried out by the lifeguard to prevent drowning or in dealing with drowned from outside the water and ending with the lifeguard's knowledge of the importance of preserving the lives of swimmers.

The researcher believes that one of the most important proper procedures carried out by the lifeguard when a drowning case occurs is to contact the ambulance and give sufficient information about the situation to be dealt with very accurately when the paramedics arrive at the place, and this reflects the lifeguard's knowledge of the procedures followed in such a case and therefore the percentage of correct answers to this paragraph was acceptable.

The researcher believes that there are statistically significant differences in favour of females may be due to the fact that females have more free time than males spent in studying and acquiring new information and knowledge related to the rescue profession, while males, due to social conditions and their presence outside the home with friends, relatives or acquaintances in general, do not resort to study or reading and acquire new knowledge related to the rescue profession.

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While the scientific qualification and age, there are no statistical differences between the lifeguards, perhaps according to the researcher's belief that the reason is that the curriculum of the rescue courses is directed to all participants in the course, regardless of the scientific qualification or age, the curriculum is the same for all, so the knowledge and information provided during the rescue courses are one and common to all lifeguards.

CONCLUSIONS

The level of cognitive outcome of lifeguards in general was low.

- Regarding the gender variable:
  - There are statistically significant differences between lifeguards in the field of (tasks and duties of the lifeguards, organizing and management of the rescue process) and in favour of females.
  - There are no statistical differences between lifeguards in the fields of (causes and manifestations of drowning, first aid).
- Regarding the variable of academic qualifications, there are no statistically significant differences between lifeguards in the knowledge outcome**.**

The researcher recommends taking advantage of the results of the current study and adopting them in the Youth Leadership Preparation Centre so that the theoretical aspect is focused on the preparation and rehabilitation courses for lifeguards in the future, and conducting more studies and research related to the field of water rescue because of the importance of this field in maintaining the safety and souls of swimmers.

AUTHOR CONTRIBUTIONS

All co-authors have contributed to the published work equally and agree to its publication in JHSE.

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ORIGINAL ARTICLE

Effects of foot orientation on serve velocity and accuracy in tennis

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ABSTRACT

The tennis serve is a technically complex biomechanical process where ball velocity serves as a primary determinant of competitive success and point dominance. This study examined how foot orientation (X, Y, and Z axes) and service side (Deuce and Ad court) influence serve velocity and accuracy in competitive players (N = 60; 30 male, 30 female). Participants performed serves in each condition using a randomized design to determine the biomechanical efficiency of varying stances. Velocity was recorded via radar technology, and accuracy was assessed based on target box success rates. In the Deuce court, foot orientation significantly affected velocity, revealing a distinct hierarchy where the Z-axis (diagonal) produced higher speeds than the Y-axis (net post) or X-axis (baseline) orientations. Conversely, no significant differences occurred in the Ad court ($p > .05$), suggesting side-specific motor stabilization. ANOVA results showed that accuracy remained consistent across axes (\chi^2(2) = 0.968, $p = .616$) and sides ($p = .738$), confirming the Z-axis velocity advantage induced no speed-accuracy trade-off. These findings highlight the asymmetrical nature of serve kinematics, suggesting that optimizing foot orientation toward the Z-axis in the Deuce court enhances mechanical efficiency and speed without compromising precision.

Keywords: Biomechanics, Ball velocity, Serve side, Biomechanical asymmetry, Serve accuracy, Service stance.

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INTRODUCTION

Tennis is a complex sport encompassing many different techniques and tactics, and one of the game's most fundamental and decisive strokes is the serve. The serve is not only the initiator of the game but also the first offensive move that provides an advantage over the opponent. Therefore, executing the serve with the highest possible speed and accuracy directly impacts both a player's success in the game and their consistent performance (Amir and Saifuddin, 2018).

Ball speed is one of the most critical factors determining serve performance. Factors affecting ball speed include the player's physical build, range of motion, muscle strength, and racket speed during the stroke (Gelen et al., 2009). In addition, the player's height and the height at which the ball is thrown also play a decisive role in serve success (Reid et al., 2011). Factors determining tennis serve speed are based on the interaction of anthropometric characteristics, physical strength and endurance capacity, and technical elements. From an anthropometric perspective, a player's height (BH), arm length (AL), and body composition (e.g., body mass index, BMI) play a determining role in serve speed (Bonato et al., 2013; Söğüt, 2016; Vaverka and Cernosek, 2013). Physical strength parameters, especially maximal isometric strength (MIS), rate of force development (RFD), and upper body strength, are of critical importance in speed production, and the development of these attributes are considered as the main targets for improving serve performance (Baiget et al., 2016; Colomar et al., 2020). From a technical perspective, lower leg thrust, hip and trunk rotations, and upper arm extension and internal rotation movements are mandatory movement patterns for effective energy transfer and increasing ball speed (Davey et al., 2017). In addition, fatigue conditions such as competitive loads and match intensity can negatively affect serve speed and accuracy (Rota et al., 2013).

An effective first serve provides an advantage to the player by paving the way for direct point-winning "*ace*" shots or a weak return by the opponent. Indeed, the percentage of points won after a first serve has been reported to be in the range of 72–81% (Keller et al., 2021). In this context, advanced kinetic chain coordination is essential for a powerful and effective serve. The fundamental elements that determine the quality of the serve include coordination of muscle groups, joint movements, and segmental kinematics; these elements also shape the speed and accuracy of different serve types (flat, slice, kick) (Brito et al., 2024).

In the tennis serve, the sequence of movements called the kinetic chain begins with the lower extremities and continues with trunk and upper extremity rotations (Elliott et al., 2003). The transfer of linear and angular momentum from the legs to the trunk and from the arm to the racket along this chain determines both the speed and control of the shot (Bahamonde, 2000). While the critical role of angular momentum in server performance is frequently emphasized (Elliott, 2006; Reid et al., 2008), research specifically examining the impact of the lower extremities on this process is limited (Martin et al., 2013). At this point, it should be emphasized that the factors affecting serve performance are not limited to upper extremity movements; lower extremity kinematics and foot positions can also play important roles. Indeed, the way the foot contacts the ground during the serve is considered a decisive factor in both maintaining balance and the efficient operation of the kinetic chain. The positioning of the lead foot, in particular, can directly influence trunk rotation and the effectiveness of upper extremity movements.

Studies on tennis serve technique in the literature generally focus on upper extremity kinematics, whereas research on the role of foot position and lower extremity structure in server performance is quite limited (Ellenbecker and Cools, 2010; Kibler et al., 2008; Vodicka et al., 2016). Lower extremity injuries have been

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reported to occur in 31–67% of tennis players (Ölmez et al., 2022), necessitating further investigation of foot and lower extremity biomechanics in terms of serve performance.

In this context, the purpose of the current study was to examine the effect of the lead foot's position on the ground during the serve on serve speed and accuracy in tennis. In this respect, the research aims to fill a gap in the tennis biomechanics literature focused on the lower extremity and to offer new perspectives on improving tennis performance.

MATERIAL AND METHODS

Participants

Thirty actively licensed, right-handed competitive young tennis players (30 males, 30 females; age range: 16–20) registered with the Turkish Tennis Federation's I-KORT system participated voluntarily in the study. The Turkish Tennis Federation's I-KORT system is the federation's official information and transaction system that brings together all participants in the tennis world; tournament, players, referees, coaches, clubs on a single online platform. The sample size was determined using a preliminary power analysis to detect differences in serve speed and accuracy with 80% power and a significance level of .05. Participants had no history of acute or chronic injuries or medication use that could affect performance.

The study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the local ethics committee. All participants or their legal guardians were informed about the purpose, procedures, and potential risks of the study and provided written informed consent.

Note: Participants were asked to refrain from intense training or alcohol/caffeine consumption for 24 hours prior to the test days to avoid environmental and individual factors affecting the study.

Measures

Serve speed

Serve speed was measured using a Bushnell Velocity Speed Gun radar. Makar et al. (2024) compared the Bushnell Velocity Speed Gun with the Stalker Pro II and found high dispersion between the devices, indicating that the Bushnell Velocity Speed Gun radar can be used effectively for education and scientific research, just like the Stalker Pro II. The radar was positioned approximately 2 m from the ball, aligned with the centre of the service box and the baseline. The device was factory-calibrated and validated before each test. Measurement accuracy was set at ±0.16–0.32 km/h (≈±0.1–0.2 mph), and all data were recorded in km/h.

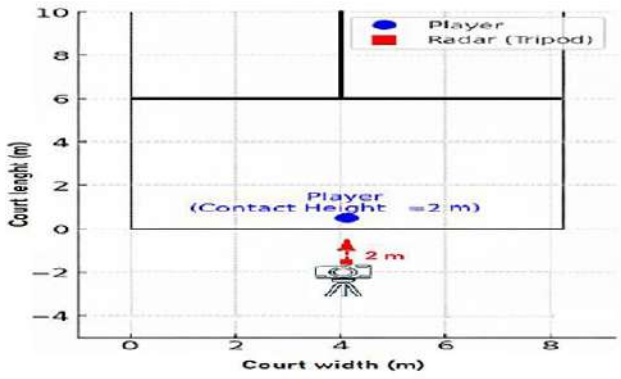


Figure 1. Schematic representation of radar gun positioning during tennis serve velocity measurement.

Accuracy

Whether serves landed in the target area was observed by three experienced tennis umpires. A consensus criterion was used for each serve. Serves that landed inside or on the service line were coded as "1," while those that landed outside were coded as "*0*." Only serves on which all three umpires agreed were included in the analysis.

Procedures

All tests were conducted on an indoor, hard-surface tennis court. Tests were conducted at the same time of day (9:00 AM–12:00 PM) to minimize the effects of biological rhythm and fatigue. Standard warm-up protocol was applied (general movements, mobilization with elastic band, a total of 16 services at a progressive speed: 8 at medium, 4 at high, 4 at maximum speed).Each participant served in three different foot orientations relative to the baseline:

- X-direction: foot parallel to the baseline.
- Y-direction: foot at a 45° angle to the baseline.
- Z-direction: foot perpendicular to the baseline, at a 90° angle.

Each participant served a total of 30 serves, 15 each from the deuce and ad courts. These 30 serves consisted of five serves for each position (X,Y,Z), with X,Y,Z on the ad court and X,Y,Z on the deuce court (Right X,Y,Z and Left X,Y,Z). The order of the trials was determined using a computer-based randomization algorithm to minimize learning and ordering effects.

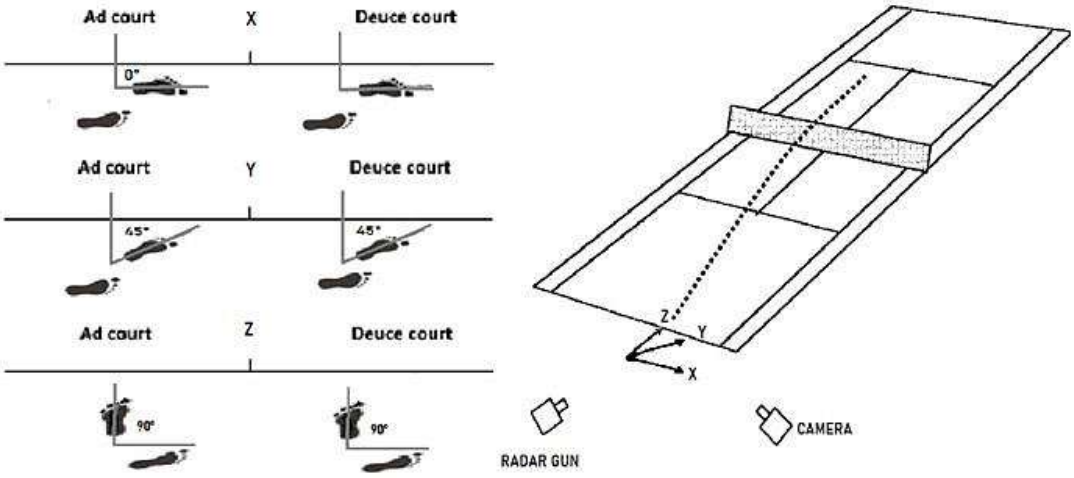


Figure 2. Schematic representation of tennis service foot positioning on the court.

4K, 60 fps video was recorded using an camera to verify the accuracy of the participants' foot positions. The camera was aligned with the baseline to clearly see the server's foot from the front; height, angle, and lighting conditions were standardized across all trials. The video was used only to verify foot positions; it was not used for speed or accuracy measurements.

A 30-second rest was given between each serve and a 2-minute rest was given between each set. During rest, fatigue level was recorded using the RPE (Borg 6–20 Scale); in cases of extreme fatigue, the trial was adjusted to repeat the trial.

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Only straight serves were included in the study; players using slice or kick serves were excluded. Participants' individual straight serve performances were measured in a during test, and individual differences were controlled for in the analyses.



Figure 3. X-axis service performed with foot direction.

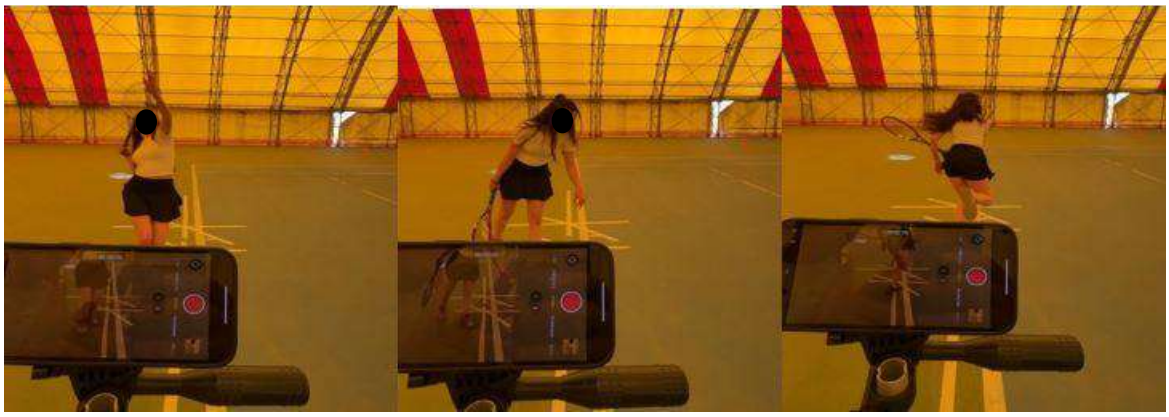


Figure 4. Y-axis service performed with foot direction.



Figure 5. Z-axis service performed with foot direction.

Statistical analysis

All statistical analyses were conducted using JASP (Version 0.18), setting the significance level at alpha = .05. Given the experimental design involving repeated measures (multiple serves per participant), Linear

Mixed Models (LMM) were employed for the continuous dependent variable, Serve Speed (km/h), and Generalized Linear Mixed Models (GLMM) for the dichotomous dependent variable, Serve Accuracy (Hit/Miss).

For the LMM (Speed), fixed effects included Gender, Axis, and Location, along with the *Location x Axis* interaction. For the GLMM (Accuracy), the model was specified with a Binomial distribution and a Logit link function. The fixed effects structure for the GLMM included Gender, Axis, and Location. Both models controlled for the variability attributable to individual participants by including Participant ID as a random intercept. Overall main and interaction effects were assessed via F-tests (LMM) and \chi^2-tests (GLMM). Subsequently, the magnitude and direction of all statistically significant findings were detailed using Estimated Marginal Means (EMMs), reported on the natural probability scale for clarity of interpretation.

RESULTS

Table 1. Descriptive statistics of serve speed (km/h) across levels of gender, serve location, and foot axis.

Serve	N	Mean	Std. Deviation
Female	900	82.34	13.34
Male	900	112.31	13.82
Right	900	96.40	20.34
Left	900	98.25	20-Ago
X	600	96.43	20.44
Y	600	97.64	19.87
Z	600	97.91	20.36

Note. N represents the total number of serves analysed for each category. Mean and Std. Deviation values are reported in kilometres per hour (km/h). Axis X, Y, and Z refer to the specific foot orientations tested during the serve.

N represents the total number of valid serves included in the analysis for each factor level. The dependent measure is Serve Speed, reported in kilometres per hour (km/h). The data illustrate that the mean speed for male athletes (112.31 \text{ km/h}) was considerably higher than for female athletes (82.34 \text{ km/h}). The sample sizes for Gender (Male/Female) and Location (Right/Left) are 900, while the sample size for each Foot Axis category (X, Y, Z) is 600.

Table 2. Linear Mixed Model (LMM) summary of fixed effects for serve speed (km/h). ANOVA summary.

Effect	df	F	*p*-Value
Gender	1,58.54	509.332	**<.001**
Location	1,1072.87	9.522	**.002**
Axis	2,1059.67	2.332	.098
Location axis	2,1585.49	10.440	**<.001**

Note. df values are calculated using Satterthwaite's method for degrees of freedom. The significant interaction ($p < .001$) between location and axis indicates that the effect of foot orientation on velocity differs depending on the service side.

The analysis of variance from the Linear Mixed Model (LMM) revealed that Gender had a highly significant main effect on serve speed ($F(1, 58.64) = 509.332$, $p < .001$), confirming that male athletes served significantly faster than female athletes (refer to Descriptive Statistics in Table 1).

A statistically significant main effect was also found for Location ($F(1, 1072.87) = 9.522$, $p = .002$). However, the main effect of Axis was not statistically significant ($F(2, 1059.67) = 2.332$, $p = .098$).

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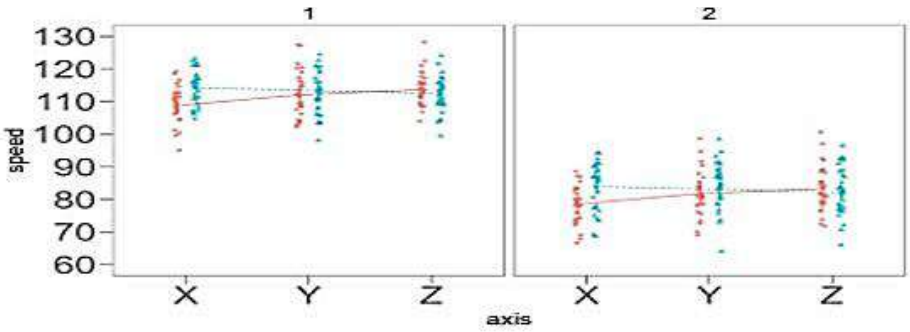
Most critically, a highly significant two-way interaction was observed between *Location x Axis* (F(2, 1585.49) = 10.440, $p < .001$). This significant interaction indicates that the effect of the foot axis position on serve speed is dependent on the side of the court from which the serve is executed. Further *post hoc* analysis is necessary to detail the direction of this interaction.

Table 3. Estimated Marginal Means (EMM) of serve speed and pairwise contrasts by serve location and foot axis.

Serve Location	Foot axis	EMM (km·h⁻¹)	SE	Comparison	Mean Difference	*p* - Value (Holm Adjusted)
Right (1)	X	93.71	0.894	X vs Y	-3.263	**.003***
	Y	96.98	0.970	X vs Z	-4.800	**.001***
	Z	98.51	0.940	Y vs Z	-1.537	.137
Left (2)	X	99.14	0.955	X vs Y	-2.427	.200
	Y	98.30	1.009	X vs Z	-2.977	.708
	Z	97.31	0.951	Y vs Z	-0.550	.725

Note. EMM = Estimated Marginal Means; SE = Standard Error. The p-values are adjusted for multiple comparisons using the Holm method to control the family-wise error rate. Asterisks (*) denote statistically significant differences (p < .05). Right (1) refers to the Deuce court and Left (2) refers to the Ad court.

Follow-up analysis of the significant *Location x Axis* interaction (F(2, 1585.49) = 10.440, $p < .001$) revealed distinct effects depending on the side of the court from which the serve was executed. Post hoc pairwise comparisons (Holm adjusted) showed that when serving from the Right (1) location, Axis X resulted in significantly lower speeds (93.71 \text{ km/h}) compared to both Axis Y (text{Mean Difference} = -3.263, p = .003) and Axis Z (\text{Mean Difference} = -4.800, p = .001), with no difference observed between Axis Y and Axis Z (p = .137). In contrast, when serving from the Left (2) location, the choice of foot axis did not produce any statistically significant differences in mean serve speed (all $p > .200$), indicating that the optimal foot placement strategy for maximizing velocity is specific to the right serving side.



Note: 1 = male, 2 = female, ● = right serve side, ▲ = left serve side.

Figure 6. Interaction of Foot orientation axis, serve side, and gender on serve velocity distribution.

The visual representation of the data provides compelling support for the proposed hypotheses concerning the differential influence of the Axis conditions based on Serve Side. While the dominant finding remains the highly significant main effect of Gender, with males (Panel 1) consistently exhibiting superior speed performance compared to females (Panel 2), the graph effectively illustrates the critical interaction effects. Specifically, the data confirms the hypothesis that the Axis condition significantly impacted speed performance for the right serve side (●): the slight non-horizontal slope of the red trend lines, particularly noticeable in the male group, suggests a modulation of speed as a function of the axis change (X, Y, Z).

Conversely, the hypothesis regarding the absence of an Axis effect for the left serve side is visually confirmed by the predominantly flat and horizontal trend lines associated with the blue triangles, indicating that speed remained stable across the three axis conditions when serving from the left. This graphical distinction between the dynamic performance profile of the right serve and the stable profile of the left serve visually corroborates the statistically significant *Serve Side x Axis* interaction effect derived from the ANOVA.

Generalized linear mixed models

Table 4. ANOVA summary of service accuracy rates across foot orientation axis, gender, and court location.

Effect	df	Chi Sq.	*p* - Value
Axis	2	0.968	.616
Gender	1	4.797	.029
Location	1	0.112	.738

Note. 2 observations were removed due to missing values.

The results of the ANOVA analysis performed on the service accuracy rates revealed that the axes representing foot orientation did not have a statistically significant main effect on accuracy [\chi^2(2) = 0.968, p = .616]. This finding is of critical importance from a biomechanical point of view, as it proves that the speed hierarchy (Z > Y > X) observed on the right service side (deuce court) occurs without any loss of accuracy (speed-accuracy trade-off). While the literature emphasizes that service performance should be optimized as a whole, not only with the speed variable but also with the accuracy rate, the absence of an accuracy difference between the axes in our study confirms that the Z-axis orientation, which maximizes speed, provides mechanical efficiency without creating a technical risk. In addition, the lack of a significant effect of the service side (location) on accuracy [\chi^2(1) = 0.112, p = .738] indicates that this stability in accuracy rate is maintained on both sides of the court. In conclusion, for athletes aiming to increase serve speed without sacrificing accuracy, the preference for Z-axis orientation, especially on the right serve side, is considered a data-driven and reliable performance optimization strategy.

DISCUSSION

The tennis serve is widely recognized as one of the most vital and technically demanding biomechanical actions, primarily due to its role as the point of initiation and its decisive impact on point acquisition (Fett et al., 2020). At the core of a successful serve lies ball velocity, which emerges from a complex integration of the player's physical morphology, strength, and range of motion (ROM), alongside the intricate synchronization of joint and racquet speeds during execution (Soyal et al., 2018). While existing literature has extensively examined upper-body kinematics—specifically the angular momentum of the upper arm, forearm, and racquet, as well as proximal-to-distal segmental sequencing (Colomar et al., 2022; Martin et al., 2013)—the role of the lower extremities remains less understood. The transfer of momentum from ground reaction forces through the kinetic chain is arguably one of the most enigmatic biomechanical concepts in tennis (Bahamonde, 2000; Girard et al., 2010).

Historically, lower-limb research in tennis has concentrated on plantar pressure distribution (Girard et al., 2010) or the vertical positioning of the feet, categorized as "*foot-up*" and "*foot-back*" techniques (Brito et al., 2024; Girard et al., 2010). Although Martin et al. (2012) underscored the significance of foot placement in tactical scenarios like serve-and-volley play, scholarly work investigating the impact of foot orientation across different serve sides (deuce vs. ad court) on velocity remains sparse (Martin et al., 2013). In this context, the pioneering study by Fett and colleagues (2020) highlighted that switching serve sides could lead to distinct body and ball kinematics. Our findings corroborate the "*side-specific asymmetrical nature of serve*

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kinematics" proposed by Fett et al. (2020), as we observed a significant effect of axis orientation on velocity in the deuce court, whereas performance remained stable in the ad court.

The axis-dependent velocity fluctuations observed in the deuce court can be interpreted through the mechanical discrepancies identified by Fett et al. (2020). While they suggested that the lead foot should ideally point toward the right net post—a position corresponding to our Y-axis parameter—our data indicates a different hierarchy: the Z-axis produced the highest velocities, followed by the Y-axis, with the X-axis resulting in the lowest performance.

The increased axial sensitivity in the deuce court may be attributed to a more open stance and a larger upper-body ROM compared to the ad court (Fett et al., 2020). This asymmetry alters the management of braking forces developed by the front foot as the centre of mass shifts forward, thereby modifying the transmission of angular momentum (Bahamonde, 2015). The superiority of the Z-axis over the Y-axis suggests that this specific orientation facilitates a more efficient energy transfer by optimizing the interaction between the lower extremity segments and ground friction during the development of angular momentum. Furthermore, lower visual perception of the target area in the deuce court may influence player behaviour, leading to these observed velocity variances (Fett et al., 2020). While a more forward impact position generally benefits ball placement (Vaverka and Cernosek, 2013), the inherent mechanical asymmetry of the deuce side seems to hinder velocity maintenance across all axes, rendering alternative orientations like the Z-axis more dominant for power generation.

Conversely, the stability of velocity across all axes in the ad court serve suggests that the standard foot position (lead foot toward the right net post, back foot parallel to the baseline) provides a more balanced motor output on this side. As noted by Girard et al. (2010), the high pressures on the lateral-anterior part of the front foot are linked to knee extension, which directly enhances serve speed. Our results indicate that on the ad side, the kinetic chain operates more homogeneously and efficiently regardless of axis variations (Bahamonde, 2015; Girard et al., 2010).

Beyond velocity, this study also rigorously evaluated serve accuracy. The finding that ball-in rates did not significantly fluctuate across different axes is a critical observation. The absence of an "*accuracy-speed trade-off*" when utilizing the Z-axis proves that the velocity advantage gained does not come at the cost of precision. Consequently, to maximize speed without sacrificing accuracy in the deuce court, we recommend that players stabilize their foot placement along the Z-axis. This orientation appears to offer superior biomechanical efficiency compared to the Y-axis orientation suggested by Fett et al. (2020). Coaches and athletes should consider integrating Z-axis alignment as an optimization strategy within training regimens to manage the specific asymmetries of deuce-side serves.

In conclusion, while serve performance discourse often centres on the upper body, our study emphasizes the critical role of foot orientation and serve side. Given that high upper-body ROM and rotational forces in the deuce court are known risk factors for lower back injuries (Fett et al., 2020), implementing biomechanical adjustments in foot positioning is essential not only for performance standardization but also for long-term injury prevention (Fett et al., 2020; Girard et al., 2010).

CONCLUSIONS

This study investigated the influence of foot orientation and serve side on serve velocity and accuracy, highlighting a critical biomechanical gap in existing tennis literature. Our findings demonstrate that while serve

velocity is fundamentally influenced by gender-based physiological factors, the mechanical efficiency of the serve is significantly modulated by the interaction between the serve side and the axis of foot orientation. Specifically, the deuce court serve exhibits a side-specific asymmetrical nature that makes velocity performance highly sensitive to axial changes. On this side, orienting the lead foot toward the Z-axis emerged as the most efficient strategy, yielding superior velocities compared to the traditionally recommended Y-axis (pointing toward the right net post) and the baseline-parallel X-axis, without any significant loss in accuracy.

In contrast, the ad court serve showed remarkable stability across all axis orientations, suggesting a more symmetrical and naturally efficient motor program on this side of the court. The absence of an "*accuracy-speed trade-off*" across all tested orientations indicates that biomechanical adjustments to foot angle can be utilized to maximize power without compromising the technical integrity of the serve.

From a practical perspective, these results provide coaches and elite athletes with a specific optimization strategy: stabilizing foot placement toward the Z-axis in the deuce court to enhance serve potency. Furthermore, considering that the deuce court requires higher upper-body range of motion and rotational forces, these biomechanical adjustments may also play a vital role in reducing the repetitive stress associated with lower back injuries. Future research should explore the longitudinal effects of axis-based training on performance consistency and its potential implications for different serve types, such as kick or slice serves, to further refine the biomechanical models of the tennis serve.

AUTHOR CONTRIBUTIONS

YDI – conceptualization of the study, research design, data collection, statistical analysis, interpretation of results, and drafting of the manuscript; SE – contribution to data analysis, interpretation of findings, and critical revision of the manuscript for important intellectual content; BF – contribution to methodology development, data acquisition, and review and editing of the manuscript.

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DISCLOSURE STATEMENT

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ORIGINAL ARTICLE

Motivation and quality of life in breast cancer survivors: A self-determination theory perspective for physical activity promotion

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ABSTRACT

Despite the well-established benefits of physical activity for breast cancer survivors (BCS), adherence to exercise guidelines remains strikingly low (5–30%), highlighting the urgent need to identify limitations and employ motivational frameworks to increase intervention effectiveness. This cross-sectional study examined the associations among exercise motivation, physical activity levels, quality of life (QoL), and healthy lifestyle behaviours in BCS, using Self-Determination Theory (SDT) as the theoretical foundation. Thirty-five BCS participated, with a mean age of 59.97 ± 10.80 years. The results showed that the highest scores were recorded in identified regulation, social well-being, sleep habits, and dietary habits, while the lowest were found for physical activity participation and additional concerns. Significant correlations emerged among self-determined motivation, basic psychological needs, lifestyle habits, and QoL, providing valuable insights into their interrelationships. These findings highlight the importance of designing and implementing motivational programs that promote adherence to physical exercise and improve the QoL in this population.
Keywords: Self-determinated motivation, Basic psychological needs, Lifestyle habits, Physical exercise.

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INTRODUCTION

Breast cancer survival has improved significantly over time, leading to a considerable increase in the number of breast cancer survivors (BCS) (Bray et al., 2024). This trend is due to substantial advances in both early diagnosis and treatment (Miller et al., 2022). However, despite disease remission, a considerable proportion of BCS sufferers face chronic multi-organ sequelae, which have a multidimensional impact on their quality of life (QoL) (Park et al., 2021; Pimentel-Parra et al., 2025).

BCS can experience extreme fatigue, pain, sleep problems, anxiety, and depression, often clustered in "*symptom clusters*" (affecting 13%) (Abrahams et al., 2018; Bjerkeset et al., 2020). Furthermore, treatments cause physical changes (hair loss, scarring, weight gain) that impact body image and sexuality (Triberti et al., 2019). Faced with the complexity of these challenges, scientific evidence demonstrates the physical and psychological benefits of exercise both during and after treatment for this disease (Kim et al., 2020; Pudkasam et al., 2018). Furthermore, non-medical interventions, especially psychological interventions and exercise, are highly recommended as first-line therapies for cancer-related fatigue, being particularly effective after completing treatment (Abrahams et al., 2018; Kim et al., 2020; Zhang et al., 2025).

Despite the well-known benefits of exercise and healthy diets, few cancer survivors engage in the necessary physical activity recommended by leading medical institutions (Rock et al., 2022). In fact, only 5–30% of patients maintain physical activity during or after treatment (Kim et al., 2020). This is due to multiple barriers, including motivational factors and limitations in functional capacity, as well as physical discomfort and lack of motivation (Cho and Park, 2018; Wurz et al., 2015) . At the individual level, common barriers include physical injuries or symptoms (such as pain and fatigue), lack of time, and lack of motivation. At the societal level, family obligations and lack of support are identified. At the organizational/environmental level, job demands/stress and the cost of healthy food are predominant barriers (Michael et al., 2021).

A recent review on exercise motivation and practice in cancer survivors highlights the need to apply theoretical frameworks to understand cognitive and motivational processes and thus develop effective interventions (Pudkasam et al., 2021). Although the Theory of Planned Behaviour (Ajzen, 1991) and the Social-Cognitive Theory (Bandura, 1986) have been widely used to explain exercise behaviours in cancer survivors, few studies have been based on Self-Determination Theory (Ryan and Deci, 2017). This theory, currently considered one of the most important, postulates that motivation for physical activity depends fundamentally on the satisfaction of three basic psychological needs (BPNs): competence (feeling efficacious), autonomy (being able to choose), and relatedness (social connection) (Ryan and Deci, 2017). When these needs are met, forms of self-determined motivation emerge (such as intrinsic motivation driven by enjoyment or regulation identified by benefit assessment), which are associated with greater exercise adherence and well-being. Conversely, the frustration of these needs leads to less healthy motivations (such as acting out of social pressure or guilt), reducing the benefits. Vallerand's Hierarchical Model (Vallerand, 2007) expands this perspective, proposing that BPN satisfaction generates positive affective, cognitive, and behavioural consequences. However, the application of this framework in the context of SCM is still scarce and limited, with findings suggesting that BPN satisfaction is linked to greater intrinsic motivation and that BPN-based interventions (online or telephone-based) can improve QoL. Research limitations persist, such as the lack of prospective studies and the need for models that integrate more variables for a deeper understanding.

Thus, the aim of this study is to analyse the levels of self-determined motivation (intrinsic regulation, integrated regulation, and identified regulation), satisfaction of BPNs (competence, autonomy, and social

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relationships), QoL (physical well-being, social/family well-being, emotional well-being, functional well-being, and additional concerns), healthy lifestyles (sleep habits, eating habits, and physical activity) among BCS. The second aim is to analyse the relationships among these variables to inform and guide future research focused on developing and optimizing effective interventions that foster adherence to physical exercise and healthy lifestyle behaviours, thereby enhancing QoL among BCS.

MATERIAL AND METHODS

Participants

A total of 35 female BCS took part in this cross-sectional study. The participants had a mean age of 59.97 ± 10.80 years. All participants were treated in accordance with the ethical guidelines of the American Psychological Association regarding participant assent, confidentiality, and anonymity. Women agreed to participate in this study by giving written consent.

Procedure

This study was conducted involving the administration of questionnaires to (Leyton et al., 2018) BCS. Two Spanish associations were contacted: the Tierra de Barros Oncology Association, located in Almendralejo, and the Spanish Association Against Cancer (AECC) in Cáceres (Spain). Both associations agreed to facilitate the distribution of questionnaires at their offices, with collection scheduled every 15 to 20 days. Each questionnaire required approximately 10 minutes to complete.

Instruments

The questionnaires used to obtain information related to the study variables are detailed below.

Motivation for physical exercise

To assess motivation for physical exercise based on self-determination theory (Deci and Ryan, 2000), the Behavioural Regulation in Exercise Questionnaire (BREQ-3) (Wilson et al., 2006) was employed. The Spanish version, validated by González-Cutre et al., (2010), evaluates intrinsic regulation, integrated regulation, and identified regulation, among other motivational constructs, in physical activity contexts. The questionnaire consists of 24 items designed to assess the type of motivational regulation related to exercise participation. Participants respond on a Likert scale with 5 response levels, ranging from 0 (completely disagree) to 4 (completely agree). Subsequently, the items are grouped into six factors: amotivation, external regulation, introjected regulation, identified regulation, integrated regulation, and intrinsic motivation, underlying the motivational continuum of SDT.

The basic psychological needs

The Basic Psychological Needs Satisfaction Scale (Wilson et al., 2006) was used to measure autonomy, competence, and social relatedness. The Spanish adaptation by Moreno-Murcia et al., (2011) consists of 18 items (six per dimension). Sample items include: competence, autonomy, and social relatedness.

Quality of life

The QoL was assessed using two validated instruments: The FACT questionnaire (Cella et al., 1993) was used, as the general questionnaire, and the FACT-B questionnaire by Brady et al., (1997) which is specific for breast cancer. It consists of 36 items, 26 of which are general and 9 are specific to breast cancer. This is divided into 5 subscales, which are: 7 items for physical well-being, 7 items for social/family well-being, 6 items for emotional well-being, 7 items for functional well-being and a subscale for additional concerns related to both the illness and breast cancer treatment with 9 items.

Healthy lifestyle

To evaluate healthy lifestyle habits related to rest and balanced eating, the Healthy Lifestyle Questionnaire was administered. This instrument was originally validated in a Spanish population (Leyton et al., 2018) and consists of 20 items assessing various health-related behaviours. For the purposes of this study, the five items pertaining to tobacco use were excluded, as they were not relevant to the research objectives. Subsequently, the items are grouped into three factors: rest habits, respect schedules, and balance diet.

Physical activity

The International Physical Activity Questionnaire (IPAQ) short version (Craig et al., 2003), validated in Spanish by Roman-Viñas et al., (2010), was used to evaluate physical activity over the past seven days. The IPAQ classifies activity into three levels (Toloza and Gómez-Conesa, 2007): 1 (low): no physical activity recorded or below the average level, 2 (medium): 3 or more days of vigorous physical activity of at least 20 min per day, 5 or more days of moderate physical activity or walking of at least 30 min, or 5 or more days of any combination of light, moderate or vigorous physical activity, and finally, 3 (high): 3 or more days of vigorous physical activity of more than 30 minutes per day or 7 or more days of any combination of light, moderate or vigorous physical activity. These will be the values established in this work to evaluate the practice of physical activity.

Statistical analysis

The collected questionnaire data were processed using IBM SPSS Statistics 24 (IBM Corp., 2016). Each variable was systematically coded and entered into the statistical software for analysis. Prior to parametric analysis, the assumption of normality was assessed through: Skewness and kurtosis indices, with absolute values below 1.0 indicating acceptable univariate normality (George and Mallery, 2010). Kolmogorov-Smirnov test confirmed a normal distribution ($p > .05$) across key variables. Given these results, parametric statistical methods were applied for subsequent analyses. Descriptive statistics (means, standard deviations, and frequency distributions) were computed to characterize the sample. For the analysis of reliability, the indice of Cronbach's Alpha (α) (equal to or greater than .70) (Nunnally, 1978), was used. Bivariate correlations (Pearson's *r*) were conducted to examine linear relationships between variables. All analyses employed a significance threshold of $p = .05$ (two-tailed).

RESULTS

A descriptive analysis of the questionnaires was performed, including means, standard deviations, and reliability coefficients (Cronbach's Alpha), for all the variables measured in the study (Table 1). The reliability of the questionnaires generally demonstrated good to excellent internal consistency for most scales, with values ranging from .62 to .93. Specifically, the motivation variables consistently demonstrated high mean scores and excellent internal consistency (α >.88) across their subscales.

The correlational analysis (Table 2) revealed significant associations among motivational, psychological, and lifestyle variables. Intrinsic, integrated, and identified regulation styles showed strong positive correlations with one another ($r = .85–.94$, $p < .01$), indicating high coherence within self-determined motivation. All three regulation styles were positively associated with competence ($r = .74–.77$, $p < .01$), autonomy ($r = .67–.75$, $p < .01$), and social relationships ($r = .43–.46$, $p < .05$), supporting the theoretical link between self-determination and psychological need satisfaction.

Functional well-being correlated with competence ($r = .40$, $p < .05$) and physical health ($r = .67$, $p < .01$), but not with emotional or social well-being.

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Table 1. Descriptive statistics and reliability analysis of the variables measured through the questionnaires.

Variables	Range	Mean	SD	Cronbach`s Alpha
(M) Intrinsic regulation	1-5	3.90	1.28	*.96*
(M) Integrated regulation	1-5	3.75	1.28	*.93*
(M) Identified regulation	1-5	4.20	1.13	*.92*
(BPNs) Competency	1-5	3.42	1.05	*.90*
(BPNs) Autonomy	1-5	3.82	1.07	*.88*
(BPNs) Social relationships	1-5	3.70	1.01	*.88*
(QoL) Physical	1-5	3.88	1.00	*.81*
(QoL) Social	1-5	4.34	.74	*.86*
(QoL) Emotional	1-5	3.21	1.18	*.62*
(QoL) Functional	1-5	3.90	.97	*.87*
(HLS) Additional preocupations	1-5	2.99	.98	*.72*
(HLS) Rest Habits	1-5	4.00	1.18	*.86*
(HLS) Respect schedules	1-5	4.39	.76	*.75*
(HLS) Balance diet	1-5	4.14	.78	*.65*
IPAQ	1-3	1.71	.82	-

Note: (M) Motivation; (BPNs) Basic psychological needs; (QoL) Quality of life; (HLS) Healthy lifestyle; SD: Standard deviation.

Table 2. Correlational analysis of all motivational, basic psychological needs, quality of life, healthy lifestyle and physical activity variables.

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Intrinsec R.	-														
2. Integrated R.	.94**	-													
3. Identified R.	.85**	.86**	-												
4. Competence	.74**	.77**	.76**	-											
5. Autonomy	.71**	.75**	.67**	.76**	-										
6. Social relationships	.46**	.43*	.45**	.54**	.53**	-									
7. Physical	.09	.09	.07	.10	.08	.05	-								
8. Social	.05	.14	.09	.28	.16	.00	.50	-							
9. Emotional	-.01	-.06	-.14	-.11	.07	-.17	.39	.29	-						
10. Functional	.29	.29	.28	.40*	.24	.01	.67**	.68**	.33	-					
11. Preoccupations	.17	.16	.17	.26	.05	.14	-.52**	-.17	-.44**	-.28	-				
12. Rest	.28	.26	.13	.47**	.28	.06	.10	.36*	.15	.42*	-.01	-			
13. Schedules	.17	.27	.26	.33*	.42*	.26	.16	.28	.13	.15	-.17	-.33	-		
14. Diet	.29	.30	.15	.11	.26	.03	.16	.12	.16	.06	-.15	.10	.65**	-	
15. Physical activity	.14	.14	.29	.16	.16	.19	-.04	-.01	-.00	-.03	.02	.06	.08	-.13	-

*Note. 1-3: Motivational variables; 4-6: Basic psychological needs variables; 7-10: Quality of life variables; 11-4: Healthy lifestyle variables; R. = Regulation; **. The correlation is significant at the 0.01 level. * The correlation is significant at the 0.05 level.*

Preoccupations were negatively associated with physical health ($r = -.52$, $p < .01$) and emotional well-being ($r = -.44$, $p < .01$), suggesting higher distress aligns with poorer health perceptions. Rest was significantly linked to competence ($r = .47$, $p < .01$), functional well-being ($r = .42$, $p < .05$), and social well-being ($r = .36$, $p < .05$).

Respect for meal schedules correlated with autonomy ($r = .42$, $p < .05$) and competence ($r = .33$, $p < .05$) and showed a strong positive association with diet quality ($r = .65$, $p < .01$).

Physical health and social well-being were unrelated to motivational or lifestyle variables ($p > .05$), except for their mutual correlation ($r = .50$, $p < .05$). Emotional well-being showed no significant associations with motivation or health behaviours.

DISCUSSION

The aim of this study was to analyse the levels of self-determined motivation (intrinsic, integrated, and identified regulation), the satisfaction of BPNs (competence, autonomy, and social relationships), QoL (physical well-being, socio-family well-being, emotional well-being, functional well-being, and additional concerns), as well as healthy lifestyle habits (rest routines, nutrition, and physical activity) in BCS.

Several studies have demonstrated the benefits of engaging in physical activity both during and after a breast cancer diagnosis (Coughlin et al., 2019; Dieli-Conwright et al., 2018; Fernández-Lázaro et al., 2020). Recent research, such as that conducted by Céspedes-Aleixandre (2024), reveals significant improvements across all dimensions of QoL following the implementation of a physical exercise program combined with health education.

In the present study, IPAQ results were found to be low, indicating that the women in the sample engage in limited physical activity. Díaz et al. (2020) confirm that during the recovery period from breast cancer, women tend to make changes in their lifestyle. These changes may be positive—such as adopting healthy eating habits, as observed in this study where nutrition scored the highest average—or negative, such as increased sedentary behaviour or psychosocial challenges. In this case, emotional well-being obtained the lowest average score.

Another important finding is the average score obtained on the Self-Determination Theory (SDT) motivation continuum, where identified regulation stands out. This indicates that the participants engaged in physical activity due to external motivations. In a systematic review, Pérez-Cerezo (2023) highlights key psychological variables associated with physical activity in individuals with cancer, such as high self-esteem and intrinsic motivation. The importance of satisfying the BPNs of autonomy and competence is also emphasized (Price and Brunet, 2022).

The second objective was to analyse the relationship between these variables in order to guide the development and optimization of effective interventions aimed at improving adherence to physical activity and healthy lifestyle habits, thereby enhancing overall QoL and well-being.

In line with the principles of Self-Determination Theory (Ryan and Deci, 2017; Ryan et al., 2021), the most self-determined forms of motivation were positively and significantly associated with the BPNs of competence, autonomy, and social relationships (Viveiros et al., 2025; Zhang et al., 2024). When individuals feel autonomous, competent, and connected, they tend to be more deeply motivated, showing greater commitment and persistence. Beyond intrinsic motivation, a person who exercises because they value its health benefits (identified regulation), or because they have integrated it into their identity (integrated regulation), is likely to feel autonomous, competent, and socially connected.

This relationship not only enhances performance but also contributes to overall well-being. In the present study, positive and significant correlations were found between healthy lifestyle variables—such as rest—and QoL indicators including functional well-being, social well-being, and physical health, all of which were associated with the BPNs of competence. Studies such as that by Majeed et al. (2017), which examined these variables in a population with depression, support these findings. However, in the study by Jang et al. (2023) involving individuals with disabilities, the BPN that was significantly related to QoL variables was autonomy. Renzi et al. (2022) found that the BPNs of relatedness was the key determinant in the adoption of positive QoL indicators and engagement in physical activity as a healthy lifestyle variable among older

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adults. These findings suggest that the strength of each BPNs may vary depending on cultural context, type of activity, or individual differences.

In a descriptive study, Mateo-Orcajada et al. (2023) identified positive relationships between BPNs and adherence to the Mediterranean diet and physical activity. Our study corroborates these results, revealing positive and significant correlations between healthy eating habits and the BPNs of competence and autonomy.

No significant relationships were found with the physical activity variable. It is worth noting that recent studies, such as Pérez-Cerezo (2023), identified a significant correlation between physical activity and all three BPNs: autonomy, competence, and relatedness. Furthermore, Fernandes et al. (2023), through structural equation modelling, concluded that higher levels of physical activity are associated with more self-determined dietary regulation, which, in turn, leads to less restrictive eating behaviours influenced by external and emotional factors.

This study presents several limitations that should be considered when interpreting the results. First, due to its descriptive and cross-sectional design, causal relationships between the psychological variables analysed cannot be established. The results reflect the psychological state of the participants at a specific point in time, without accounting for the evolution of these variables over time.

Second, the sample consisted exclusively of women diagnosed with breast cancer who voluntarily agreed to participate, which may introduce selection bias. It is possible that patients with greater psychological resources or a stronger interest in emotional aspects were more willing to participate, thereby limiting the generalizability of the findings to the broader population of women with this disease.

Additionally, certain contextual and clinical factors that could influence the psychological state of the participants such as treatments received, perceived social support, or mental health history, were not considered. The absence of these variables may restrict a more comprehensive understanding of the phenomenon under study.

Future research could address these limitations through longitudinal designs, larger and more representative samples, and the inclusion of additional variables that allow for a more comprehensive understanding of the psychological impact of breast cancer.

Finally, this descriptive study focused on the analysis of psychological variables in women with breast cancer offers insight into the emotional impact of the disease, highlighting psychological needs that are often overlooked in this patient group. It provides an empirical foundation for the development of more effective and personalized psycho-oncological interventions.

CONCLUSION

This study presents a description of variables related to QoL, healthy lifestyle habits, and self-determined motivation in a group of BCS. The results showed that the highest scores were recorded in identified regulation, social well-being, rest habits, and eating habits, while the lowest scores were observed in physical activity and additional concerns. It is recommended that future research develop and implement motivational programs aimed at promoting physical exercise to improve the QoL of BCS.

AUTHOR CONTRIBUTIONS

Ana Ferri Caruana contributed to data collection, manuscript writing, and the preparation of figures and tables. Marta Leyton Román was involved in the literature review, manuscript writing, and interpretation of results. Ruth Jiménez Castuera was responsible for the conceptualization of the study, data collection, statistical analysis, critical revision of the manuscript, and final review of the document prior to submission. Santiago Fresno Alba contributed to data collection, manuscript writing, and the preparation of figures and tables.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

Mixed reality and children's motor skills: Bibliometric analysis of Scopus database one decade (2015-2025)

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ABSTRACT

The advancement of science and technology continues to develop and has a significant impact on human life, especially on motor skills. In this context, Mixed Reality provides understanding and improvement of skills. This study presents a bibliometric analysis of articles related to Mixed Reality and motor skills published from 2015-2025. A total of 259 articles match the keywords in the Scopus database. This study examines the growth rate of research year by year, with the use of commonly used keywords, articles that are widely cited, countries that have collaborations with other countries, and countries with the most documents and new research keywords. The results of this study convey that the number of publications in one decade (2015-2025) is the most in 2024 as many as 48 publications, and the most keywords are Mixed Reality, Argument Reality, and Virtual Reality, while (S. Gallagher and R. Lindgren), and (H. F. Al Janabi et al) are the most cited documents, the countries with the most documents are the United States, Germany and Japan, for the novelty of keywords seen from the yellow image, such as motor tasks, arthroplasty, haptic feedback, and virtual environments. Germany, United States, United Kingdom are countries that have high collaboration. With the presence of this research, it is expected to provide a meaningful contribution to researchers in the future related to Mixed Reality, especially in the field of motor skills.
Keywords: Mixed reality, Motor skills, Children, Bibliometrics.

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INTRODUCTION

In today's era, science and technology continue to develop. One of them is mixed reality (MR) technology. MR is the process of combining the real world and the virtual world to create new representations and environments where digital and physical items can coexist and communicate in real-time (Rokhsaritalemi, Sadeghi-Niaraki, and Choi 2020). MR combines elements of virtual reality and augmented reality by using "*glasses*" that have transparent screens that allow viewing of 3D digital objects, such as holograms, and interaction with these digital objects is mostly done through hand gestures, voice commands, or simply fixing the gaze at a certain point. MR technology is usually paired with Head-Mounted Displays (HMD), usually in the form of a headset or glasses that make learning easy to access and interesting (Barteit et al. 2021). One of the top ten ICT innovations in 2020 is MR technology (Flavián, Ibáñez-Sánchez, and Orús 2019).

In addition, research on MR has shown that motivation can be increased and effective in learning. Specifically, MR in education allows the development of MR applications that help visualize abstract concepts more effectively. This device allows participants to interact by exploring materials and more interesting ways. This content can be displayed on devices used such as MR glasses, with the presence of information provided by MR devices, research that has been done says that Mixed Reality can improve children's motor skills and provide direct feedback.

Some technologies have begun to develop in education, one of which is immersive technology which includes (AR, VR, and MR) (Ryan et al. 2022), immersive technology provides a real experience (Tang et al. 2022). There are several previous studies that convey that the application of MR in increasing, provides insight into the growing trends in this field. Recently, research on this topic has grown significantly, MR training over a longer period of time or 6-8 weeks, with training sessions occurring 2-3 times per week can improve motor and cognitive skills (Heyn et al. 2014; Leung and Shi 2023), and When providing the main variables analysed, many studies have the same theme.

The purpose of this study is to explore, analyse the development and trends of global research published in 2015-2025 in the Scopus database. The specific objectives of this study are to determine which keywords are most frequently used in scientific publications and to utilize bibliometric mapping based on keyword co-occurrence to analyse relationships between topics, between countries and provide an overview of current research and major opportunities for future development.

METHODOLOGY

This study is a bibliometric analysis with quantitative evaluative and descriptive techniques, this is used to identify patterns and research from publications. By using bibliometric visualization, the arrangement of regions can be displayed (Garfield 2009). A total of 259 searches on the article search engine with the Scopus database, with the provisions of research between 2015-2025 as many as 221 articles, and with English being 217, articles that are included with the criteria that match the researcher's search are 175, this includes research articles. The search keywords in this study are mixed reality and motor skills. Using the VOSviewer application with three views with publications between 2015-2025. The indicators can be known by paying attention to the quantity of publications, the number of citations, and the overall link strength between the objects being displayed.

The years 2015-2025 are the initial and final years of researchers conducting searches and collecting meta data on literacy and learning outcomes using the Scopus database. VOSviewer is used to analyse author

bibliographies, keywords, countries, and years of publication. VOSviewer is a software that produces network visualizations of frequently used terms in a particular field (van Eck and Waltman 2017; Orduña-Malea and Costas 2021; Oyewola and Dada 2022; Sovacool, Daniels, and AbdulRafiu 2022). A very helpful and popular application for bibliometric analysis is VOSviewer (van Eck and Waltman 2010; Shah et al. 2020) In addition to creating network visualizations, VOSviewer is also used in analysing the evolution in a particular field based on commonly used terms (Guleria and Kaur 2021; Huang et al. 2022). The five stages of research in bibliometric analysis are outlined below by (Dewi et al. 2021).

The five stages of bibliometric analysis techniques are depicted in the figure above. Specifically, as follows: 1) Selection of research terms or keywords: Before starting data collection, researchers search for information on keywords related to Mixed reality and motor cycles; 2) Limiting the scope of the first search; in this case, researchers use the Scopus database to find articles based on the keyword list; 3) Researchers manually browse all search results using the VOSviewer tool, reducing the total initial search volume if necessary; 4) Creating an initial statistical image: combining information to describe the topic, such as collecting results from visualizations of countries, organizations, journals, publications, and author bibliography pairs, along with author keywords; 5) Analytical narrative interpretation of the data: VOSviewer is used to assess the data and explain the study's conclusions based on the selection results. VOSviewer visualization provides a representation of the data in the form of a variable map that is linked to keywords and has room for improvement.

A deductive approach is used for data analysis, which begins with broad conclusions and develops into more focused conclusions. Country Bibliography, Publication Bibliography, Author Bibliography, and Keyword Appearance are some examples. So that readers can follow the information provided from comprehensive information to more specific information (Ersozlu and Karakus 2019; Lee, Felps, and Baruch 2014)

Research questions

RQ1: What is the total number of publications on MR and motor skills in the period 2015-2025?

RQ2: What keywords appear most frequently in searches for MR and motor skills? And what research is most often cited by authors in the period 2015-2025?

RQ3: Which countries have collaborations with other countries? Which countries have the most publications? And what are the latest research in this decade?

RESULTS

Based on the search results on the Scopus database using the keyword Together visualized with VOSviewer, all present the results of bibliometric analysis (Ellili 2022; Donthu et al. 2021). From the search on the Scopus page, which initially obtained 259 articles that matched the keywords mixed reality and motor skills. However, the data was refined by several procedures until there were 175 publications left, as can be seen in Table 1.

Based on Figure 1, it can be said that the publication trend of the first era (2015-2017) was small and erratic. The year 2015 started with about three documents, increased to about five documents in 2016, and then dropped drastically to about two documents in 2017. Initial growth (2018-2019): About 8 documents were recorded in 2018 and increased to about 18 documents in 2019, indicating the beginning of productivity development. Temporary decline (2020-2021): a period of stagnation or decline in productivity is reflected by a small increase in 2021 (about 12 documents) and a subsequent decline in 2020 (about 11 documents).

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Significant production growth (2022-2024). The peak occurred in 2024, which was around 48 documents, the highest value during the monitoring period. After the previous highest value, there was a significant decrease in the number of documents in 2025, reaching around 18 documents.

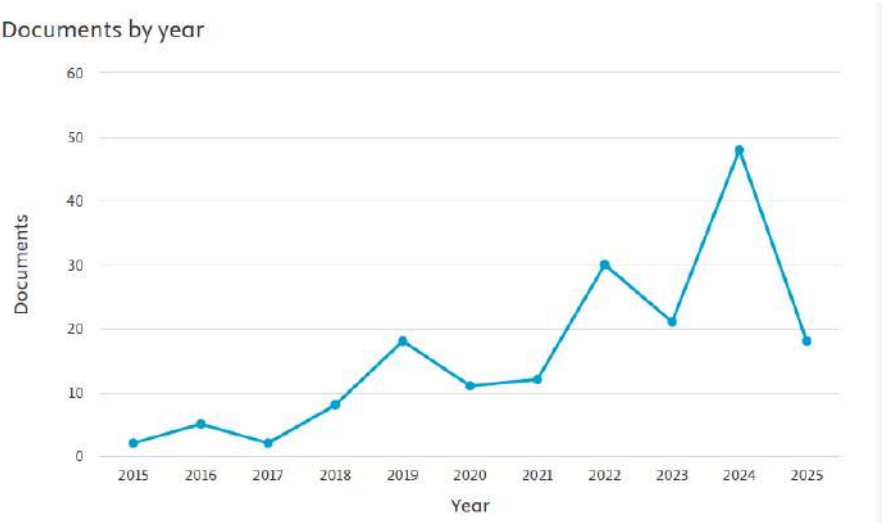


Figure 1. Year of publication.

Table 1. Number of publications and citation trends.

TAHUN	TP	NCP	TC	H	G	C/P
2025	18	0	0	0	0	0.0
2024	48	29	81	5	5	1.7
2023	21	20	117	8	9	5.6
2022	30	28	262	9	14	8.7
2021	12	12	173	5	12	14.4
2020	11	9	256	6	11	23.3
2019	18	17	174	7	12	9.7
2018	8	7	148	5	8	18.5
2017	2	2	102	2	2	51.0
2016	5	5	121	4	5	24.2
2015	2	2	167	2	2	83.5
Total	175	131	1601	53	80	

Based on Table 1. It can be seen that with a number of indicators, including the total number of publications (TP), Number of Citation Papers (NCP), Total Citations (TC), H-Index (H), G-Index (G), and citations per publication (C/P), the table displays publishing statistics from 2015 to 2025. Although 2024 has the most articles (48), the low C/P value (1.7) indicates that most papers have not been screened much. Although only 11 publications, 2020 is famous for the second highest C/P value (23.3) and the most locations (256). With the largest C/P value (83.5), 2015 shows excellent effectiveness and indicates that, although it only has two publications, the publications are very important. In general, early-stage publications have a higher impact (as seen from high C/P values), while new papers are often less screened. This illustrates that scientific impact takes time to develop and does not always correlate with publication volume.

Table 2. Publications with the most citations.

Year	Author	Title	Journal name	Quote	Quotes per year
2015	(Gallagher and Lindgren 2015)	Enactive Metaphors: Learning Through Full-Body Engagement	Educational Psychology Review	145	14.50
2020	(Al Janabi et al. 2020)	Effectiveness of the HoloLens mixed-reality headset in minimally invasive surgery: a simulation-based feasibility study	Surgical Endoscopy	120	24.00
2021	(Georgiev et al. 2021)	Virtual Reality for Neurorehabilitation and Cognitive Enhancement	Brain Sciences	90	22.50
2017	(Frank and Kapila 2017)	Mixed-reality learning environments: Integrating mobile interfaces with laboratory test-beds	Computers & Education	90	11.25
2018	(Pellencin et al. 2018)	Social perception of others shapes one's own multisensory peripersonal space	Cortex	87	12.43
2016	(Colomer et al. 2016)	Effect of a mixed reality-based intervention on arm, hand, and finger function on chronic stroke	Journal of Neuro Engineering and Rehabilitation	83	9.22
2019	(Aruanno and Garzotto 2019)	MemHolo: mixed reality experiences for subjects with Alzheimer's disease	Multimedia Tools and Applications	38	6.33
2020	(Jansen et al. 2020)	ShARe: Enabling Co-Located Asymmetric Multi-User Interaction for Augmented Reality Head-Mounted Displays	UIST 2020 - Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (2020) 459-471	37	7.40
2020	(Riegler, Riener, and Holzmann 2020)	A Research Agenda for Mixed Reality in Automated Vehicles	ACM International Conference Proceeding Series (2020) 119-131	32	6.40
2019	(Sagheb et al. 2019)	SWISH: A Shifting-Weight Interface of Simulated Hydrodynamics for Haptic Perception of Virtual Fluid Vessels	UIST 2019 - Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (2019) 751-761	32	5.33

Data from publications on Mixed Reality (MR) show that this technology is increasingly being used in various industries, including autonomous driving, education, and healthcare. Although research on MR has been around for a long time, the application of the technology began to grow rapidly around 2020, as seen from the publications in 2015 that had the highest number of citations. The number of publications with high citations in 2020, such as in the fields of user interfaces and surgery, shows this. It is interesting to note that publications published in 2021 had the highest average annual number of citations (22.5), indicating that MR is highly valued in the field of cognitive rehabilitation. According to most publications, MR applications involving direct user experience, such as in learning or therapy, attract more attention and are often cited by

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other researchers. This shows that MR has great potential as a leading technology in the real world, as it can be used to support human life in addition to providing pleasure.

Trends in research collaboration between countries

Figure 3 shows international research collaboration in the fields of mixed reality and motor skills. The circles in the figure represent countries that have produced scientific articles on the subject. Only countries with at least three publications are shown in the research figure meeting the three-document criterion.

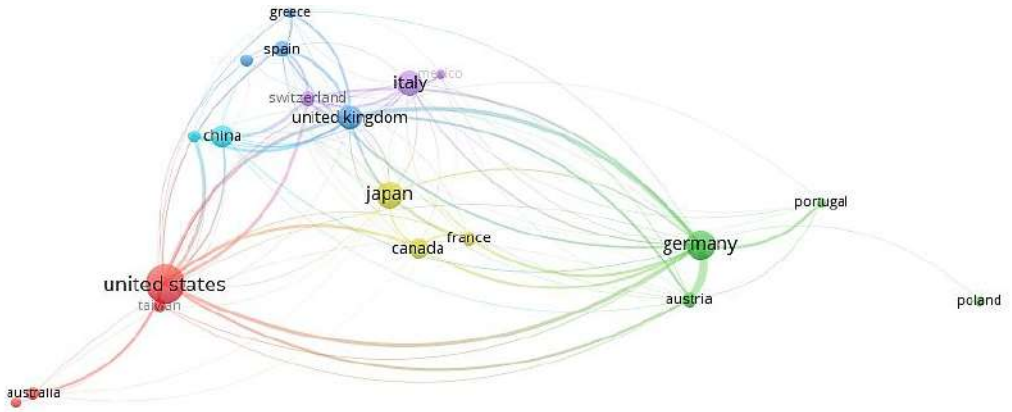


Figure 2. Relationships between countries.

This figure shows a map of the international scientific collaboration network based on the relationships between co-publishing. The large, thick circles and the many lines connecting them to other countries such as China, Japan, Germany, the United Kingdom, and Australia indicate that the United States is the largest hub of collaboration. This suggests that the main hub of global cooperation is the United States. With many connections to countries such as Austria, France, Portugal, and Poland, Germany is also an important node in Europe and plays a significant role in regional cooperation. In addition, there is an active collaborative network between Italy, Japan, and the United Kingdom involving other countries. Although they are still connected to the main node, the involvement of many countries including Greece, Mexico, and Taiwan in this network indicates a more limited level of cooperation. This network generally illustrates how international scientific collaboration works, with prosperous countries with strong research infrastructures at its core.

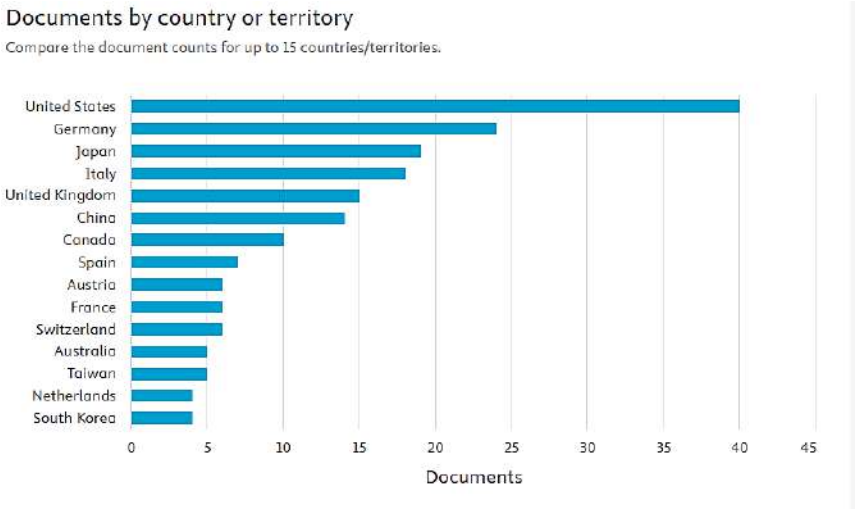


Figure 3. Documents by region.

With nearly 42 documents, the United States has more publications than any other country, according to the "*Documents by Country or Region*" chart. With 24 records, Germany is in second place, followed by the United Kingdom, Italy, and Japan, each with 17-20 documents. Significant contributions from China and Canada are next, with around 15 and 12 documents, respectively. With between six and nine documents, countries such as France, Austria, Spain, and Switzerland have the fewest documents. With fewer than six papers submitted, South Korea, Taiwan, Australia, and the Netherlands are in last place. According to these statistics, industrialized countries continue to produce the majority of scientific papers. The supremacy of the United States is a reflection of the strength of its infrastructure and research capabilities. The differences in the number of documents among countries are a reflection of the variations in funding, resources, and research priorities that support scientific endeavours.

Research focus

Figure 4 shows the emphasis of research on motor skills and mixed reality. Figure 5 illustrates the originality of the research. The VOSviewer program with a threshold of 5 was used to display the images. This indicates that there are at least five separate papers that use the keywords displayed.

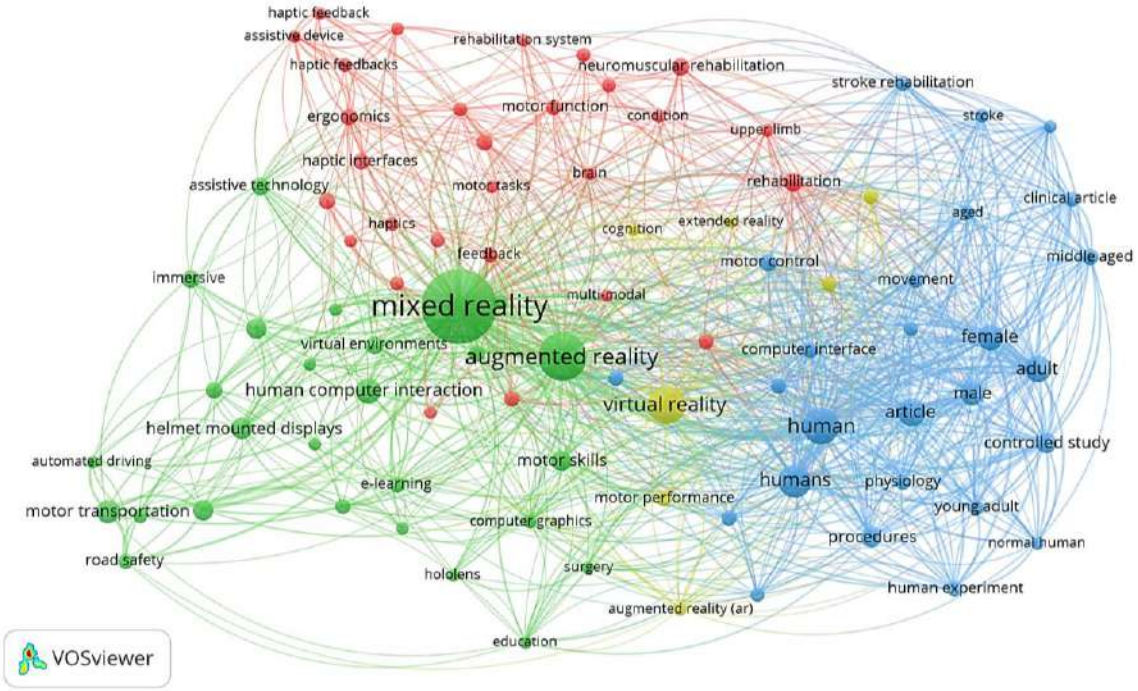


Figure 4. Research emphasis.

Using Vosviewer, the figure above visualizes the term network map (Co-occurrence) in research on reality technologies including virtual reality, augmented reality, and mixed reality. According to several studies, the phrases "*mixed reality*," "*augmented reality*," and "*virtual reality*" emerge as the largest size centres, indicating their high frequency of presence. Green, red, and blue are the three primary colour clusters. With an emphasis on the elements of technology interaction and education, the green cluster covers subjects including motor transportation, e-learning, human-computer interface, and helmet-mounted displays. With terms such as rehabilitation, haptic feedback, and motor function, the red cluster emphasizes neurological and motor rehabilitation. Meanwhile, the blue cluster is mostly related to clinical features and human populations, including adults, stroke, physical, and humans. This map highlights the interdisciplinarity in

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immersive technology research by depicting the close relationship between several sectors, ranging from education and transportation to rehabilitation.

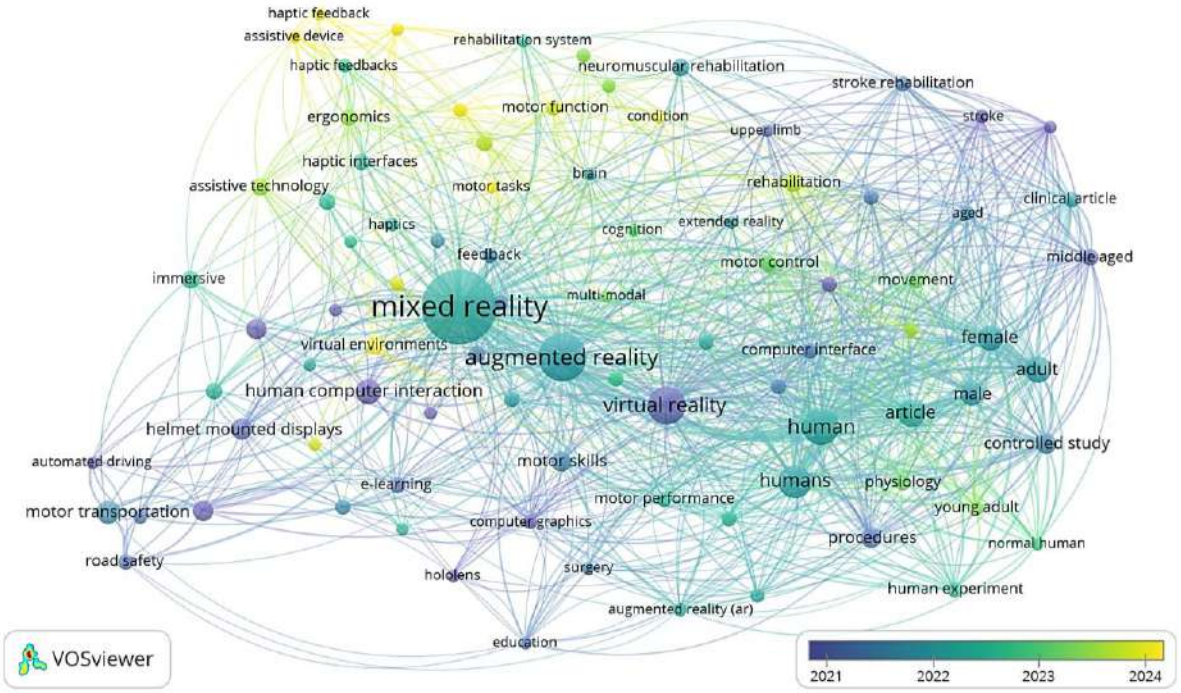


Figure 5. Research novelty.

Figure 5 shows a bibliometric representation of terms used in mixed reality, augmented reality, and virtual reality research from 2021 to 2024. The node colours show the temporal distribution; purple indicates terms that were more prevalent at the beginning of the era (2021), while yellow indicates more recent trends (2023-2024). Keywords such as "*augmented reality*," "*mixed reality*," and "*virtual reality*" continue to be the focus of studies. The use of mixed reality in rehabilitation technology and haptic feedback is becoming more popular, as seen by the bright yellow terms "*haptic feedback*," "*rehabilitation systems*," and "*motor function*." On the other hand, the blue cluster is mostly related to clinical aspects and human populations, such as human, adult, stroke, and physiology. This map shows the close relationship between the fields, highlighting the interdisciplinarity in the study of immersive technologies, from rehabilitation to education and transportation.

DISCUSSION

The results of this study convey that publications on MR and motor skills, sourced from the Scopus database from 2015 to 2025 have been visualized with the help of VOSviewer, with keyword frequency bibliometric techniques, mapping of author collaborations between countries, and publication trends for a decade (2015-2025).

Bibliometric visualization findings show that research related to mixed reality, augmented reality, and virtual reality has experienced significant development during the period 2021 to 2024. This is reflected in the strength and connection of the keywords displayed on the map, where "*mixed reality*" is the main centre with a wide keyword network. This study shows that mixed reality is not only an important issue but also functions as a bridge connecting various disciplines, including technology, health, and human-computer interaction

(Suryodiningrat et al. 2024). The shift in focus from the development of hardware technology to its application in the medical and rehabilitation disciplines is also reflected in the latest research trends, which are marked in yellow on phrases such as haptic feedback, rehabilitation systems, and motor function. This shift shows that mixed reality technology is starting to be widely used in real life, not just as a technological advancement, but has been used in patient rehabilitation and motor function recovery (Mandolini et al. 2025).

Information on the use of MR and motor skills from 2015 to 2025 is presented based on the findings and objectives of this study, which shows a significant increase in publications and academic interest in the field of MR and motor skills. This study highlights emerging trends, such as key contributions, and possible future integration paths between motor skills and MR are emphasized in this study. Overall, the results of the study indicate that MR has great potential to change the way skills are learned and taught. It is hoped that as technology advances, research and use of MR in skill improvement will expand and improve overall educational standards.

CONCLUSION

Based on the results of the study, it can be said that the bibliometric analysis describes the publication trend on MR and motor skills in the 2015-2025 period. The document selection process involves a search engine from the Scopus database and is filtered to get 259 of the keyword matches. Based on the data analysis, the most publications were in 2024 with 48 documents showing that the use of MR has increased in motor skills. A picture of a trend that will continue to increase in the coming year.

The findings of this analysis convey that the keywords that often appear in research related to the application of MR with motor skills. These keywords are "*mixed reality*" virtual reality, argument reality and motor skills. Among these keywords, MR is the central centre that most often appears in research discussions. The United States, Germany and Japan are the countries with the most documents and Germany, the United States, and the United Kingdom are countries with high collaboration. In this analysis, we found new keywords such as motor tasks, arthroplasty, haptic feedback, and virtual environments. This is expected to be a guideline and motivation in conducting future research.

AUTHOR CONTRIBUTIONS

This work was carried out as a team, but the division of responsibilities was as follows: Research concept and design: Yanuar Kiram, Wilda Welis, and Sri Gusti Handayani. Data compilation: Wilda Welis, Anton Komaini, and Sri Gusti Handayani. Data analysis and interpretation: Yanuar Kiram, Heru Andika, and Rully Effendi. Report review: Anton Komaini, Heru Andika, and Rully Effendi.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

Exploring the roles of artificial intelligence and wearable feedback technologies in figure skating performance analysis: A scoping review

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ABSTRACT

The application of artificial intelligence (AI) unlocks an exciting perspective for performance analysis in figure skating. A better understanding of AI and wearable feedback technologies of figure skating is warranted. The purpose of this study is to overview the roles of AI and wearable feedback technologies in figure skating performance analysis. Systematic searches through PubMed, Web of Science, and Scopus online databases were conducted for articles reporting AI and wearable feedback technologies applied to figure skating. Twelve studies were included in the review; three themes of AI and wearable feedback technologies emerged as being applied in figure skating. Emerging themes were wearable inertial and force sensors, marker less computer vision systems, and pose (marker) based deep learning. Body-worn IMU systems primarily support jump detection and counting, achieving very high accuracy for discrete event identification in controlled or semi-controlled settings. Body-worn IMU systems primarily support jump detection and counting, achieving very high accuracy. The current state of technology used for performance analysis in the area proposes a promising future with regard to figure skating. Further evaluation research based on real figure skaters is warranted to establish the predictive performance of specific AI and wearable technologies.

Keywords: Machine learning, Inertia measurement unit, Gyroscope.

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INTRODUCTION

The implementation of innovative systems on information and communication technologies in combination with sophisticated processing methods is becoming increasingly essential for the analysis of data in sports (Baca et al., 2009). The pursuit of athletic excellence in figure skating calls for an exceptional synthesis of artistic expression, technical accuracy, and physical competence (Gzenda et al., 2019; Stienstra et al., 2011). Traditionally, the analysis of jumps, spins, footwork, and overall performance has relied on the subjective eye of the coach, supplemented by video replay (Lockwood et al., 2006). This approach is fundamentally limited by human perceptual constraints and subjective assessment, making the analysis complex in biomechanical components such as angular momentum, force distribution, and aerial positioning. The arrival of artificial intelligence (AI) and wearable feedback technologies plays a role in overcoming these challenges, offering the promising solution for objective and data-based feedback in a sport (Kim et al., 2024; Novikova et al., 2024).

Artificial intelligence, over machine learning and computer vision systems, can transform sports performance from video in extraordinary detail to automatically classifying technical elements. Wearable feedback technologies like inertial measurement units (IMUs), pressure-sensitive insoles, and electromyography (EMG) sensors provide a continuous stream of physiological and biomechanical data directly from the athletes. These devices provide real data on jump height, rotational velocity, edge quality, muscle activation, and balance in real time, metrics that are classically inaccessible during training (Kim et al., 2024; Shi et al., 2020).

The transformation of this change lies in the use of biomechanical tools in the form of wearable inertial measurement units and 3D motion capture that breaks down complex skills into measurable units (Adesida et al., 2019). Studies indicate that IMUs offer objective information about the jump kinematics and accurate determination of the rotation speed, height, and landing forces (Vitali et al., 2017). At the same time, motion capture analysis can be used to identify potentially harmful biomechanical behaviours and prevent injuries. This technological basis shifts coaching towards a reactive error-correcting model rather than a proactive performance engineering and injury prevention model (Bandodkar et al., 2014; Tate et al., 2010; Zhang et al., 2019).

Although artificial intelligence and wearable feedback technologies are increasingly used to support performance analysis and injury prevention across a range of sports (Bandodkar et al., 2014; Souaifi et al., 2025; Valero et al., 2025), existing reviews focus on general sports biomechanics and do not address the demands of figure skating. Evidence for figure skating remains scattered across isolated studies. To date, no review has systematically mapped how artificial intelligence and wearable feedback technologies are being applied to figure skating performance analysis or what gaps remain to guide future research and practice in this domain.

Therefore, this paper presents the overview of the current literature on the application of AI and wearable feedback technologies in figure skating. Our objectives are first, to evaluate the types of AI and wearable devices being deployed, and second, to suggest accurate AI and wearable technologies for predicting performance in figure skating. Thirdly, we aim to identify potential areas for future research in the field of figure skating. Specifically, our review aimed to answer the following questions: (1) What types of AI and wearable technologies have been applied to analyse performance in figure skating? (2) Which AI and wearable technologies are accurate for predicting performance in figure skating? # (3) What is the research gap on figure skating in relation to technology use?

MATERIALS AND METHODS

Procedure

The review methodology adopted the PRISMA guidelines (15). The JBI data extraction tool was used to extract relevant data. The quality appraisal was completed by the two authors. The Population (P), Intervention (I), Comparison (C), Outcomes (O), and Study Design (S) (PICOS) search formula was used to retrieve articles (Table1).

Table 1. PICOS framework.

Component	Description
The Population (P)	Figure skaters who are amateur and professional levels and Videos of figure skating
Intervention (I)	Application of artificial intelligence, such as machine learning, deep learning, computer vision, and reinforcement learning, to analyse and wearable technologies in performance analysis of figure skating
Comparison (C)	Traditional performance analysis methods such as manual assessments, conventional statistical techniques or comparisons among different AI-based methodologies.
Outcomes (O)	Quantitative metrics such as accuracy, precision, recall, F1-score, mean absolute error and qualitative outcomes such as tactical decision support, improved training strategies, enhanced performance monitoring
Study Design (S)	Empirical studies including experimental, observational, and quasi-experimental designs, as well as systematic reviews and meta-analyses that report on AI and Wearable Feedback Technologies applications in figure skating performance analysis.

Data sources and search strategy

A comprehensive literature search was conducted across multiple high-impact databases, including PubMed, Web of Science, and Scopus. Search terms were developed based on adapted PICOS questions to identify relevant literature. Keywords such as "*Figure skating*," "*Performance analysis*," "*Wearable technology*," and "*Artificial intelligence*" were used to develop a search strategy to identify articles. We employed "*AND*" and "*OR*" Boolean operators. A PRISMA critical appraisal follow-up chart was used to determine the number of studies.

Eligibility criteria and selection process

The studies were included based on the following inclusion criteria, with two authors double-checking. If doubt arose, the third author was involved in the final decision. The inclusion criteria were:

1. The study was written in English.
2. The study was published in a peer-reviewed journal as a full-text and original research paper.
3. Data was just for the figure skating report's empirical findings on qualitative and quantitative performance metrics such as accuracy, precision, recall, or F1-score.
4. The participants were amateur and professional figure skaters as well as video databases.
5. The AI and wearable feedback technologies must be described and tested.

Quality Assessment and data collection

The quality of all studies was evaluated using evaluation criteria (Table 2) described by Saw et al (Saw et al., 2016) .Scores were allocated based on how well each criterion was met, assuming a maximum possible score of 7 (low risk of bias). Studies with a risk of bias score of 4 or less were considered poor and excluded. Once the studies to be included were selected, we performed a review by checking reference lists (*Checking reference lists to find additional studies for systematic reviews - Horsley, T - 2011 | Cochrane Library*, n.d.) to identify additional peer-reviewed studies.

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Table 2. Risk of bias assessment criteria.

Criteria		Definition	Scoring		
			0	1	2
A	Peer-reviewed	Study published in peer-reviewed journal	No	Yes	-
B	Real-world approach	The approach was performed with real results/data of the athletes	No	Yes	-
C	Population defined	Age, gender, sport, and level was described	No	Partly	Yes
D	Experimental design	Experimental design of the study period was described and replicable	No	Partly	Yes
E	Artificial intelligence	The artificial intelligence or wearable device were described	No		-

RESULTS

Identification of studies

The initial search returned 435 articles (for details, see Figure 1). After the removal of duplicated articles (n = 143), a total of 292 studies were retained for further screening and eligibility assessment. Following eligibility assessment, 14 were retained for final risk of bias assessment. 2 studies with a risk of bias score of 4 or less were considered poor and were excluded. The remaining studies were evaluated between 6 and 7 points in terms of quality (supporting document Table 3). During the revision of the reference lists, we haven't found anything that meets all the criteria for inclusion in the analysis. This scope review included a total of 12 studies (Bruening, 2018; Chen et al., 2025; Hara et al., 2024; Seiji Hirosawa et al., 2023; Li et al., 2021; Y. Liu et al., 2023; Panfili et al., 2022; Tanaka et al., 2023a, 2024; Tian et al., 2023; Zhao, 2025).

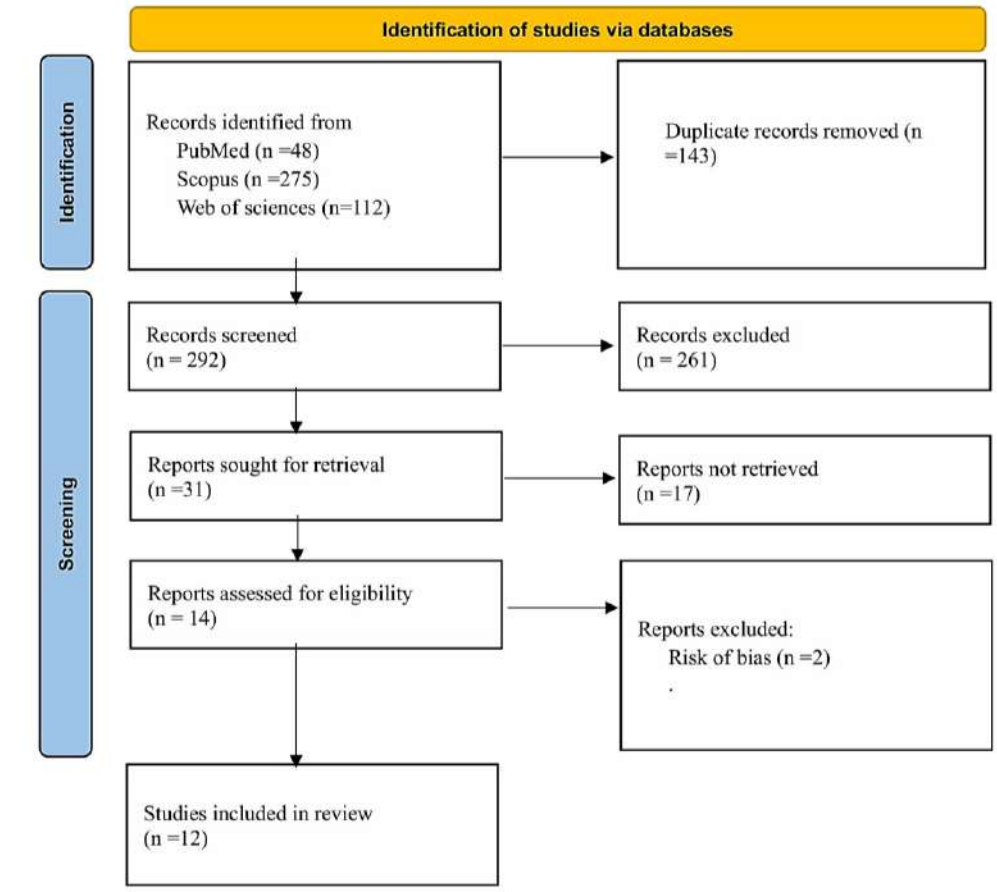


Figure 1. Identification of studies via databases.

Table 3. Risk bias evaluation result.

	List of studies	A (Peer-reviewed)	B (Real-world approach)	C (Population defined)	D (Experimental design)	E (AIor wearable device	Total
1	Antonio	1	1	2	2	1	7
2	Royota	1	1	1	2	1	6
3	Dustin	1	1	2	2	1	7
4	Congran	1	1	0	2	1	5
5	Ekelund	1	1	2	2	1	7
6	LI	1	1	0	2	1	5
7	Dan Chen	1	1	1	2	1	6
8	Limao	1	1	2	2	1	7
9	YU	1	1	1	2	1	6
10	Reyota	0	1	2	2	1	6
11	Sieji	1	1	1	2	1	6
12	Yuse	1	1	1	2	1	6

Characteristics of included studies

The majority of the included studies used video databases, and the human samples were tiny. About half of the 12 included research employed some kind of artificial intelligence (AI) or machine learning (ML) model; 33% used body-worn wearables alone, 33% used pure vision, and the remaining studies used wearables plus vision or other external sensors in combination. About half of the studies used deep learning, such as convolutional neural network (CNN), graph convolutional network (GCN), transformer, or recurrent neural network (RNN) based architectures for pose estimation, action segmentation, or scoring; one-third of the studies used rule-based or classical methods; and one-sixth used simple machine learning.

Types of AI or technology used

Wearable inertial and force sensors

Body-worn sensors are wearable inertial and force sensors, which are designed to sense and measure multidimensional aspects of human motion, including overall body movement, jump detection, jump counting, flight time, and rotational velocity. These tools are a cornerstone of modern sports performance analysis systems, which allow accurate biomechanical evaluation and real-time feedback. The inertial sensors are usually combined with accelerometers, gyroscopes, and magnetometers to detect dynamic movement, but the force sensors are used to measure the contact forces and pressure distributions during athletic movements. Wearable inertial and force-sensing systems are typically divided into two broad categories, namely, body-worn sensors (Bruening, 2018; Panfili et al., 2022), and force-plate-integrated wearables, depending on their configuration and integration (Hara et al., 2024).

The body-worn wearables without external cameras were able to reach great levels of accuracy for motion analysis investigations in figure skating. For example, during controlled pattern skating, Panfili et al. used a combination time-of-flight laser and IMU system to detect jumps with 97–99% accuracy (Panfili et al., 2022). Similarly, Bruening et al used a single waist-mounted IMU to identify jump counts, estimate flight times, and measure rotation speeds with a 95% accuracy rate (Bruening, 2018). In contrast, only 8% (1 out of 12) of studies used instrumented skate or force-plate wearables. Hara et al. constructed custom, wearable force plates integrated in the skating blades that reliably recorded 3D (three-dimensional forces (Hara et al., 2024).

Marker less computer vision systems

Marker less motion capture is a technology that captures human movement without the need for physical markers on the body. It uses depth-sensing cameras or computer vision algorithms to track and analyse the

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subject's movements in real time. In this review, marker less computer-vision systems, which constituted approximately 33% (4 out of 12) of studies, leverage 2D and 3D pose estimation based on video input rather than body-worn sensors. These approaches typically employ frameworks such as MediaPipe or OpenPose-like architectures, using multi-view or monocular RGB camera setups for 3D reconstruction and the extraction of skeletal and kinematic features. Chen et al. reported 79.09% overall accuracy in real-time blade-type discrimination with a MediaPipe-based pipeline, which suggested the automatic identification of edges was possible (Chen et al., 2025). Liu and Zhou reported a true positive rate of 98% on jumping-action recognition by combining skeleton-based pose features with deep reinforcement learning (Y. Liu et al., 2023). Additionally, Zhao et al. propose AutoSco, a broadcast video-driven automated figure skating scoring model that integrates the C3D feature and the Bi-LSTM networks with multi-layer attention mechanisms to enhance long-term temporal action sequence analysis (Zhao, 2025).

Pose (marker) based deep learning

Pose-based deep learning systems take up approximately half of the studies (six out of twelve). They combine high-end machine-learning models with pose-estimation algorithms to obtain spatiotemporal information in skeletal data from an athlete. These systems rely on spatio-temporal graph convolutional networks (ST-GCN), transformer-based 3-D pose estimators such as MotionAGFormer, and temporal-action segmentation networks such as FACT to identify jump phases and other technical details at the fine scale.

Tanaka (2024) coupled MotionAGFormer and FACT into an automated assessment system and obtained 83 percent accuracy on skater data based on 3-D joint positions reconstructed by monocular cameras (Tanaka et al., 2023b, 2023a). A CNN proposed by Hirosawa et al. uses gaze-guided and temporal attention to estimate the grade of execution (GOE) of each individual jump; using gaze data of expert judges, the hybrid model reduced the RMSE to 0.775, which was lower than human judges and baseline models (Seiji Hirosawa et al., 2023). Tian et al. constructed a multi-view 3-D reconstruction pipeline with the OpenPose to achieve accurate motion capture. Their method had a joint reconstruction success rate of 93.38, 92.57, and 91.55 within 70 mm, 50 mm, and 30 mm error margins, respectively (Tian et al., 2023).

The recent development of deep learning in combination with other methods has been further expanded by the ST-GCN of Liu and Zhou, which uses deep reinforcement learning and has a true positive rate of 98 percent in jump recognition (Y. Liu et al., 2023), Similarly, the skeleton-based AQA model by Li et al. outperformed the traditional RGB-only approaches to the long-term performance scoring, like SENet and C3D (Li et al., 2021). On the same note, the AutoSco system developed by Zhao, which is based on Bi-LSTM and multi-layer attention networks, improved the ability to model long-term temporal dependencies in automated figure skating scoring. All these results highlight a paradigm shift to hybrid AI systems with skeleton-based motion features, human perceptual features, and temporal deep-learning models, and they achieve high, human-comparable scoring and performance-evaluation accuracy (Zhao, 2025) (Table 4).

Table 4. Types of AI or technology used description.

Type	Description
Wearable inertial and force sensors	MUs (accelerometers + gyroscopes) for jump detection and rotation, uniaxial accelerometers for energy expenditure, and instrumented skates with embedded force sensors, primarily analysed with threshold-based algorithms or linear/statistical models.
Marker less computer-vision systems	MediaPipe or OpenPose-like 2D pose estimators, multi-view RGB setups with custom 3D reconstruction, and broadcast-video pipelines for skeleton extraction without body-worn devices.
Pose-based deep learning	Spatio-temporal GCNs on skeleton sequences, transformer-based 3D pose estimators (e.g., MotionAGFormer) and temporal action segmentation networks (e.g., FACT) for fine-grained jump phase recognition.

DISCUSSION

The present scoping review mapped emerging technological and artificial intelligence (AI) approaches in figure skating performance analysis, revealing three main technological themes, each with distinct functions and accuracy profiles that together outline the current landscape of automated evaluation in figure skating. Body-worn IMU systems primarily support jump detection and counting, achieving very high accuracy for discrete event identification in controlled or semi-controlled settings (Panfili et al., 2022; Ridge et al., 2025), whereas instrumented skates provide rich three-dimensional force and moment data for detailed technique analysis but are less practical for routine deployment and do not report a single summary accuracy value (Hara et al., 2024).

Other validation and review papers on body-worn IMU systems used in various sports, including jump-dominant sports, demonstrate that jump event detection accuracy is typically around 99% when compared to gold-standard references, where IMU-based systems achieved high jump detection accuracy or sensitivity values from controlled match analysis protocols (Clemente et al., 2022; Pino-Ortega et al., 2018).

However, applications that are run on iced surfaces are still limited by the issues that are related to sensor mounting, motion interference, and contact with the ice substrate. Experiments with force-integrated systems, such as custom instrumented skating blades, have provided priceless information about three-dimensional ground reaction forces and blade dynamics and thus highlight the opportunities for improving models of kinetic skating technique. However, they are not very common, as less than 10 percent of the reviewed literature uses such systems, which is likely due to challenges in integrating equipment, the complexity of calibration, and the lack of generalizability across proficiency levels (Bruening, 2018; Panfili et al., 2022; Ridge et al., 2025).

Vision-only computer vision approaches, which operate on RGB video without sensors, span applications from blade edge discrimination (Chen et al., 2025) to jump recognition and automated scoring. Scoring models are typically reported in terms of relative improvements over RGB-only baselines rather than simple accuracy (Zhao, 2025). Another published review of vision-based human action quality assessment (AQA) reports that most AQA studies in sports start from RGB video features and then compare new architectures (pose-based, multi-stream, or multimodal) to RGB-only baselines using relative improvements in correlation or error, not simple accuracy, especially for scoring and quality assessment tasks (J. Liu et al., 2025).

Nevertheless, a general survey of action quality evaluation shows that, in dynamic sports like diving, gymnastics, and figure skating, pipelines that are trained on RGB imagery alone are always able to achieve better detection and segmentation results, but score prediction is often measured using correlation and ranking metrics; performance improvements are often reported relative to RGB-only baselines (J. Liu et al., 2025; Zhou et al., 2024). However, the ongoing differences in camera setup, lighting, occlusion management, and video quality still pose a major constraint, compromising the data integrity and reproducibility across different rinks and broadcasting systems. The recent introduction of hybrid systems, where inertial measurement unit signals are combined with vision-based features, provides promising opportunities to improve the generalization to untested athletes and heterogeneous environmental conditions (Chen et al., 2025; G. Liu, 2025; Y. Liu et al., 2023; Zhao, 2025).

Pose-based deep learning and other machine learning methods are central to this ecosystem. They combine skeleton-based representations with spatiotemporal architectures such as ST-GCN, transformers, and Bi-LSTM networks. Sometimes, they also use expert gaze information. These methods achieve around 80-83%

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accuracy when evaluating figure skaters and up to 98% true positive rates for jump recognition. Some models even outperform human judges in predicting execution grades (Tanaka et al., 2023a; Tian et al., 2020, 2023). Other published reviews of sports reported that pose-based deep learning with skeleton inputs and ST-GCN, transformer, or Bi-LSTM architectures is now the most effective to evaluate complex skills. These reviews highlight typical evaluation accuracies above 80% and very high event detection rates. They also mention that pose- and gaze-augmented models can match or exceed human judges for scoring or grade of execution, often exceeding RGB-only baselines (J. Liu et al., 2025; Lu, 2024; Zhou et al., 2024).

Integration of human perceptual cues represents a new frontier. Hirosawa's gaze-guided attention model showed that combining expert gaze features with temporal convolutional networks improved model interpretability and lowered prediction errors below human-level baselines. This finding suggests a future of hybrid intelligence where algorithmic insights and human expertise come together to improve judging consistency and training feedback (S Hirosawa et al., 2024; Seiji Hirosawa et al., 2023; Tanaka et al., 2024; Tian et al., 2020, 2023).

Taken together, these findings indicate that IMU-based wearables and ST-GCN or deep reinforcement learning models provide the highest performance for jump detection and recognition, while transformer-based, skeleton-driven, and gaze-augmented models currently offer the strongest performance for action quality assessment and automated scoring, suggesting that a hybrid pipeline combining robust event detection with advanced pose-based scoring is likely to yield the most reliable and comprehensive evaluation framework (S Hirosawa et al., 2024; Tanaka et al., 2023a, 2024; Tian et al., 2023).

Although tremendous progress has been achieved, some methodological deficiencies have emerged in current studies. Data sets are still of limited size and variability, and models have been trained on data sets of limited numbers of figure skaters only or in simulated settings. Additionally, some degree of standardization is still lacking in benchmark settings and evaluation metrics. Furthermore, few studies focus on ethical and privacy related questions on athlete data, especially on broadcast settings. Future studies should focus on the implementation of open data sets, multimodal data fusion incorporating physiological data, and the combination of AI techniques that can be used for an increased trustworthy automated evaluation. Longitudinal validation studies on professional and amateur groups could also help identify how AI related kinematic knowledge can be used as an aid for coaching and injury prevention.

Overall, the technological trajectory that emerges from this review is indicative of the maturing of the integration of the fields of biomechanics, computer vision, and AI research. Because a certain level of technical proficiency as well as an artistic judgment of figure skating components is necessary for proficient skating skills, it can be said that the trend towards vision-based deep learning models and hybrid models is poised to bring a revolution to the art of evaluating skating skills, from technical evaluation of jumps and turns to artistic interpretations of their executions.

CONCLUSIONS

In conclusion, this scope review mapped the existing literature on technology used in figure skating performance analysis, those used in figure skating were wearable inertial and force sensors, Marker less computer vision systems, pose based deep learning. The current state of technology used to performance analysis in the area proposes a promising future with regard to figure skating. Further evaluation research based on real figure skaters is warranted to establish the predictive performance of specific AI and wearable technologies.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

DECLARATION OF GENERATIVE AI USE

In preparing this manuscript, AI-assisted technologies were employed to improve the clarity, flow, and readability of the text. The AI tools were used strictly as language enhancement assistants, helping refine grammar, sentence structure, and overall coherence. The author reviewed and took full responsibility for the content of the publication.

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REVIEW ARTICLE

Entrepreneurial culture, social-emotional skills, and self-esteem in students participating in sports programmes in Colombia

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ABSTRACT

This research presents the results of a systematic review that analyses the relationship between entrepreneurial culture, social-emotional skills and self-esteem in students enrolled in sports programmes in Colombia, with the aim of identifying the factors that influence their positive attitude towards entrepreneurial capacity. In the literature review, 100 articles and academic research papers were selected between 2019 and 2025, prioritised from 42,958 results from different resources such as reference databases, multidisciplinary databases, academic repositories and academic journals. The databases with the highest number of results were Scopus, Web of Science, Wiley, Springer Nature, Science Direct, Ebsco Host, among others such as (COnnecting REpositories), Taylor & Francis, and Google Scholar. The results showed an interest in academia to research and reflect on the relationship between entrepreneurial culture, emotional skills, and young people. However, in most studies, entrepreneurial culture is associated with variables such as emotional intelligence and social skills in university contexts, leaving the field of the relationship between these variables and the field of sports somewhat lacking in studies. Studies that explore this relationship in depth conclude that athletes develop socio-emotional skills that make them strong candidates for entrepreneurship. However, there are limitations in the implementation of mechanisms that promote an entrepreneurial culture ( ) in university contexts for young people studying sports programmes.

Keywords: Physical education, Culture, Social-emotional skills, Self-esteem.

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INTRODUCTION

Entrepreneurship and business development have become fundamental components in strengthening local and global economic dynamics and, in turn, opportunities for personal growth. Entrepreneurship has been studied in different dimensions, including its relationship with the socio-emotional skills, motivation and resilience of entrepreneurs. In the sports sector, there is growing recognition of the role of entrepreneurial attitudes among young people in university education. This has led to a shift in the academic focus towards the development of entrepreneurial skills in the younger generation, particularly among university students and young people with a background in sports. While the positive relationship between sport and entrepreneurial intention in sports students has been explored, more research is needed, especially focused on characterising entrepreneurs in the field of sport, their socio-emotional skills applied to entrepreneurial contexts, and the mechanisms of training for entrepreneurship in higher education contexts.

This research aimed to analyse the relationship between three variables: entrepreneurial culture (entrepreneurial intention, attitude towards entrepreneurship, entrepreneurial self-efficacy, entrepreneurial knowledge, support networks), socio-emotional skills (self-awareness, self-control, motivation, empathy, social skills) and self-esteem: (Personal Worth, Self-Satisfaction, and Self-Confidence) in sports degree students in Colombia. To achieve this purpose, a methodology based on systematic review of 100 articles and academic research published between 2019 and 2025 was implemented. Based on the methodology implemented, searches were conducted in Spanish, English, and Portuguese, taking into account the inclusion criteria, by key terms (Entrepreneurial Culture, Socio-Emotional Skills, Self-Esteem, Sport), including other related terms; by time period (2019-2025); by population type (youth, academic sports programmes); by type of study (indexed journals); and by geographical area (international and local).

Based on the systematic review, there is evidence of an increase in research seeking to explain the relationship between entrepreneurial culture, socio-emotional skills and self-esteem as key factors in young people's entrepreneurial intentions. However, there is less research focused on clarifying the influence of these factors on students studying for a degree in sport. Studies that investigate this relationship agree that athletes develop skills that facilitate the task of starting the path to entrepreneurship.

The findings showed that entrepreneurship education is essential for developing entrepreneurial skills, including socio-emotional skills such as resilience and proactivity. Entrepreneurial culture, defined by risk tolerance, proactivity, and autonomy, is linked to the psychological characteristics of athletes, who naturally develop these skills that make them potential entrepreneurs. Studies (Vidal-Vilaplana et al., 2025) highlight that elite athletes, especially older ones, show high entrepreneurial intentions due to their resilience and creativity. The results show that high resilience in athletes reduces fear of failure and enhances entrepreneurial commitment, while creativity, together with entrepreneurial intention, emerge as crucial skills for all identified entrepreneurial profiles.

Analysis of national and international studies shows that a comprehensive entrepreneurial culture not only drives economic development but also provides opportunities for students' personal and professional growth and strengthens their role as agents of social change. Although there is abundant international research (USA, Spain, United Kingdom, China, etc.), little specific research was found on entrepreneurship among sports students in Colombia. National studies focus on the general characterisation of Colombian entrepreneurs, highlighting the need to strengthen business training and emphasising organisational skills when creating a business. On the other hand, some studies investigate entrepreneurial culture in university contexts and the factors that influence the entrepreneurial attitude of young people in sports contexts. For

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example, the study by González et al. (2019) highlights the importance of implementing entrepreneurial training strategies in university sports curricula.

In conclusion, entrepreneurial culture, socio-emotional skills and self-esteem are key variables in the training of sports professionals with entrepreneurial skills. This research shows that the academic and sporting environment can become a breeding ground for social leaders, capable of creating impact through solid, sustainable and contextualised entrepreneurial initiatives.

METHOD

Search strategy

The methodology focused on an exhaustive literature review in the Scopus and Web of Science reference databases. The former yielded more results in Science Direct, while the latter referred its results to different journals and publishers included in its platform. Multidisciplinary and international databases such as Core (COnnecting REpositories), Wiley, Taylor & Francis, Springer Nature, Esbsco Host and PubMed were also included, as were open-access databases from Latin America such as Dialnet and Scielo, among others.

Searches were performed using the Boolean operators AND, OR, and NOT in the following search equations: "*Social-Emotional Skills AND Entrepreneurship*," "*IT Entrepreneurship AND IT Emotions*," "*Culture of Entrepreneurship AND Social-Emotional Skills AND Young*," "*Entrepreneurship*" AND "*Emotional Skills*," "*Entrepreneurial intention AND young people*", "*Entrepreneurship AND self-esteem*", "*Entrepreneurial Culture AND Social-Emotional Skills AND athlete*", "*Entrepreneurial Culture AND Social-Emotional Skills AND Young*", "*Culture of Entrepreneurship AND Social-Emotional Skills AND Young*", "*Culture of entrepreneurship AND Social-Emotional Skills AND university students AND sport*". Similarly, filters were applied for time ranges and publication types (academic, peer-reviewed). A total of 42,958 results were obtained from which 100 articles were selected that included at least two of the search terms among the first 100 results.

As shown in Figure 1, the databases with the highest number of results contain information resources involving sports science, administration, finance, psychology, and entrepreneurship studies.

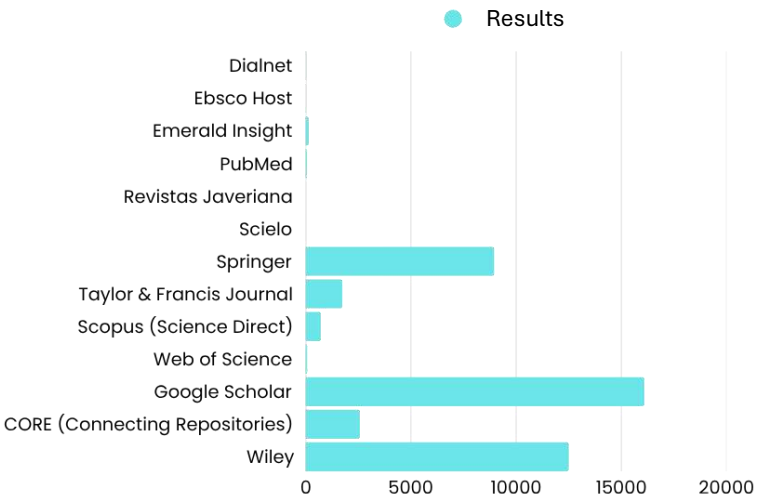


Figure 1. Search by descriptors in databases.

In the case of Springer Nature, it includes scientific journals such as the International Entrepreneurship and Management Journal, the Journal of International Entrepreneurship, Sport and Business and Management, which publish research on this topic. For its part, the Taylor & Francis Journal database is a publisher that includes on its platform a considerable digital collection of scientific and research journals and articles addressing the topic of entrepreneurship in sport, as well as related fields such as sports management and the sports business.

Platforms such as CORE (Connecting Repositories) and Google Scholar connect various resources that provide freely accessible information, including articles, books, book chapters, postgraduate theses, and doctoral dissertations. These are useful tools in the literature review process.

Likewise, WoS and Scopus are databases that index thousands of academic journals from different publishers and provide a selection of prestigious academic resources that enrich document analysis. WoS includes many journals that specialise in sport t management, business, sports sociology, economics, and business studies, such as Sport Management Review and the Journal of Sport Management. For its part, Scopus is also a comprehensive source of information on entrepreneurial culture in sport due to its extensive coverage of journals and other publications in the social sciences and business.

Variables analysed

Dependent variables

- Entrepreneurial Culture: (Entrepreneurial Intention, Attitude towards Entrepreneurship, Entrepreneurial Self-Efficacy, Entrepreneurial Knowledge, Support Networks). This variable will indicate the values, norms and beliefs that individuals in the selected group have regarding creating businesses, innovating and, in turn, their willingness to take risks and seize opportunities to develop business ideas.
- Social-Emotional Skills: (Self-Awareness, Self-Control, Motivation, Empathy, Social Skills). This will allow us to assess a person's ability to manage emotions and establish healthy relationships and face challenges.
- Self-esteem: (Personal worth, self-satisfaction and self-confidence). This scale, due to its psychometric properties, which include high internal consistency and validity, allows us to measure self-esteem.

Analysis of the quality of studies and/or data analysis

Entrepreneurship education has proven to be a key tool for fostering entrepreneurial skills in university students. Authors Lindh and Thorgren (2016) describe the importance of local partnerships between universities and businesses for developing entrepreneurial skills. This involves not only technical knowledge, but also the development of socio-emotional skills such as resilience, teamwork and e decision-making in uncertain environments (Smith and Yang, 2022). Furthermore, entrepreneurial culture becomes an adaptive behaviour in the face of contemporary changes in the world of work. Entrepreneurship is understood to generate benefits in terms of economic growth and job creation. On the other hand, Rae and Melton (2013) indicate that fostering an entrepreneurial mindset in students enables them to face complex situations and take calculated risks.

Entrepreneurial culture is understood as the set of values, norms, and beliefs that motivate individuals to create businesses, innovate, take risks, and seize opportunities (Shane et al., 2003, as cited in Sánchez-Oliver et al., 2019).

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Entrepreneurial culture is incorporated into personal and psychological elements that influence young people's ability to become entrepreneurs. Studies have shown that qualities such as self-efficacy, autonomy, innovation and stress tolerance are key characteristics of entrepreneurs (Hausmann and Heinze, 2016). These attributes are also associated with the subject's self-control and motivation to achieve goals, which are necessary components for competing with challenges and achieving success in business creation (Baron and Markman, 1999).

In this research paper, the concept of entrepreneurial culture is explored based on the research carried out by Stephan (2009), which highlights the essential components of entrepreneurial culture: The ability to apply new ideas (innovation); the ability to take risks and manage uncertainty (risk tolerance); the ability to anticipate opportunities and act on them (proactivity); and the ability to make decisions without relying on others (autonomy). Stephan has contributed significantly to the understanding of how entrepreneurial culture influences individuals' behaviour and attitudes towards business creation.

In the context of sport, the culture of entrepreneurship takes on greater relevance, given that sport cuts across different sectors, such as technology, health, the environment, education, society and the economy. Sport is widely recognised internationally, is a field in constant growth and innovation, and offers a wide range of possibilities in the market.

In this regard, Vidal-Vilaplana et al. (2025) provide significant empirical evidence by exploring the entrepreneurial intentions of elite athletes, demonstrating that entrepreneurship is a viable option for these professionals due to the transferable skills they have developed during their sporting careers. The study, carried out with a sample of 200 Spanish elite athletes using non-probabilistic intentional sampling, reveals that variables such as resilience, creativity and proactivity have a decisive influence on the entrepreneurial intentions of these elite athletes. The results of these studies show that high resilience reduces fear of failure and enhances entrepreneurial commitment, while creativity, together with resilience, emerge as crucial skills for all the entrepreneurial profiles identified. In particular, older athletes with developed skills show greater entrepreneurial intentions, suggesting the importance of educational training for post-sport entrepreneurial success.

It is crucial that institutions offering degrees in sports and physical activity implement various exploration and learning mechanisms in their curricula that expose students to the exercise of ideas and innovation, carrying out processes in which the knowledge learned, experience, and socio-emotional skills are applied and respond to the needs of the context, from the initial formulation of the project to its final execution.

In this context, Sánchez-Oliver et al. (2019) contribute significantly to the understanding of the implementation of an entrepreneurial culture in the university field through the presentation of the EmprendeSport project, an initiative developed by the University of Seville between 2015 and 2018 with the aim of improving business knowledge and promoting entrepreneurial culture in the university context. The initiative consisted of seminars aimed at students and professionals in the sports sector, with an average attendance of 200 participants in four editions, and revealed a significant problem: There is limited literature on the entrepreneurial intentions of young people, as well as a marked lack of knowledge and interest in entrepreneurship among attendees, a situation that is exacerbated in the Spanish context, where risk aversion and fear of failure prevail, placing the country among the lowest levels of entrepreneurship in the European Union.

The authors emphasise that universities play a crucial role in entrepreneurship and innovation ecosystems, being fundamental to the promotion of emotional skills such as self-confidence and overcoming the fear of failure, elements that inhibit entrepreneurial initiatives. The results of the EmprendeSport project demonstrate that entrepreneurial culture and values improve motivation for entrepreneurial activity, showing that educational interventions can create a culture of entrepreneurship in higher education and promote entrepreneurial skills among students and teachers, thus providing a valuable framework for the design of institutional policies and s aimed at strengthening university entrepreneurial activities in the field of sport.

Another interesting study by Steinbrink et al. (2020) provides evidence regarding the entrepreneurial potential of athletes through a comparative study involving 163 participants, including 110 high-performance athletes, categorised according to high- and low-risk sports, and a control group of non-athletes. The findings reveal that athletes share important personality traits with entrepreneurs, being less neurotic and more sociable than the reference groups, as well as showing significant differences in dimensions such as conscientiousness and risk propensity.

The research, based on the measurement of the five major personality traits (neuroticism, extraversion, openness, conscientiousness, and agreeableness), including risk propensity, suggests that these psychological traits predict both entrepreneurial intention and the potential for entrepreneurial success in athletes. Based on the theory of person-job fit, the authors argue that athletes can successfully become entrepreneurs due to the alignment between their psychological characteristics and the demands of entrepreneurship. The study highlights the importance of providing personalised entrepreneurial education to athletes during their transition to entrepreneurial careers, emphasising that understanding athletes' entrepreneurial temperament is critical to developing effective entrepreneurship programmes that maximise their potential as ideal candidates for entrepreneurship. However, limitations of the study in terms of sample size were evident, preventing the generalisation of the results.

Social-emotional skills emerge as a determining factor in the development of entrepreneurial competencies in educational contexts, being fundamental to the construction of a solid entrepreneurial culture. Ou and Kim (2024) and González and Lack (2019), focus their research on the impact of emotional skills on the culture of entrepreneurship. On the one hand, Ou (2024) shows through a study with 327 participants that the integration of psychological principles into business education substantially improves students' cognitive and emotional skills by establishing crucial connections between self-efficacy, student perseverance, and entrepreneurial inclinations.

On the other hand, González and Lack (2019) complement this position with a study of 58 university students aspiring to become entrepreneurs, showing that socio-emotional skills are crucial for managing personal resources in entrepreneurship, considering them key factors for business success, particularly in areas such as communication and happiness. Both studies demonstrate the need to integrate emotional dimensions into entrepreneurship-oriented educational programmes, as educational contexts improve both students' entrepreneurial aspirations and cognitive frameworks, providing empirical evidence on the importance of adopting holistic approaches that strengthen emotional resilience and socio-emotional competencies as fundamental pillars for successful entrepreneurial development.

In the Colombian context, some research focuses on characterising the Colombian entrepreneur, without delving into the sporting context. For example, Corzo and Rey (2020) characterise the Colombian entrepreneur in a way that allows us to understand the conceptual foundations of national entrepreneurship. Their research identifies three entrepreneurial profiles among entrepreneurs: ideators, nascent

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entrepreneurs, and established entrepreneurs. This classification is based on an analysis of organisational competencies that include strategic behaviours that create economic value, personal effectiveness, and leadership behaviours. The organisational competencies identified in the study, such as strategic behaviours, personal effectiveness and emotional leadership, are relevant for application in the field of sport, where these skills are naturally developed during academic training and sports practice.

In their research, González et al. (2019) highlight that, in Colombia, young people with sports degrees face significant challenges in entrepreneurship due to the lack of business training in their academic curricula. However, the National Sports University (IU END) located in the city of Cali, Colombia, has begun to implement activities such as courses, business fairs, and consulting services to promote entrepreneurship. The study shows that family context and access to start-up capital are determining factors in the intention to become an entrepreneur, while the university environment still has a limited impact on the generation of business ideas. These findings reflect the need to strengthen the culture of entrepreneurship in Colombia, especially in the sports sector, through educational policies that integrate business training and social innovation as tools to reduce social and sporting gaps in the country.

RESULTS

According to Figure 2, the selected search results showed greater relevance in the multidisciplinary databases Springer Nature, Web of Science, Scopus, Ebsco Host, Taylor & Francis Journal, CORE (Connecting Repositories), Emerald Insight, and Google Scholar. Although there are more results in Google Scholar, the selection process is time-consuming due to the lack of precision in its results, according to the search equation entered.

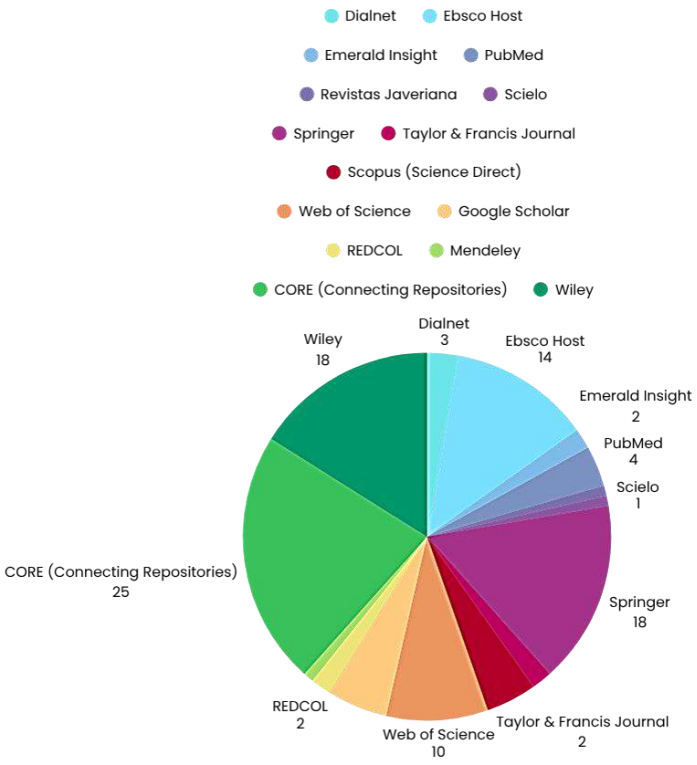


Figure 2. Distribution of results by database.

Some limitations in the searches are determined by the duplication of information in different databases, redundancy and noise in the results. In view of these conditions, rigorous searches, review and selection of the first hundred results were applied, related terms were used and regional databases such as Scielo and REDCOL were taken into account.

The results were mainly concentrated at the international level in countries such as the United States, China, Spain, Portugal, Germany, the United Kingdom, and some African countries. These studies show that the topics of greatest interest are related to the relationship between entrepreneurial culture, the development of soft skills, self-perception and emotional intelligence from an educational, political and cultural context. They also focus on topics such as age and entrepreneurial intention or the skills that young people develop in sporting environments that favour success in their entrepreneurial intentions. On the other hand, there are also studies that highlight the importance of developing soft skills and resilience in university students in a sporting context.

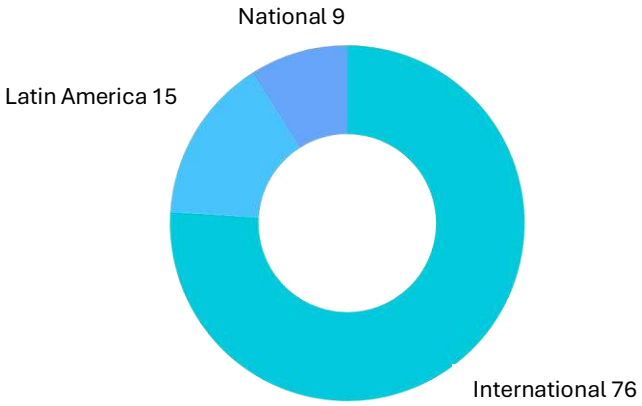


Figure 3. Distribution of results by country.

In Latin America, studies are oriented from a regional perspective that seeks to highlight the characteristics of emerging countries, the particularities of the cultural context, the barriers faced by the working class in the face of neoliberal policies, and the development of skills for entrepreneurship and the search for opportunities.

From a national perspective, studies characterise the Colombian entrepreneur, relating variables such as entrepreneurial culture, higher education, and soft skills in sports contexts.

DISCUSSION

The findings of this systematic review allow us to affirm that entrepreneurial culture, socio-emotional skills, and self-esteem constitute a dynamic system of factors that significantly influence the entrepreneurial intentions of university students, particularly those involved in sports programmes. This relationship cannot be understood in isolation, but rather as a complex process involving psychological, educational, cultural, and contextual dimensions, as suggested by contemporary approaches to competency-based entrepreneurship and entrepreneurial mindset (Mukhtar et al., 2021; Ou & Kim, 2024).

Firstly, the results confirm that entrepreneurial culture continues to be a central construct in explaining young people's willingness to create business initiatives. In line with Stephan's (2009) approach, entrepreneurial

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culture is expressed through values such as innovation, proactivity, risk tolerance and autonomy, elements that are consistently reflected in the studies analysed. These cultural components not only influence entrepreneurial intention, but also shape the way students interpret failure, manage uncertainty, and perceive opportunities in their environment, aspects that are particularly relevant in sports contexts characterised by competition and constant demands (Ratten & Jones, 2020; Pellegrini et al., 2020).

From a psychological perspective, the findings reinforce the validity of the model proposed by Baron and Markman (1999), by showing that cognitive and emotional mechanisms continue to be decisive in differentiating individuals with greater entrepreneurial potential. However, recent literature broadens this approach by demonstrating that these mechanisms are not static traits, but rather competencies that can be developed through appropriate training experiences and learning contexts (Ou & Kim, 2024). In this sense, sport emerges as a privileged setting for the acquisition of these skills, as it exposes students to situations of pressure, rapid decision-making and emotional regulation, skills that are highly transferable to the business world (Smith & Yang, 2022).

A relevant finding of this research is the mediating role of socio-emotional skills between sporting experience and entrepreneurial culture. Recent studies agree that competencies such as resilience, perseverance, self-awareness and social skills are significant predictors of entrepreneurial intention in young university students (Malete et al., 2022; González & Lack, 2019). In the case of students in sports programmes, these skills are developed intensively throughout their academic and sporting careers, positioning them as a group with high entrepreneurial potential. However, the results also show that this potential does not always translate into concrete business initiatives, due to the absence of institutional structures to support this process.

In line with Steinbrink et al. (2020) and Vidal-Vilaplana et al. (2025), the studies analysed show that athletes, especially those with long or high-performance careers, have psychological profiles aligned with the demands of entrepreneurship. Variables such as low risk aversion, discipline, goal orientation, and resilience in the face of failure partly explain the greater entrepreneurial intentions observed in this group. Likewise, age and sporting experience appear to be modulating factors, suggesting that the emotional and cognitive capital accumulated over time strengthens self-confidence and the perception of entrepreneurial self-efficacy (Kibler et al., 2024).

However, the review highlights a significant gap between the entrepreneurial potential of sports students and the effective implementation of training strategies in higher education institutions. As pointed out by González et al. (2019), Matic et al. (2022) and Da Costa and Miragaia (2024), entrepreneurial education in sports programmes is often insufficient, fragmented or disconnected from the realities of the sector. In many cases, institutional initiatives are limited to isolated courses, business fairs or extracurricular activities, without real integration into the curriculum or a pedagogical approach that articulates theory, practice and socio-emotional development.

In the Colombian context, the results coincide with the studies by Corzo and Rey (2020), who show that youth entrepreneurship faces structural barriers related to access to capital, support networks and business training. In the field of sport, these limitations are accentuated by the historical prioritisation of physical and technical performance over the development of entrepreneurial and management skills. Despite this, emerging institutional experiences, such as those developed in universities with sports programmes, demonstrate that it is possible to strengthen entrepreneurial culture through comprehensive strategies that include academic support, mentoring, partnerships with the productive sector, and spaces for social innovation (Cardella et al., 2021; Sánchez-Oliver et al., 2019).

Self-esteem, for its part, is consolidated as a cross-cutting variable that influences both entrepreneurial intention and persistence in the face of the challenges of the business process. Recent literature indicates that strong self-esteem promotes a sense of control, reduces fear of failure, and strengthens decision-making in contexts of high uncertainty (Ou & Kim, 2024). In sports students, self-esteem is built on the recognition of achievement, personal improvement, and belonging to sports groups, which can become a key psychological resource for entrepreneurship, provided it is accompanied by appropriate training processes.

Finally, there is a clear need to move towards more comprehensive and contextualised approaches to entrepreneurship in sport. Although international scientific output has grown significantly in recent years, there is still limited empirical research in Latin American countries, particularly in Colombia. This gap limits the formulation of evidence-based educational policies and reinforces the importance of studies such as this one, which contribute to raising the profile of sport as a strategic space for training entrepreneurs with social and territorial impact.

In summary, the results of this systematic review support the idea that entrepreneurial culture, socio-emotional skills, and self-esteem not only coexist but also mutually reinforce each other in students enrolled in sports programmes. Strengthening these components in higher education represents an opportunity to train professionals capable of innovating, generating economic and social value, and responding creatively to the challenges of the contemporary work environment.

CONCLUSIONS

Based on the systematic review, there has been an increase in research seeking to explain the relationship between entrepreneurial culture, socio-emotional skills, and self-esteem as key factors in young people's entrepreneurial intentions. However, there is less research focused on clarifying the influence of these factors on students pursuing a degree in sport. Studies that investigate this relationship agree that athletes develop skills that facilitate the task of starting the path to entrepreneurship.

Entrepreneurial culture, socio-emotional skills and self-esteem are key variables in the training of sports professionals with entrepreneurial skills. This research shows that the academic and sporting environment can become a breeding ground for social leaders capable of making an impact through solid, sustainable and contextualised entrepreneurial initiatives.

Analysis of national and international studies supports the idea that a strong entrepreneurial culture not only drives economic development but also transforms students' vision of their role as agents of change.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

ETHICAL APPROVAL

This work was approved by the Ethics Committee of the National School of Sports (Escuela Nacional del) University Institution Sports - Minutes # 01 - March 13, 2025, for this scientific article and for carrying out all

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the necessary procedures in the academic development of the doctoral thesis entitled "*Entrepreneurial Culture and its Link to Socio-Emotional Aspects in Sports Degree Students*."

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ORIGINAL ARTICLE

Anthropometric profile and physiological performance of Colombian elite mixed martial arts athletes

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ABSTRACT

It is essential to describe performance profiles and implement training loads for MMA athletes participating in competitions, as well as to explore and develop new training models as a priority for MMA coaches. The objective of this study was to evaluate the anthropometric characteristics and physical performance of contemporary elite male mixed martial arts (MMA) athletes. Professional Colombian Mixed Martial Artists were assessed before participating in the sport combat championship (Mean age = 30.80 ± 4.56 years, height = 174.00 ± 3.43 cm, weight = 77.97 ± 8.84 Kg). Athletes underwent evaluations on body composition and sports performance parameters including bioelectric impedance analysis (BIA), VO_{2max}, maximal aerobic speed (MAS) and handgrip strength and other variables. The evaluations revealed a mean muscle mass of 64.67% ± 5.20% (95% CI, 67.89%-61.44%), body fat percentage of 10.93% ± 4.31% (95% CI, 13.60%-8.25%), Ponderal index of 14.79 ± 1.50 (95% CI, 15.72-13.86) and bone mass 3.45 ± 0.27 (95% CI, 3.61-3.28). Mean VO_{2max} was 63.23 ± 5.50 ml/min-1/Kg-1 (95% CI, 66.64-59.81). This information can assist in assessing and evaluating sports performance as well as in developing and optimizing specific training regimes and identifying talents.

Keywords: Performance analysis, MMA, Strike fighting style, Combat sports.

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INTRODUCTION

MMA encompasses various martial arts that incorporate both striking and grappling techniques, such as Brazilian jiu-jitsu (BJJ), kickboxing, wrestling, Muay Thai, and other styles (Coswig et al., 2016; Matinlauri et al., 2019) these styles involve short-term high-intensity and explosive actions, emphasizing the importance of glycolytic pathways during fights (James, Robertson, et al., 2017; Schick et al., 2010). The term "*pan*," meaning all, and "*kratos*", meaning power together define mixed martial arts (Amtmann & Berry, 2003). Additionally, the physiological demands primarily stem from the glycolytic and oxidative systems (Bishop et al., 2013; Powers S, 2021 p.54) justifying the change in MMA bout length to five rounds.

On the other hand, developing new sports conditioning models is crucial for MMA coaches (Kirk et al., 2021; Kostikiadis et al., 2018) to implement training loads based on exercise physiology, physical fitness tests, and sports monitoring (Tota et al., 2014), this should align with the demands and intensity of official MMA competitions, emphasizing the importance of contributing to the scientific community of sports science. As a result, sports assessments underscore the necessity of researching MMA athletes as the periodization of the training process vital for achieving high performance. Athlete characteristics inform talent identification, performance testing, and training strategies. Understanding, the relationship between competition and training can offer valuable insights into developing the optimal performance profile for MMA athletes.

Sports coaches must develop various factors to achieve high performance including physical, technical, and tactical characteristics). Therefore, knowledge of the physical demands is one of the most important aspects of competence (Kirk et al., 2021). Understanding these physical demands is crucial for improving physical training (e.g., endurance, speed, and strength), reducing the occurrence of neuromuscular fatigue, and decreasing the risk of injury (Štyriak et al., 2023).

Finally, it is all essential to understand the physiological and performance profiles of MMA athletes to properly program load plans specific to the sport. With this knowledge, coaches can design training programs tailored to the individual needs of players. Therefore, the primary purpose of this study was to examine the physical and physiological characteristics of MMA athletes.

MATERIALS AND METHODS

Participants

A total of 10 mixed martial arts (MMA) athletes from Bogotá, Colombia (ranked as "*Tapology*" Professionals Colombian Mixed Martial Artists) who have been active in MMA competition within the last two years and have over 10 years of experience in elite competition between 2010 and 2023, volunteered to participate in the study. Subjects signed declarations of informed consent. Participants were asked to complete a health history questionnaire and were accepted into the study if they had no contraindications such as osteomuscular injuries. This study has been approved by the Institutional Ethics Committee of the University of Applied and Environmental Sciences UDCA (Sports Science program with approval No.: 01/2025; and an approval date of 9 February 2025, following the latest update of the Declaration of Helsinki (2013).

Measures

All participants completed a ten-minute standardized warm-up before the jump test. The warmup included jogging, dynamic flexibility exercises, joint mobility exercises, and three counter movement jumps (CMJ) performed in increasing order of intensity. Subsequently, anthropometric measurements were assessed. A stadiometer (Seca Corp. Chino, CA, USA) was used for measuring height. A digital scale InBody 370 (InBody,

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Seoul, South Korea) was used to measure body mass, body fat, and average lean muscle weight. Body mass index BMI was calculated as body mass in kilograms divided by height in meters squared (kg/m2). Neuromuscular performance measurement was performed for all athletes, who each completed three standardized countermovement jumps (CMJ).

Procedures

VO_{2max} cardiovascular test

Participants completed a maximal graded exercise test on a treadmill (Reims) calibrated monthly for accuracy of grade and speed. The maximal graded exercise test protocol began with a warm-up at a self-selected pace (3 mile/h = 4.9 km/h) on a treadmill for 7 to 15 minutes. During the warm-up, the research staff explained on how to use the Borg Rating of Perceived Exertion (Borg, 1982) scale and informed athletes that they were expected to achieve the maximum level of exertion. The participants were then equipped with a Bluetooth-enabled heart rate monitor worn on the chest (Polar). The preprogrammed treadmill protocol started with participants running at 3.1 mph (5 km/h) for 5 minutes (with a 0% incline). The workload was then increased by 1.0 mile/h = 1.6 Km/h, total: 6.4 Km/h). This was achieved via an enlarge in speed (1.0 mph per minute, 1.6km/h) each minute until the athlete until a maximal speed was reached. If a participant's capacity allowed them to continue beyond neuromuscular fatigue, the treadmill´s grade (i.e., incline) remained constant, but the speed increased, until volitional fatigue was reached. The protocol continued until the participant signalled to stop. The Borg Rating of Perceived Exertion scale was assessed during the final 10 seconds of each minute. Additionally, participants completed an incremental protocol to determine their maximal aerobic speed (MAS) (Bueno et al., 2022; Chaabène et al., 2015). Upon reaching volitional fatigue, participants were encouraged to walk until fully recovered while the treadmill was immediately slowed to 1.5 mph. Finally, maximal VO_2 (ml min−1 kg−1) was calculated using the ACSM treadmill running equation (equation 1) for the last stage of the running test (Deborah Riebe, 2016 pp.156).

Equation 1 $$VO_{2max} \text{ (ml min−1 kg−1)} = S * 0.20 + 3.5$$

S = speed (meters/min)

Handgrip Strength (HGS)

For each assessment, two maximal efforts of 5 seconds were performed with both the dominant and non-dominant hand, with a 1-minute rest between efforts. A hand dynamometer was held with the elbows at the side of the body and the arm at right angles. Grip strength was assessed using a hand dynamometer (Hand dynamometer, Camry Instrument Company, China). Grip strength assessment has been used in previous research on combat sports and was therefore chosen for this study (Constantine et al., 2019; Coswig et al., 2016). The instrument was adjusted so that its base rested on the first metacarpal and the handle rested on the middle of the participant's four fingers. A maximal isometric effort was sustained for 5 seconds, without any additional body movements. The trial with the highest force was selected for analysis.

Squat and countermovement jump

Squat jump (SJ) and countermovement jump (CMJ) trials were conducted on a calibrated force plate (Kinvent, Montpellier, France) to evaluate force-generating capacity which is considered a reliable and valid measure of this capacity (Anicic et al., 2023; Bosco et al., 1983). Subjects performed a total of three attempts with the best trial being used for data analysis based on jump height. The squat jump (SJ) was performed following the protocol outlined by Van Hooren et al. (Van Hooren & Zolotarjova, 2017). Athletes were instructed to assume a semi-squat position and hold it for 3 seconds until the evaluator said "*START!*". Each player was directed to begin the test with a knee flexion (90°). Countermovement or any pre-stretching was not allowed

before the acceleration (concentric) phase, and during the test, to prevent the use of upper limbs; arms had to remain on the pelvis. The jump had to be repeated if any of these characteristics were violated.

The countermovement jump (CMJ) was carried out similarly to the SJ, performing an explosive, fast countermovement without maintaining a knee flexion position (F. Ayala a, 2012; Folhes et al., 2022; Franchini, 2023). Participants were instructed to execute a quick downward movement (approximately 90° of knee flexion) followed by a fast upward movement to achieve maximum jump height. This jump tested the elastic properties of the players muscle-tendon structure and their concentric strength.

Isometric Midthigh Pull (IMTP)

This test can be used to assess various measures, including maximal strength. Participants were positioned in the IMTP rack, in a barbell position corresponding to the second pull of the clean, with hip- and knee angles of 140-145^{0} respectively (Beckham et al., 2018). The IMTP was selected for this study as it is considered the gold standard in strength testing (Haff G., 2019; James, Beckman, et al., 2017). Each athlete was instructed to assume their preferred second pull power-clean position by self-selecting the hip and knee angles. The barbell height was then adjusted up or down to ensure it was placed at mid-thigh level. All participants were strapped to the barbell and used an overhand grip. Athletes were instructed to pull the barbell as hard and fast as possible and to maintain maximal effort for 5 seconds. They were asked to relax before the command countdown of "*3, 2, 1, Pull!*" and received strong verbal encouragement throughout to ensure maximal effort. The force-time curve for each trial was recorded by a dual force plate (Kinvent, Montpellier, France) with a sample rate of 1,000 Hz.

Chin up (pull up) test

To be considered a complete pull-up, the subject was reported to lift his body from a full-arm extension hanging position (width-pronated grip) until his chin was above the bar. The pull-ups were performed on a standard, horizontal bar. The athletes were asked to complete the maximum number of free-hanging pull-ups with a pause of 1 to 2 s between repetitions (Kotarsky et al., 2018; Sanchez-Moreno et al., 2016). Half-repetitions were counted if the subject reached 90 degrees of elbow flexion. All participants completed an identical 15-minute warm-up, including arm and shoulder movements, and 3 submaximal sets of pull-ups.

V-sit and reach (VSR)

The legs were stabilized in an extended position by a researcher and two assistants. The participant was instructed to sit on the floor with the legs extended, the feet spaced 30 cm apart, and to keep the ankle joints in a neutral position. To perform the VSR, the athletes lined up one hand over the other, reached towards their toes until discomfort, and flexed at the waist. The action was performed three times, and the measurement was taken on the third attempt; the athletes were required to hold the position while the measurement was obtained (Guidetti et al., 2002; Haff, G., 2019). The researcher reviewed and measured from the edge of the baseline "*zero*" (located at the floor) line to the tip of the middle finger. A measurement of "*0*" indicated the fingertip was in line with the edge of the baseline "*zero*" tape line. Measurements were registered to the nearest half-centimetre. If the fingers had not reached the edge of the line, it indicated a negative number; if they had, it showed a positive number. The inability to obtain the "*zero*" line on the tape was defined a priori as a dysfunction on the VSR (Hansberger et al., 2019).

Mc Call test (hamstring strength tests)

For hamstring isometric strength testing, athletes were positioned supine with the heel of one leg on a cuff, knees flexed, and the opposite leg extended on the floor. The degree of knee flexion was determined by the distance of the hip from a chair and measured with a goniometer. Athletes were located supine, with arms

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crossed over their chest, the heel of one leg on the cuff, knees flexed, and the opposite leg extended for hamstring isometric strength testing. The distance from the hip to a chair was similarly measured to determine knee flexion using a goniometer. In this test, the knee is flexed at either 90° or 30° to primarily target the hamstrings (biceps femoris, semitendinosus, semimembranosus), and the peak force exerted is measured in a supine position with the heel of the testing leg placed on a raised force platform (Huebner et al., 2023; I Lovell et al., 2013; James, Beckman, et al., 2017).

Analysis

All data were analysed and conducted with JASP (version 0.18.3, University of Amsterdam, Netherlands). Significance was set at $p \leq .05$ a priori. Anthropometric and physiological performance characteristics were expressed as mean ± standard deviation (SD).

RESULTS

The anthropometric characteristics of the participants are presented in Table 1. The physical performance of the participants is presented in Table 2. McCall and Isometric mid-thigh pull tests in Table 3. The jump test performance of the participants is presented in Table 4.

DISCUSSION

The purpose of this study was to characterize the anthropometric profile and physiological performance of Colombian Elite Mixed Martial Artists (MMA) fighters. Understanding the characteristics of fighter athletes is essential to justify the need for information on the combat sport profile, given the growth of MMA.

Data on athletes' heights around 1.74 (cm) and weights around 77.97 (Kg) are consistent with values for MMA athletes found in previous studies (Schick et al., 2010; Spanias et al., 2019). In terms of physical fitness and performance, results show that MMA athletes vary in body fat percentage, ranging from 8.5 to 14.9 ± 7.2% and have a mesomorph body type (predominance) (6.4 ± 0.8) (Franchini, 2023; Marinho et al., 2016).

Other measures used to describe the morphological profile include the ponderal index (Berthelot et al., 2015; Bishop et al., 2013; James, Beckman, et al., 2017), muscle (64.67%), and bone mass (3,45 Kg). Therefore, muscle mass development and bone strength are crucial components for mixed martial arts athletes and most combat sports (Schick et al., 2010; Spanias et al., 2019; Tota et al., 2014).

On the other hand, MMA fights require high cardiovascular fitness (Del Vecchio & Franchini, 2013) due to their intermittent nature (3 to 5 rounds of 5 minutes each). Our results (63.23 ± 5.5 ml·kg-1 ·min-1/ MAS: 17.92 ± 1.65 km/hr) are concerning as the level of glycolytic fitness has been linked to fatigue resistance (Panissa et al., 2013) and a high fitness level is a key factor for success in fights (Bueno et al., 2022). The VO_{2max} values are higher than those found among MMA fighters in previous studies (Andrade et al., 2019; James et al., 2018; Spanias et al., 2019).

Upper-body muscular endurance in athletes was assessed using maximum repetition chin-up tests. Our results (mean 11.20 ± 4.59 reps) were similar to those presented by MMA fighters (De Oliveira et al., 2015; Franchini et al., 2015; Schick et al., 2010). However, the results fall short of values reported for boxers (Chaabène et al., 2015; Guidetti et al., 2002) and karate fighters (Franchini et al., 2018). Compared with Jiu-Jitsu athletes, results varied, ranging from higher (Lima et al., 2017) to lower (Andreato et al., 2017; Andreato & Branco, 2016) than those reported in the literature.

Table 1. Anthropometric characteristics of elite male mixed martial arts (MMA) Athletes descriptive outcomes.

	Height (cm)	Age (years)	Weight (kg)	PI*	Fat (%)	Muscle (%)	Bone (kg)
Mean	174.000	30.800	77.970	14.792	10.930	64.670	3.450
95% CI Mean Upper	176.127	33.630	83.452	15.721	13.602	67.895	3.618
95% CI Mean Lower	171.873	27.970	72.488	13.863	8.258	61.445	3.282
Std. Deviation	3.432	4.566	8.846	1.500	4.310	5.203	0.272

*Note. *PI (Ponderal index) = weight (kg)/ height^3 (m).*

Table 2. Physical performance characteristics of elite male mixed martial arts (MMA) athletes.

	VO_{2Max} (ml min−1 kg−1)	MAS (Km/h)	Chin up test rep	V sit and reach	Handgrip strength R	Handgrip strength L
Mean	63.233	17.920	11.200	4.767	47.055	47.470
95% CI Mean Upper	66.647	18.944	14.045	9.917	51.296	51.902
95% CI Mean Lower	59.818	16.896	8.355	-0.384	42.814	43.038
Std. Deviation	5.509	1.652	4.590	8.310	6.842	7.151
Minimum	56.832	16.000	4.000	-9.000	39.250	37.900
Maximum	72.832	20.800	18.000	17.667	56.400	59.750

Note. MAS: Maximal aerobic speed. L: Left; R: Right.

Table 3. McCall and Isometric mid-thigh pull tests characteristics of elite male mixed martial arts (MMA) athletes.

	McCall test MF 90° (Kg) L	McCall test MF 90° (Kg) R	McCall test MF 30° (Kg) L	McCall test MF 30° (Kg) R	RFD (Kg/sg) 90° L	RFD (Kg/sg) 90° R	RFD (Kg/sg) 30° L	RFD (Kg/sg) 30° R	IMTP L (Kg)	IMTP R (Kg)	IMTP total (Kg)
Mean	19.824	18.078	19.804	18.956	3.242	3.210	3.248	4.091	106.110	109.600	215.690
95% CI Mean Upper	23.865	20.385	23.833	22.021	4.386	3.914	4.549	5.697	117.875	125.389	233.030
95% CI Mean Lower	15.782	15.770	15.774	15.892	2.098	2.506	1.947	2.485	94.345	93.811	198.350
Std. Deviation	6.520	3.723	6.502	4.944	1.846	1.136	2.099	2.591	18.981	25.475	27.978
Minimum	11.660	13.360	11.210	10.970	0.470	1.430	0.410	0.250	79.200	73.800	167.500
Maximum	31.400	26.310	29.400	27.400	5.410	5.160	6.630	9.290	140.000	159.400	257.500

Note. L: Left. R: Right. MF: Max force. RFD: Rate force development. IMTP: Isometric mid-thigh pull.

Table 4. Squat jump and countermovement jump characteristics of elite male mixed martial arts (MMA) athletes.

	SJ MF L (Kg)	SJ MF R (Kg)	Total	FT (sc)	JH (cm)	RFD (N/s)	CMJ MF L (Kg)	CMJ MF R (Kg)	Total	FT (sc)	JH (cm)	RFD (N/s)	Max Power (W)
Mean	79.65	83.32	162.98	0.490	29.80	2185.92	79.92	96.14	175.84	0.514	32.60	4247.04	3665.54
95% CI Mean Upper	87.26	91.80	178.75	0.513	32.59	2601.97	90.75	109.85	191.95	0.527	34.25	6059.14	3965.62
95% CI Mean Lower	72.03	74.83	147.20	0.467	27.00	1769.86	69.09	82.42	159.72	0.501	30.94	2434.93	3365.45
Std. Deviation	12.28	13.68	25.45	0.038	4.51	671.27	17.47	22.12	26.00	0.022	2.67	2923.71	484.16
Minimum	65.10	68.50	133.50	0.430	23.0	1238.90	40.90	75.90	146.30	0.490	30.00	1249.50	3078.70
Maximum	106.90	111.60	218.50	0.540	36.0	3179.10	104.30	137.80	219.20	0.560	39.00	10549.50	4495.30

Note. SJ: Squat Jump. MF: Max force. FT: Flight time. JH: Jump height. RFD: Rate force development. CMJ: Counter movement jump. L: Left; R: Right.

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Flexibility has gained attention and importance in MMA training, particularly due to its association with improved skill execution and a broader range of motion. The flexibility of athletes assessed in the current study (4.76 ± 8.31 cm) was lower than that of taekwondo (Nikolaidis et al., 2016; Spanias et al., 2019), judo (Franchini et al., 2015), and MMA athletes.

The handgrip (HG) strength test (Boone, 2015) and the isometric middle-thigh pull (IMTP) (James, Beckman, et al., 2017; Plush et al., 2021) were used to evaluate athletes' isometric maximal strength. The HG isometric strength for the left hand was 47.47 ± 7.15 and for the right hand 47.05 ± 6.84. The HG values were related to values found in BJJ (I Lovell et al., 2013), boxing (Gatt et al., 2018), sambo (Trivic et al., 2020), judo (Turnes et al., 2022), kickboxing (Rydzik & Ambroży, 2021), and wrestling athletes (Cieśliński et al., 2021; Huebner et al., 2023). The IMTP was measured via a Kinvent force plate (Plakoutsis et al., 2023). The absolute values ranged from 215.69 ± 27.97 (kg) and established a profile of high muscle strength for athletes in martial arts.

The isometric posterior chain (hamstring) of MMA athletes was evaluated. Using a force plate (Kinvent, Montpellier, France) to estimate the isometric endurance of each lower limb (Matinlauri et al., 2019; McCall et al., 2015) The results for Max Force, Left 90°: were 19.82 ± 6.52 (Kg). and for Max Force Left 30°: were 19.80 ± 6.50 (Kg). The RFD Left 90° (Kg/sg): was 3.24 ± 1.84. RFD Left 30° (Kg/sg): 3.24 ± 2.09. For the right-side Max Force right 90°: was 18.07 ± 3.72 (Kg). and at 30°: was 18.95 ± 4.94 (Kg). The RFD for Right 90°: was 3.21 ± 1.13(Kg/sg) and for Right 30°: was 4.09 ± 2.59(Kg/sg).

Our results show that the values for SJ (FT 0.49 ± 0.03, JH 29.80 ± 4.51, RFD 2,185 ± 671.2 (N/s), are lower compared to other studies on MMA fighters. However, the values for CMJ (FT 0.51 ± 0.02, JH 32.60 ± 2.67, RFD 4,247 ± 2,923 (N/s), Max Power (W) 3,665 ± 484.169 (Kostikiadis et al., 2018), are higher than those reported in previous studies. The higher values in our study may be attributed to the different sports demands of the subjects who are currently undergoing training to increase their rate of force development and peak concentric forces (James et al., 2020).

CONCLUSIONS

This study showed MMA fighters demonstrate satisfactory performance characteristics. Additionally, this study suggests that athletes have higher VO_{2max} values compared to athletes in other sports. Flexibility scores are low, which could impact performance, highlighting the importance of focusing on this motor skill. On the other hand, handgrip strength was higher than that of athletes in different combat sports. These findings offer insight into the profiles of elite Colombian MMA athletes and allow for comparisons with international data. These neuromuscular and physiological variables serve as valuable reference points for identifying sports talent, enhancing training skills, and achieving high performance.

Some limitations of this study included a small sample size of the athletes. Future research should take into consideration these limitations and strive to expand the scope of data collection. This should involve incorporating diverse assessment parameters, longer time periods, and a range of MMA categories.

AUTHOR CONTRIBUTIONS

Conceptualization, CY. and P.B.; methodology, N.O. and A.B.; data curation, C.Y, J.A. and N.O.; writing - original draft preparation, C.Y. and N.O.; writing -review and editing, K.A., J.A. and P.B.; supervision, N.O.;

project administration, C.Y. and A.B. All authors have read and agreed to the published version of the manuscript.

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ORIGINAL ARTICLE

Home advantage in EuroLeague basketball: Quantifying the interactions between team quality, competitive balance, and season dynamics

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ABSTRACT

Home advantage (HA) remains a persistent phenomenon in elite basketball. This study quantified HA across eight EuroLeague seasons (2016–2025) and examined how team quality (TQ) and competitive balance (CB) influence it. Data from 2,154 regular-season games were obtained from the official EuroLeague website. HA% and home win percentage (HW%) were calculated, while CB was measured using the Standard Deviation Ratio (SDR). TQ was determined using a Two-Step Cluster Analysis based on win percentage (W%), classifying teams into high, medium, or low-quality groups. One-way ANOVA examined seasonal and TQ variation, while Spearman's correlation and multiple regression assessed relationships among the variables. The results showed that EuroLeague teams won 62.9% of home games on average. HA% peaked in 2021–2022 and dropped in 2020–2021, reflecting the impact of pandemic-related spectator restrictions. CB fluctuated moderately, with a notable imbalance in 2018–2019 (CB = 2.17). Regression results showed that TQ significantly predicted HA% ($p < .01$), with lower-quality teams exhibiting greater HA% effects (B = 10.06, SE = 2.15), whereas CB was not a significant predictor ($p = .088$). HA remains a consistent structural phenomenon in EuroLeague basketball, more likely due to psychological and situational factors, resilient to changes in league parity.

Keywords: Performance analysis, Game location, Home-away, Basketball.

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INTRODUCTION

The strength and consistency of home advantage (HA) are among the most enduring and extensively studied phenomena in sports science (Dosseville, Edoh, & Molinaro, 2015; Gómez, Pollard, & Luis-Pascual, 2011; Jamieson, 2010; Nevill & Holder, 1999; Pollard, Prieto, & Gómez, 2017; Yang & Kolbinger, 2024). Despite significant changes in sports over the years, HA has remained notably consistent. It describes the tendency for teams to perform better at home than on the road (Allen & Jones, 2014; Pollard & Gómez, 2015a). This is evident when home teams win more than half of their games in a home-and-away schedule (Courneya & Carron, 1992). In many team sports, such as basketball, handball, soccer, and baseball, numerous studies indicate that home teams win significantly more often than visiting teams. Several factors contribute to this advantage, including familiarity with the playing environment, support from the home crowd, reduced travel fatigue, officials' decisions, and the psychological comfort associated with routine and local support (Bilalić, Gula, & Vaci, 2021; Leite, Pollard, & Gómez, 2021; McHill & Chinoy, 2020; Pollard & Pollard, 2005).

In basketball, HA has been widely studied (Alonso et al., 2024a; Alonso, Lorenzo, Ribas, & Gómez, 2022; Pollard & Gómez, 2007; Pollard & Gómez Ruano, 2013). The standard method for measuring HA follows Pollard's approach, which calculates the number of home games won as a proportion of all games won at home and away (Pollard & Gómez, 2007), usually expressed as a percentage (Alonso et al., 2022). This measure indicates overall success, not just home performance, and provides a standard numerical value for HA. Another popular metric is the home win percentage (HW%), which shows the percentage of games won by the home team (Alonso et al., 2024a; López-García, Alonso-Pérez-Chao, Navarro Barragán, & Jiménez-Sáiz, 2024). Research across various basketball leagues consistently confirms the existence of HA (Cabarkapa et al., 2023; Góes & Almeida, 2025; Kulenović & Demšar, 2024; López-García et al., 2024; Pojskić, Šeparović, & Užičanin, 2011).

A key factor in understanding how HA varies across seasons is competitive balance (CB), which measures the level of parity in skill and performance potential among teams. When games are played under a balanced home-and-away schedule, CB acts as a moderating factor for HA (Fort, 2017). Leagues with greater competitive imbalance, where a few teams dominate, may show smaller or more stable HA, as stronger teams can often win regardless of venue (Pollard & Gómez, 2014). Conversely, in leagues with higher parity, HA can significantly affect game outcomes (Leite & Diniz da Silva, 2022; Pollard et al., 2017). Additionally, team quality (TQ), which assesses a team's combined skill and performance during a season or tournament, also influences home-court advantage. Better teams generally depend less on home conditions, while weaker teams may benefit more from playing at home. TQ is usually measured using indicators such as win percentage (W%), representing the ratio of games won to total games played (Alonso et al., 2024a).

The EuroLeague provides a unique setting for studying HA, as it unites top teams from across Europe, each with their own fan cultures, extensive travel demands, tactical intricacies, varying rules, and diverse playing styles (Foteinakis et al., 2025). Known as Europe's premier basketball competition, it employs a double-round-robin format that requires teams to adapt to various environments and travel schedules. The EuroLeague is often regarded as more tactical and team-oriented than the NBA (Foteinakis and Pavlidou, 2025). Unlike domestic leagues, EuroLeague teams frequently cross borders and time zones, which can either bolster or diminish home advantage due to travel fatigue, affecting player performance and recovery during a busy international season (Gasperi et al., 2025). This arrangement offers an ideal setting for studying HA, especially since the EuroLeague grants home-court advantage to the top regular-season teams in the playoffs, making consistent home wins a crucial competitive aim.

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Despite the league's international prominence and the abundance of detailed performance data, systematic research into the factors, development, and interactions among HA, CB, and TQ remains limited in EuroLeague basketball compared to studies in the NBA or national leagues. Earlier studies have mainly focused on descriptive win–loss records or overall statistics, without combining contextual and structural elements into a comprehensive analytical framework.

The present study employs a multidimensional approach to (a) measure the extent of HA across recent EuroLeague seasons and (b) examine how CB and TQ interact to influence HA effects. This research aims to expand the current literature on European basketball by providing new insights into how league structure, team quality, and competition parity collectively impact HA outcomes. The results are expected to improve both theoretical understanding and practical applications, offering coaches, analysts, and sports scientists an evidence-based model for analysing contextual factors that affect team performance and for guiding strategies to enhance competitive success and playoff positioning.

METHODS

Sample and data acquisition

The dataset included all EuroLeague teams that participated in the championship, covering eight seasons, excluding the 2019–2020 season, which was suspended due to the COVID-19 pandemic. Data were collected from the 2016–2017 to the 2024–2025 seasons and obtained from the open-access official EuroLeague website (https://www.euroleaguebasketball.net/, accessed on September 1st, 2025). Only regular-season games were analysed, since the regular season follows a balanced round-robin format in which each team plays every other team twice, once at home and once away. Playoff and Top 16 phases were excluded to prevent bias from unequal home–away distributions.

The final dataset included 2,154 games across eight seasons, involving 28 teams that participated during the study period, yielding a total of 135 aggregated team-season cases. Because the study used publicly available, televised, and non-identifiable data, no ethical approval or informed consent was required, in accordance with the American Psychological Association's Ethical Principles of Psychologists and Code of Conduct (APA, 2002).

Procedure

For each team and season, the following variables were collected: total wins (W) and losses (L), total home wins (HW) and home losses (HL), total away wins (AW) and away losses (AL), total home games (HG), total away games (AG), and total games played (G). The data were organized and processed following the procedure described by Leite and Silva (2022). All values were compiled into a custom Microsoft Excel spreadsheet (version 16.0; Microsoft Corporation, Redmond, WA, USA) for subsequent analysis.

Variables and Computations

The HA% magnitude was calculated for each team and season. The formula for this method is: HA% = [(HW/W) × 100] (Alonso et al., 2022; Pollard & Gómez, 2015b), where HW is the number of home wins and W is the total number of wins. Additionally, the percentage of home wins was calculated as HW(%) = [(HW/HG) × 100], where HW represents the number of home wins and HG is the total number of home games played (Gómez & Pollard, 2011). To assess the league's competitive balance (CB) for each season, the method proposed by Fort (2017) was used, calculating the Standard Deviation Ratio (SDR), defined as: SDR = ASD/ISD, where ASD is the actual standard deviation of the win percentages across all teams in each season, and ISD is the ideal standard deviation assuming equal winning probabilities (50%) for all teams.

Higher SDR values indicate greater competitive inequality (lower parity), while lower SDR values suggest a more balanced competition.

Team quality (TQ) was determined by calculating the overall winning percentage (W%) across all seasons for each team: (W%) = [(HW+AW)/G] × 100 (Alonso et al., 2022; Alonso et al., 2023), where AW stands for away wins and G is the total number of games played. Then, a Two-Step cluster analysis was conducted to classify teams into different quality levels. The analysis automatically identified an optimal three-cluster solution, as shown by the Bayesian Information Criterion (BIC) and the silhouette measure of cohesion and separation. The average silhouette coefficient was 0.60, indicating a moderate level of cluster quality (Kaufman & Rousseeuw, 2005). This suggests that the clusters were reasonably well-separated and internally consistent, reflecting meaningful patterns in team performance profiles. The distribution of clusters, along with the sample size and proportion of teams, was as follows: Cluster 1 (high-quality teams): W% = 65.9% ± 6.6%, n = 49 teams, making up 36.3% of the dataset, consisting of teams with higher winning rates that consistently perform at elite levels. Cluster 2 (medium-quality teams): W% = 50.03% ± 4.5%, n = 44 teams, representing 32.6% of the dataset, composed of teams with moderate success. Cluster 3 (low-quality teams): W% = 31.3% ± 5.2%, n = 42 teams, representing 31.1% of the dataset, made up of teams with limited success across seasons.

Statistical analysis

Normality was assessed using the Shapiro–Wilk test. Both HA% and HW% displayed normal distributions ($p > .05$), while CB exhibited a non-normal distribution ($p < .05$). Therefore, both parametric and non-parametric analyses were conducted to ensure reliability. Descriptive statistics were calculated for all variables, including HA%, HW%, CB, and TQ. A one-way ANOVA tested whether levels of HA% and HW% differed across EuroLeague seasons and TQ. When a significant main effect was found, Tukey's post hoc tests were used to compare group means pairwise (Field, 2018). To evaluate the practical significance of the findings, effect sizes (ES) were interpreted using Cohen's (1988) benchmarks: negligible ($\eta^2 < 0.01$), small ($0.01 \leq \eta^2 < 0.06$), medium ($0.06 \leq \eta^2 < 0.14$), and large ($\eta^2 \geq 0.14$). To explore the relationship between CB and HA%, a Spearman rank-order correlation was performed, with correlation strength interpreted as follows (Cohen, 1988): < 0.20 (very weak), 0.20 - 0.39 (weak), 0.40 - <0.59 (moderate), 0.6 - < 0.79 (strong), and ≥ 0.80 (very strong).

To further identify the determinants of HA% across EuroLeague seasons, a multiple linear regression analysis was conducted with HA% as the dependent variable and CB and TQ as predictors. TQ was included as a categorical variable with three levels, based on the previous Two-Step Cluster Analysis of team performance profiles. The model was estimated using the Enter method, and bootstrapping (5000 samples) was applied to obtain bias-corrected and accelerated (BCa) 95% confidence intervals for all coefficients.

Multicollinearity was assessed using the Variance Inflation Factor (VIF), with VIF values below 2 indicating no multicollinearity issues. Model fit was evaluated through the coefficient of determination (R^2, adjusted R^2), ANOVA F-statistics, and information criteria such as AIC and BIC. Predictive accuracy was measured by the Root Mean Square Error (RMSE), which measures the average prediction error of the model. The strength and significance of each predictor were determined by unstandardized regression coefficients (B), bootstrap significance levels (p), and 95% confidence intervals (CI).

The level of statistical significance was set at $p < .05$. JASP software (Version 0.18, JASP-Team, Netherlands) was used for the data analysis.

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RESULTS

A total of 2,154 games across eight seasons of the EuroLeague Championship were analysed, during which 1,349 home wins and 805 home losses were recorded. Table 1 shows descriptive statistics for the studied seasons, including the number of games, home wins and losses per season, HA% and HW%, and the league's CB for each season.

Table 1. Descriptive statistics, HA%, HW%, and CB in the EuroLeague championship, divided by season.

Season	Games (n)	HW	HL	HA% (M ± SD)	HW% (M ± SD)	CB
2016-2017	240	152	88	63.75 ± 8.16	63.33 ± 20.51	1.73
2017-2018	240	151	89	63.94 ± 9.37	62.91 ± 17.29	1.71
2018-2019	240	155	85	68.53 ± 13.86	64.58 ± 19.88	2.17
2020-2021	306	167	139	56.44 ± 9.17	54.59 ± 14.99	1.84
2021-2022	210	143	67	69.15 ± 10.78	68.01 ± 18.13	1.77
2022-2023	306	194	112	63.40 ± 7.51	63.40 ± 17.76	1.64
2023-2024	306	200	106	66.67 ± 8.83	65.35 ± 18.91	1.90
2024-2025	306	187	119	62.24 ± 10.30	61.11 ± 16.40	1.73
T/A	2154	1349	805	64.26 ± 9.75	62.91 ± 16.18	1.81

Note: n – total number of games per season; M ± SD – Mean ± Standard Deviation; HW – home wins; HL – home losses; HA% – home advantage %; HW% – home winning %; CB – competitive balance per season; T/A –total or average.

A one-way ANOVA examined whether HA% differed across seasons. The results were statistically significant, $F(7, 127) = 2.86$, $p < .001$, indicating that mean HA% varied by season. The effect size was medium ($\eta^2 = .136$), suggesting practically meaningful differences between seasons. Figure 1 displays the HA% for each season. The shaded band around the line represents the standard deviation (SD) above and below each season's HA% and illustrates seasonal variability. The long-term average HA% is 64.26% (dashed red line). Seasons with higher HA% included 2021–2022 and 2018–2019, both well above the average, while 2020–2021 had the lowest HA%, well below the long-term average. Most other seasons clustered between approximately 63–67% (Figure 1).

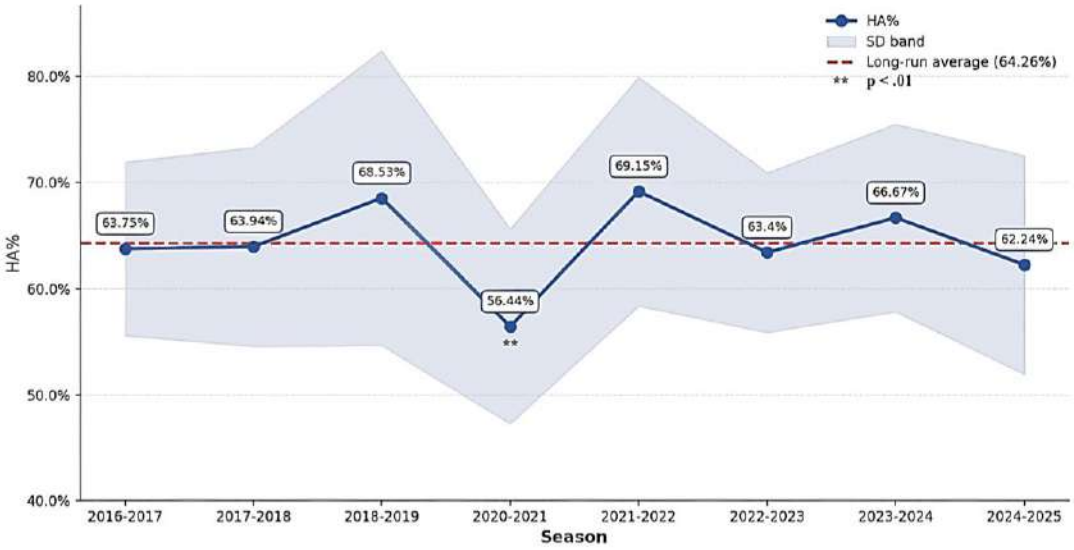


Figure 1. EuroLeague HA% by season.

Tukey post hoc pairwise comparisons primarily revealed differences involving the 2020–2021 season: HA% was significantly lower in 2020–2021 compared to 2018–2019 (mean difference = −12.09, $p < .01$) and 2021–2022 (mean difference = −12.71, $p < .01$). A smaller, marginal pattern was observed with 2023–2024 exceeding 2020–2021 (mean difference = 10.24, $p < .05$). No other pairwise comparisons showed statistically significant differences.

Regarding HW%, a one-way ANOVA tested whether HW% varied across the 8 seasons. Despite visible year-to-year differences, HW% did not change significantly across seasons, F (7, 127) = 0.82, $p = .57$, $\eta^2 = .04$. Season HW% ranged from 54.59% (2020–2021) to 68.01% (2021–2022). For the remaining seasons, HW% remained near the long-term average (62.9%), showing a stable pattern (Figure 2).

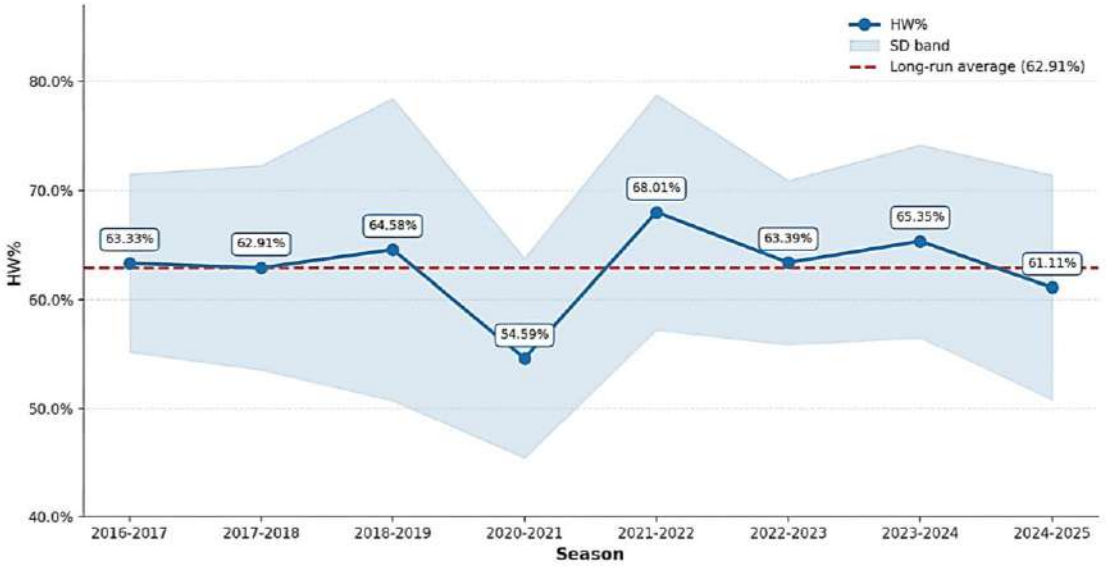


Figure 2. EuroLeague HW% by season.

Tukey post hoc comparisons showed that the largest observed, but not significant, difference ($p = .40$) was between the 2021–2022 and 2020–2021 seasons, with the 2021–2022 season showing a 13.41% higher HW%. Another relatively large but nonsignificant difference was between the 2023–2024 and 2020–2021 seasons (mean difference = 10.76, $p = .625$). All other pairwise differences were minor, with wide confidence intervals that crossed zero.

Figure 3 shows the mean values of HA% and HW% regarding the TQ. The one-way ANOVA revealed that differences in HA% were statistically significant, F(2, 132) = 12.56, $p < .001$, indicating that mean HA% varied across TQs. The effect size was large ($\eta^2 = .16$), suggesting practically large and significant differences between the groups. Tukey post hoc pairwise comparisons revealed that HA% were significantly different between the high and low-quality groups ($p < .01$). At the same time, smaller differences were observed between the high– medium and medium–low quality groups ($p < .05$). Significant differences (F (2, 132) = 110.06, $p < .001$, $\eta^2 = .62$, big) were also observed between the groups for HW%, with all pairwise comparisons significant at $p < .001$, revealing the superiority of HW% of the higher-quality teams than medium and lower-quality teams.

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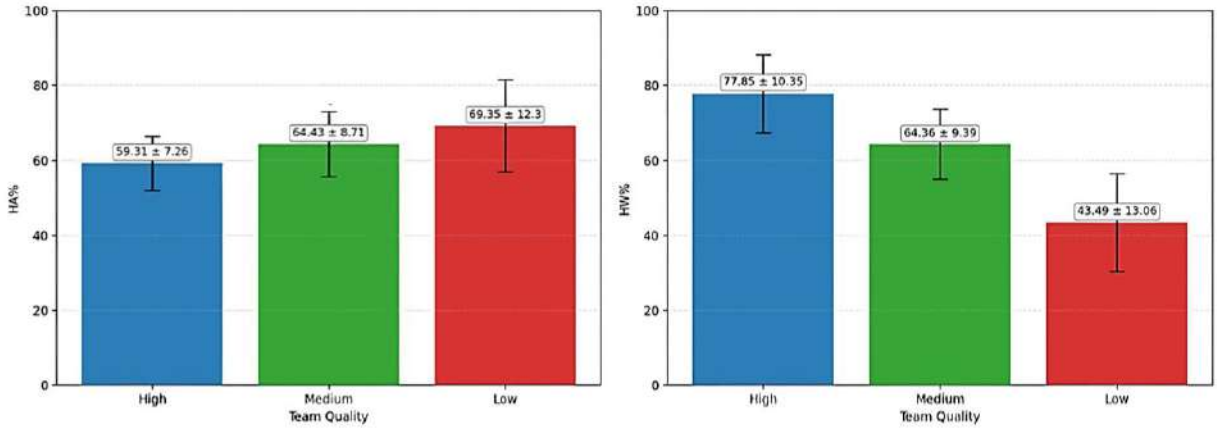


Figure 3. Comparisons in HA% and HW% between high, medium and low-quality groups.

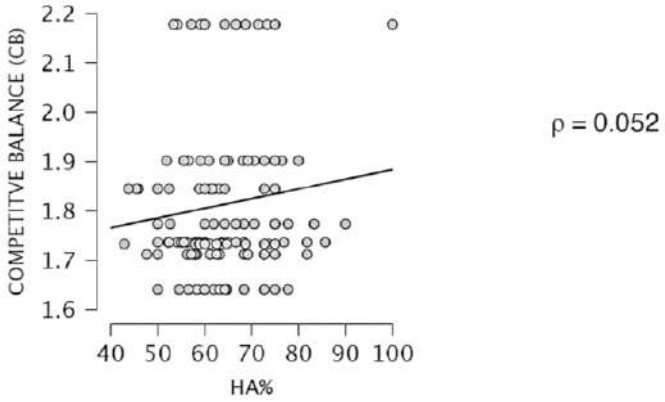


Figure 4. Association between HA% and CB in EuroLeague.

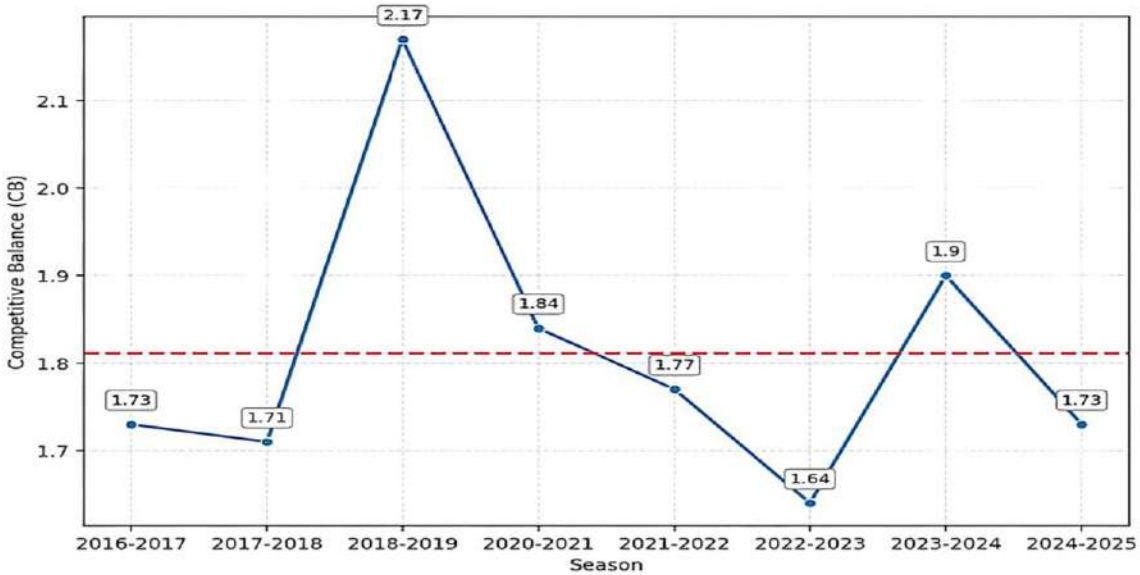


Figure 5. EuroLeague CB by season.

A Spearman rank-order correlation (Figure 4) was used to examine the relationship between HA% and Competitive Balance (CB). The correlation was small and not statistically significant (ρ = 0.052, *p* = .548), indicating no association between HA% and CB in the EuroLeague data. In practical terms, variation in CB does not seem to be meaningfully related to changes in HA.

Figure 5 displays the longitudinal variation of CB observed in the EuroLeague over the seasons analysed. CB showed a 10.3% effect (R^2 = 0.103; weak) for HA.

CB shows slight variation across the 8 seasons, with no major year-to-year shifts, indicating relative stability during the period. The only exception was the 2018-2019 season, which dips below the usual range but isn't different enough to suggest a regime change in parity, meaning overall league CB doesn't drastically change from one season to the next.

A multiple linear regression analysis was performed to determine whether TQ and CB predicted HA% magnitude across EuroLeague basketball seasons. Preliminary assumption testing confirmed that the data met the requirements of normality, linearity, and homoscedasticity. Multicollinearity diagnostics were within acceptable limits (VIF < 2). Bootstrapping with 5000 resamples was used to address minor non-normality in CB and to obtain bias-corrected confidence intervals.

The regression model was statistically significant, F (3,131) = 9.48, *p* < .001, explaining 17.9% of the variance in HA% (R^2 = .179, AdjR^2 = .160). The model's predictive accuracy was adequate (RMSE = 9.47). On average, the predicted HA% differed from the observed HA% by ± 9.47 percentage points, indicating moderate predictive accuracy. Bootstrapped coefficients confirmed the robustness of the findings, with nearly identical estimates and bias-corrected confidence intervals (Table 2).

Overall, the findings showed that TQ, but not CB, was a key factor affecting HA% in EuroLeague basketball. Compared to high-quality teams (reference group), medium-quality teams exhibited a 5.02% higher HA% (*p* = .007), while low-quality teams had a 10.06% higher HA% (*p* < .001). These results suggest that teams with lower competitive strength gain a greater home advantage. Regarding CB, the results indicated a positive but nonsignificant relationship with HA% (*p* = .088), implying that league balance did not systematically influence the extent of home advantage.

Table 2. Results of bootstrapped multiple linear regression examining the effects of TQ and CB on HA%.

Predictor	**B (Bootstrap)**	**SE**	***p*-Value**	**95% CI**	
				Lower	Upper
Intercept	43.16	10.89	.003	17.82	61.25
Team Quality (Medium)	5.02	1.67	.007	1.65	8.20
Team Quality (Low)	10.06	2.15	<.001	5.98	14.38
Competitive Balance (CB)	8.96	5.98	.088	-1.07	23.05

Note. B (Bootstrap) – Bootstrapped unstandardized coefficient; SE – Standard error; p – significance level; 95% CI – 95% confidence intervals.

DISCUSSION

This study aimed to quantify the extent of HA in EuroLeague basketball and to evaluate how the quality of teams and the championship's CB influence and predict this phenomenon. Our analysis showed that EuroLeague teams won 62.9% of their home games (HW%), consistent with previous research (Jiménez,

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Valido, & Jiménez, 2025; Kulenović & Demšar, 2024). The home court advantage, measured by both HA% and HW%, peaked during the 2021-2022 season and was lowest during the post-pandemic 2020-2021 season. Meanwhile, HA remained relatively stable across other seasons, maintaining a consistent overall trend.

The significant decline in HA during the 2020–21 season can be linked to disruptions caused by pandemic restrictions, especially the absence of spectators. Research indicates that the lack of fans significantly reduces HA in European basketball (Alonso et al., 2022; Alonso et al., 2024a; Durmuş & Gülü, 2022; Paulauskas, Stumbras, Coutinho, & Figueira, 2022). While factors such as technical and tactical elements, familiar court routines, and travel fatigue remained steady contributors to HA, the limited or non-existent attendance of fans, along with their psychological influence on players, coaches, and referees, seems to be the main reason for this decline.

On the other hand, the rebound in HA during the 2021-22 season likely reflects the return of spectators to arenas, the reestablishment of home routines, and fewer disruptions compared to the pandemic season. These factors restored many of the advantages that home teams usually enjoy, bringing HA back toward pre-pandemic levels. Notably, the impact of spectators was especially significant, as players had been without fans for a long period, a trend also seen in football (Schank, Voigt, & Orthey, 2024). However, Leite, Silva, and Almeida (2025) suggested that fluctuations in home advantage during COVID-19 were more closely related to team performance than to the absence of a crowd, indicating that changes in home advantage may differ across various leagues.

The CB in the EuroLeague has shown a nonlinear evolution, with significant imbalance observed during the 2018–2019 season, followed by a gradual stabilization in subsequent years. While no statistically significant correlation was found between CB and HA%, seasons marked by greater inequality, such as 2018–2019 (CB = 2.17), tended to show a higher HA% (68.53%). This suggests that dominant teams were better able to leverage home conditions to maintain their superiority. In contrast, during seasons with greater parity, such as the 2022–2023 season (CB = 1.64), where 42% of regular-season games were decided by two possessions or fewer (Foteinakis, Pavlidou, & Stavropoulos, 2024), the level of HA% did not show a notable decline. This indicates that improved team balance and tactical homogenization across clubs did not necessarily reduce the relative impact of HA. Other contextual factors, such as fan presence, scheduling, officiating, and travel, may have a greater influence on HA.

The significant decline in CB during the 2018–2019 season can likely be linked to structural and organizational factors, including the stabilization of the 16-team round-robin format and the presence of long-term licenses that ensure participation for top clubs. Basketball attracts audiences because of its unpredictable outcomes. According to Pivovarnik, Lamb, Zuber, & Gandar (2008), low CB results in decreased fan engagement, which then lowers revenue from spectators and viewers, leading to minimal market value (Brandes & Frank, 2006). Therefore, a certain level of competitive uncertainty is vital across all sports (Brandes & Frank, 2006). The narrowing gap between top and bottom teams, as shown by the relatively stable CB, indicates a more dynamic and unpredictable competition. This trend is encouraging for the league, as it creates more exciting matchups and reduces predictability in team hierarchies.

The regression analysis examining the factors influencing HA in the EuroLeague showed that TQ is a significant predictor of HA, while CB is not. Specifically, lower-quality teams exhibited significantly higher HA than medium and high-quality teams. This suggests that the contextual and psychological factors associated with the home setting particularly benefit less competitive teams. These findings align with previous research

in elite European basketball, which has identified TQ as a key moderator of home performance (Alonso et al., 2023; Alonso et al., 2024b; Pojskić, Šeparović & Užičanin, 2011). Additionally, earlier studies (Pollard & Gómez, 2014) indicate that lower-ranked teams benefit more from situational home factors, such as crowd influence and travel comfort, and depend more heavily on familiar environments to secure victories. Factors like limited resources to handle travel-related stress and other challenges that can impair away performance may explain these patterns among lower-quality teams (Alonso et al., 2024b). In contrast, higher-quality teams, which tend to have more consistent performance and superior skills, tactics, and overall quality, appear less reliant on the home environment to maintain their competitive advantage (Alonso et al., 2023). Ultimately, differences in team quality seem to outweigh home-court advantage, as stronger teams are more likely to win both at home and away (Alonso et al., 2022).

In contrast, the non-significant relationship between CB and HA indicates that changes in league parity do not directly affect home-court advantage. The correlation analysis conducted in this study also supports this conclusion. Evidence from other European basketball leagues shows that CB generally influences overall league unpredictability rather than home performance trends across seasons (Pollard & Gómez, 2013). The persistent presence of HA, even as competitive levels vary, suggests that this phenomenon stems from the structural and situational dynamics of the EuroLeague, including officiating tendencies, fan engagement, and travel demands, rather than fluctuations in competitive equality from one season to the next.

From an applied perspective, the findings have important implications for coaches, analysts, performance staff, and team stakeholders. The observation that lower-tier teams benefit more from home conditions highlights the importance of situation-specific tactical preparation, especially for away games where they lose their home-court advantage. The persistence of a significant HA, even in well-balanced competitive environments like the EuroLeague, emphasizes the need for comprehensive preparation for away games. Coaches should design training and tactical routines that simulate high-pressure away environments, focusing on building psychological resilience and adaptability to crowd influence and officiating dynamics. Additionally, recognizing that the home advantage is more affected by situational and psychological factors than by the level of competition reinforces the importance of integrating sports psychology, crowd management, and officiating research into performance optimization and season planning at the EuroLeague level.

The generalizability of these findings is limited by the study's focus solely on the EuroLeague and by unmeasured factors known to influence HA. To enhance external validity, future research should examine various leagues and geographic contexts to determine if the findings remain consistent. Additionally, employing multilevel models that include psychological, tactical, and situational factors could offer a more complete understanding. Combining contextual data—such as crowd density, travel fatigue, and officiating tendencies—with performance metrics would help clarify the underlying mechanisms of HA in elite basketball. This approach is particularly important given the sport's strategic evolution, including the documented rise in three-point shooting in modern basketball (Foteinakis & Pavlidou, 2024, Karamousalidis et al., 2025), and its impact on HA.

CONCLUSION

This study used a dataset of EuroLeague home and away game results from the 2016-17 to 2024-25 seasons. The main aim was to measure the size of the home advantage (HA) in EuroLeague basketball and, second, to analyse how TQ and CB affect HA. EuroLeague teams won about 62.9% of their home games, showing a steady home advantage. The biggest change in this trend occurred during the COVID-19-affected

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2020-2021 season, when HA dropped sharply due to spectator restrictions. However, HA bounced back in the 2021-2022 season with fans returning, highlighting the important role of crowd presence in shaping game results.

Regression analysis showed that TQ is a key factor influencing HA, with lower-quality teams experiencing greater HA. This is probably because they rely more on psychological and environmental factors. In contrast, CB did not significantly predict HA, suggesting that differences in league parity across seasons do not significantly affect the home-court advantage. HA in the EuroLeague appears to be a consistent, contextually rooted feature, influenced more by psychological factors, officiating patterns, and logistical factors than by shifts in league competitiveness. Future research could explore combining performance data with other contextual metrics and officiating trends to understand better the mechanisms underlying home advantage in top-tier European basketball.

AUTHOR CONTRIBUTIONS

P.F.F: conceptualization, data collection, data analysis, formal analysis, investigation, methodology, project administration, supervision, validation, visualization, writing –original draft, writing – review & editing. S.P: data collection, data curation, methodology, writing – original draft, writing –review & editing. G.K: data collection, validation, writing –review & editing, N.Z.: formal analysis, investigation, methodology, writing – review & editing, T.S.: data collection, data curation, writing –review & editing, C.K.: methodology, writing – review & editing, A.A.: data collection, validation, visualization, writing – review & editing, A.C.: conceptualization, methodology, supervision, writing – review & editing. All authors have read and agreed to the published version of the manuscript

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Kinematic analysis of badminton smash techniques of badminton players

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ABSTRACT

Objective: To analyse the kinematic characteristics of smash in badminton and to explore the key factors affecting the effectiveness. Method: Forty badminton athletes at national level were selected from a university, and each of them performed 10 smashes in situ. They all wore sensors equipped with motion capture system, which are designed to collect their three-dimensional coordinate movement trajectories. The data then could be used to calculate the joint angular velocities, respectively of the knee, hip, shoulder, elbow and wrist. The calculation of peak angular velocities and the time lag naturally render the descriptive statistics of mean and standard deviation. Results: The transmission sequence of the badminton smash action is knee→hip→shoulder→elbow→wrist, and the joint torsion speed gradually increases during this process with the joint torsion speed increasing gradually with the transmission of the dynamic chain. The shoulder joint forward flexion contributes the most, the elbow joint speed should not be too fast, otherwise it will lead to the blockage of speed transmission, and the wrist joint rotation and deviation contribute more. The acceleration of the racket hand and the position of the centre of gravity are strongly correlated. Conclusion: The power source of the badminton smash action comes from the ankle, upper limb joints contributed significantly more than lower limb joints. A good position of gravity is beneficial for the player to start and move quickly and thus get more active opportunities to hit the ball.

Keywords: Performance analysis, Badminton, Smash, Kinematic analysis, Motion capture.

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INTRODUCTION

Badminton is the fastest racket-holding sport in the world. As of 2021, the global badminton lovers have exceeded 300 million (data collected in 2021). Badminton is popular because it involves confrontation and is fun to watch. It is a combination of fashion, fitness and social intercourse. In particular, the smash action in badminton is known for its high speed and aggressive nature. In fact, the world's fastest smash has reached 426 km/h. Smash is now the main approach of scoring in the game and has become the focus of much researches (Zhang et al., 2016). The previous reports (Song et al., 2015; Liu et al., 2002) shows that the acceleration of the upper limb action is positively correlated with the ball speed, and the acceleration of the upper limb action comes from the transmission of the limb power chain, in which the proximal link to the distal link of the limb is accelerated and braked in turn, so that the end link produces the maximum speed, which is also called the whipping (Liu, 2004). However, previous studies lean heavily on the transmission of dynamic chain only of the upper limbs, losing sight of the whole body movement.

Motion capture technology is widely used in all kinds of sports as a means of capturing movements (Wang et al., 2018; Manin et al., 2014; Peploe et al., 2019; An et al., 2017). As far as badminton is concerned, it was initially video capture, where pictures were obtained through high speed cameras and video recorders; then, motion simulation was performed using those pictures, and later inertial measurement units were introduced by placing sensors on the racket for motion capture. Thanks to technology advancement, the sensors are getting smaller and the impact on the players are remarkably reduced. With the help of a whole-body motion capture system (Perception Neuron PRO), we first test the smash movements of professional high-level athletes (national level). Then, we collect data to analyse the kinematic parameters of knee, hip, shoulder, elbow and wrist as well as the dynamic chain conduction sequence, and the motion of shoulder joint in sagittal, frontal and horizontal planes. A model of the smash movements is therefore established and then used to analyse the kinetic chain conduction sequence of high-level athletes and the motion characteristics of the shoulder joint in the three-dimensional direction. In order to examine the practical significance of the research, the kinematical analysis of those high-level athletes is compared with that of players who are less good at smash. The factors affecting the quality of smash are explored using the data, and a corrected coaching plan is proposed to provide guidance for badminton training and teaching.

METHODS

Subjects

Forty professional badminton players, half male and half female, are selected for this study. The subjects are all first-rate national athletes. They join in this study of their own accord and are free of physical diseases or injuries within a month prior to testing. They have also signed the informed consent (Table 1).

Table 1. Basic information of the subjects.

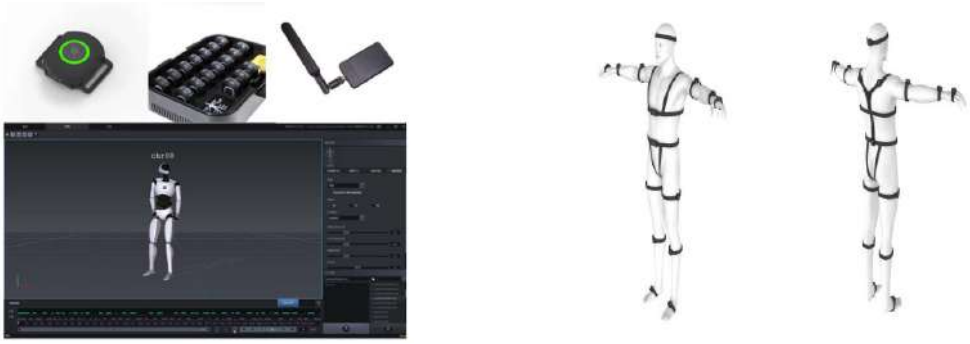
Gender	N	Height/cm	Age/Years	Training year/year	Professional level
Male	20	175.45 ± 3.37	19.4 ± 1.16	10.75 ± 1.65	Level 1
Female	20	170.85 ± 5.44	19.2 ± 2.13	9.25 ± 1.29	Level 1

Data acquisition

In the gymnasium of Beijing Jiaotong University (BJTU), the motion capture system was used to collect 40 players' smash data under the guidance of professionals and coaches. The motion capture equipment (Perception Neuron PRO) is an IMU sensor-based full-body motion capture system with excellent accuracy and reliability. The Perception Neuron PRO motion capture system has a shooting frequency of 300 frames

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per second and a static accuracy of <1deg roll angle, <1deg pitch angle and <1deg yaw angle. The equipment consists of one all-weather master node and 17 wireless sensors (see Figure 1), which are lightweight and small in size and do not affect the players' movements. The sports equipment is provided by Unix, our sponsor. The rackets are Extreme 700 with a string poundage of 28 ± 2b, and the shuttlecocks are Unix 5.



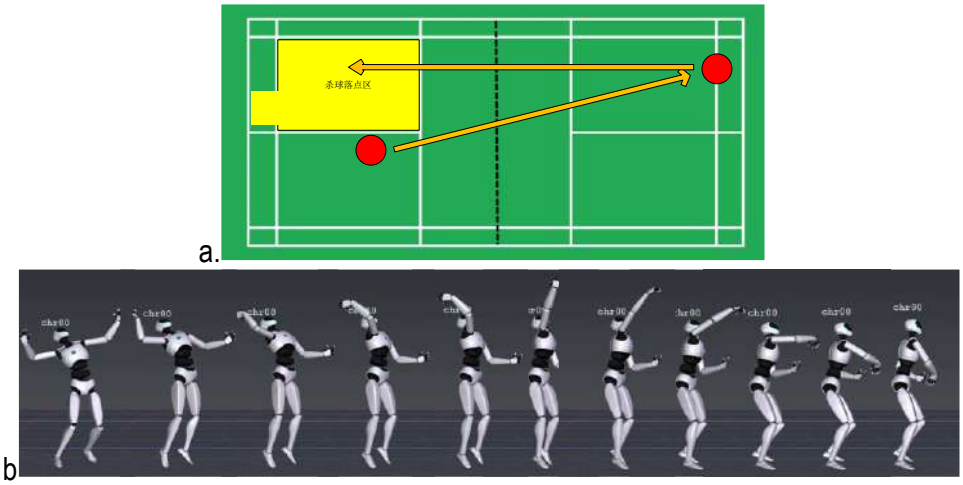
a. Perception Neuron PRO b. Dynamic capture device

Figure 1. Motion capture equipment and wearing diagram.

Before starting, 40 subjects were instructed in the test procedure and precautions (Figure 2). After that, they had 20 minutes to prepare. 3 testers and 1 coach participated in the test; 1 tester debugged the field, the main node of the equipment, as well as the computer; the other 2 testers helped the subjects to put on the dynamic capture equipment in order not to affect the movement and in the correct anatomical position as the best standard. To ensure the quality of the smash, the system was calibrated according to the standard A-Pose, with the body being upright, eyes level, arms down, palms forward, feet together and toes forward, at which time the data of all joints were 0. This test includes two contents.

Component 1: Smash technique data collection

After the "*start*" command is issued, the test subject starts to smash the straight ball , and the ball falls within the smashing zone and the hitting point is on the front side of the body for effective smashing. After the smash is finished, the coach will shout "*stop*", and each player will complete 10 effective smashes, totalling 400 times. (Figure 2).



a.

b

Figure 2. a Diagram of the route after hitting a shuttlecock, b Trajectory for smash.

Content 2: Athletes' starting, moving and hitting data collection
This part tests the relationship between the position of the centre of gravity at the moment of a player's start and the effect of hitting the ball. 40 players are grouped by the coaches, with two players in the same group and close to the same level, for a total of 20 groups. Each pair of players in turn played an 11-run game in which both players wore motion capture equipment. After the "*start*" command, the athletes began to play, and began to collect data, 11 points after the game, the next pair of athletes in turn.

Data processing
When the subject performs the movement, the master node collects the signal from the sensor by radio, and the computer records the raw data such as displacement coordination, acceleration, and angular velocity in three-dimensional space in real time at 300 frames per second. The technical movements are made by the combination of the movements of different joints of the human body, so the data are further converted, and according to the human anatomy method, the human body movements are divided into three mutually perpendicular tangential planes and three mutually vertical basic axes, namely sagittal plane, frontal plane, horizontal plane and sagittal axis, frontal axis and vertical axis (Figure 3).

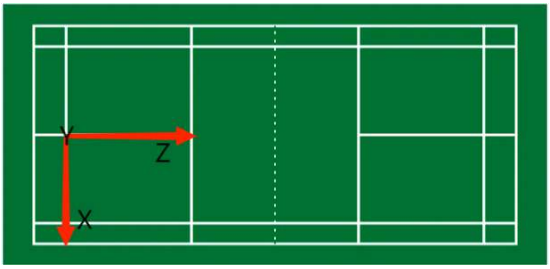


Figure 3. Illustration of 3D coordinate axes in badminton court.

Through the relative position changes of the two sensors, mathematical operations are performed to calculate the angular velocity changes of different joints in the three vertical planes and axes. For example, if the motion of the elbow joint through the relative motion of the large and small arm sensors are to be calculated, the following formula could be applied:

Angular velocity
The measured part of the athlete is assumed to be in uniform circular motion during the short period, i.e., the angular velocity ω is assumed to be a constant quantity. The angular velocity ω is expressed as the ratio of the angular displacement $\triangle\theta$ of the measured joint part of the badminton player to the line of gravity of the body and the corresponding time interval Δt , as shown in Equation (1).

$$\omega = \Delta\theta / \Delta t \qquad (1)$$

Where, the angular displacement $\triangle\theta$ is the difference of angles in the time interval Δt . Define the coordinate point of an athletic joint at the moment t as $(x_t,\ y_t,\ z_t)$, then the joint is in the frontal plane, i.e. z_t = 0. The angular displacement $\triangle\theta$ at the moment t is calculated as shown in Equation (2).

$$\Delta\theta = \arctan\left(\frac{y_t - y_{t-1}}{x_t - x_{t-1}}\right) \qquad (2)$$

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The joint definitions, angles and directions of motion for different joint movements are explained in Table 2.

Table 2. Calculation of joint activities.

Joint	Definition of the joint	Movement parameters
Hip	Connection of the pelvis to the right thigh	Internal rotation (+)/External rotation (-)
Knee	Connection of the right thigh to right calf	Internal rotation (+)/External rotation (-)
Shoulder	Connection of the right shoulder to the right upper arm	Internal rotation (+)/External rotation (-) Flexion (+)/Extension (-) Inward (+)/Outward (-)
Elbow	Connection of the right upper arm to the right lower arm	Flexion (+)/Extension (-) Inward (+)/Outward (-)
Wrist	Connection of the right upper arm and hand	Internal rotation (+)/External rotation (-) Flexion (+)/Extension (-)

Acceleration

The ratio of the change in angular velocity Δω of the rotating rigid body from instantaneous time t to the corresponding time interval Δt is called the average angular acceleration. The angular displacement $\triangle\theta$ at time t is calculated as shown in Equation (3).

$$\alpha = \Delta\omega / \Delta t \quad (3)$$

Centre of gravity

In the space where the athlete is located take the spatial right angle coordinate system O-xyz shown in Figure 3, the athlete's weight is M. The athlete can be divided into N masses according to the test joint parts. Biomechanics theory considers the human body as a non-homogeneous object and the divided body parts are considered to be homogeneous, then each mass, corresponding to the respective coordinates(X_i, Y_i, Z_i) and mass mi. known, let the athlete's centre of gravity be G (X, Y, Z), then the equation for the centre of gravity is shown in equations (4)-(6).

$$X = (x_1 m_1 + x_2 m_2 + \ldots + x_i m_i + \ldots + x_N m_N) / M \quad (4)$$

$$Y = (y_1 m_1 + y_2 m_2 + \ldots + y_i m_i + \ldots + y_N m_N) / M \quad (5)$$

$$Z = (z_1 m_1 + z_2 m_2 + \ldots + z_i m_i + \ldots + z_N m_N) / M \quad (6)$$

The centre of gravity coordinates are further subjected to a maximum difference calculation, i.e., the difference between the maximum and minimum values on each of the three axes is calculated in a complete killing action, indicating the distance travelled in different directions.

Gravity lines and support lines

As shown in Figure 4, the gravity line refers to the vertical line of the body's centre of gravity on the ground at the moment of initiation, and the support line refers to the edge line connecting the two feet on the ground part (Lin, 1983). It is known that, let the coordinates of the point mapped on the ground by the gravity line be $M\ (X, Z)$, then the calculation formula is equation (7) and (8).

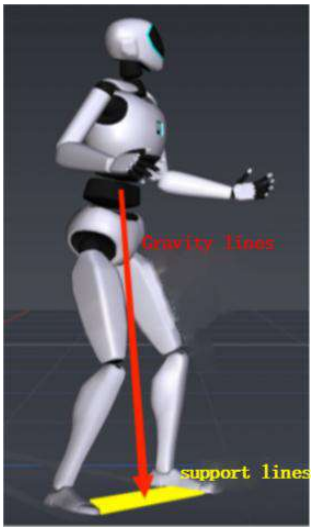


Figure 4. Diagram of athlete's centre of gravity at the moment of start (Quoted from Lin Chuanchao 1983).

The coordinate points of the two feet are known to be $N1(x1, y1, z1)$ and $N2(x2, y2, z2)$, Then the formula of the support line is shown in equations (7) and (8).

$$k = (y_2 - y_1)/(x_2 - x_1) \quad (7)$$

$$y = kx - kx_1 + y_1 \quad (8)$$

Then, it is known that the ground mapping point M of the gravity line and the formula of the support line, let the distance from M to L be S, then the formula of S is shown in equation (9).

$$S = \frac{|(kx_0 - y_0 - kx1 + y1|}{\sqrt{1+k^2}} \quad (9)$$

Data processing

Firstly, the original data are converted, filtered and smoothed, etc. The Perception Neuron PRO analysis system is used to convert the original data and obtain the angular velocity of different joints in three-dimensional space from anatomical point of view, and a hitting cycle is selected from the end of the previous action to the end of the next action. The technical movements were divided into four stages: preparation, introduction, hitting and follow-through swing. The weighted filtering of each resolved 3D coordinate curve is performed using the Savitzky Golay Filter, and the weighted weights are obtained by least-squares fitting of a given higher-order polynomial, which makes the filtered and smoothed data more effective in retaining the signal variation information (He et al., 2018).

Mathematical statistics

Descriptive statistics were performed on subjects' age, height, years of training, and test results as mean and standard deviation. Independent samples t-tests were conducted for different joint angular velocities of male and female athletes respectively using SPSS 19.0. Then, descriptive statistics for mean and standard deviation were conducted.

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RESULTS

Power chain conduction sequence characteristics of smash

The statistics of the change of angular velocity of different joints during the smashes by high-level players are shown in Figure 5.

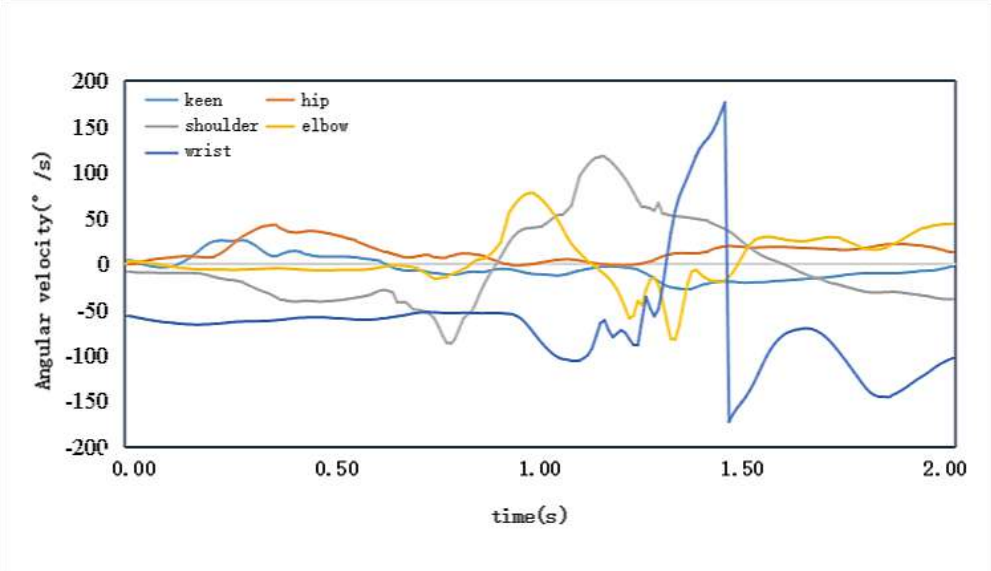


Figure 5. The curve of angular velocity of smashes conducted by high level players.

Table 5. Statistics of time difference and peak angular velocity of different joints.

Indicators	Joint	Males		Females	
		Average value	Standard deviation	Average value	Standard deviation
Time difference (s)	Knee → Hip	0.09	0.04	0.15	0.06
	Hip → Shoulder	0.13	0.03	0.18	0.07
	External shoulder rotation → Elbow flexion	0.15	0.04	0.3	0.08
	Elbow flexion → shoulder internal rotation	0.25	0.08	0.44	0.12
	Shoulder internal rotation → Elbow extension	0.37	0.09	0.52	0.12
	Elbow extension → wrist	0.56	0.06	0.94	0.08
	Total time	1.55	0.07	2.54	0.08
Peak angular velocity (°/s)	Knee	33.04	1.72	26.09	3.21
	Hip	48.34	1.91	39.82	5.36
	Shoulder external rotation	69.61	1.63	40.43	5.34
	Elbow flexion	98.54	1.16	54.75	6.12
	Shoulder internal rotation	129.45	5.06	85.65	5.47
	Elbow Extension	167.09	7.70	84.36	7.12
	wrist	173.14	4.65	143.37	5.71

From Figure 5, it can be seen that there are differences in the timing of the peak angular velocity of different joints: following the order of knee-hip-shoulder-elbow-wrist, and the peak angular velocity increases in this sequence. In addition, there are respectively two high and two low peaks in the shoulder joint and elbow joint. The peak maximum angular velocity of and the time difference between the occurrence of adjacent peaks of the five joints of knee, hip, shoulder, elbow and wrist during the smash of 40 male and female students were counted (Table 5). In Table 5, the mean value of the "*hip-knee*" time difference represents the difference between the moment of the peak velocity of the knee joint and the moment of the peak velocity of the hip joint, i.e.

As can be seen from Table 5, the whole hitting phase was divided into 6 parts: knee → hip, hip → shoulder, shoulder external rotation → elbow flexion, elbow flexion → shoulder internal rotation, shoulder internal rotation → elbow extension, and elbow extension → wrist. The time differences among different joints of male athletes were smaller than their female counterparts. Meanwhile, the mean value of the total time difference for male players was 1.55s, which was 0.99s less than female players, whose time difference was 2.54s. The data also showed that the average time spent on smashes was shorter for male athletes. In addition, the angular velocity of the males' wrist was 173.14°/s, which was 29.77°/s higher than the 143.37°/s of the females, indicating that the former were faster than the latter.

Upper limb kinematic characteristics of badminton smash

As mentioned in the previous section, in badminton smash action, the velocity change of the upper limb joints is significantly greater than that of the lower limb, and this part mainly analyses the angular velocity change characteristics of the three joints of the upper limb in the three techniques (see Figure 7).

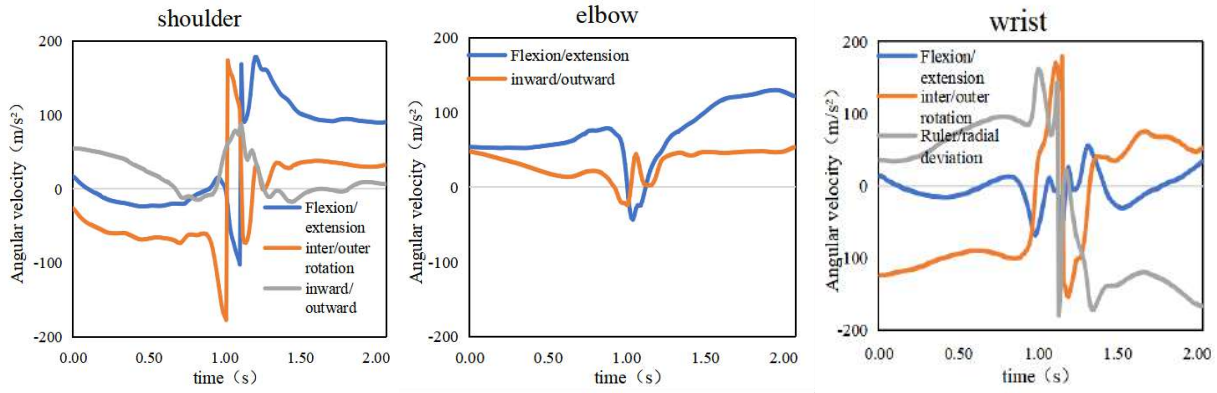


Figure 7. Upper limb joints movement diagram during the smash.

The shoulder joint has three dimensions of change, flexion/extension, rotation, inward/outward respectively. In terms of time sequence, external rotation appeared first, followed by inward and extension, then turned to internal rotation and flexion; the elbow joint has changes in two dimensions, flexion/extension and inward/outward respectively. The elbow joint changes from flexion to extension at the moment of hitting the ball, with no significant changes in inward and outward dimensions, and the angular velocity change of the elbow joint was much smaller than that of the shoulder and wrist joints; the velocity change of the wrist joint was larger than that of the shoulder and elbow, with significant changes in the angular velocity of the ulnar deviation and radial deviation and rotation dimensions, and the angular velocity change of the ruler/radial deviation and rotation dimensions The change in angular velocity in the flexion/extension dimension was smaller.

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As mentioned in the previous section, the shoulder joint of the racket holder needs to be externally rotated and then internally rotated during the smash. Since the shoulder joint is the most complex joint in the human body and plays an important role in the dynamic chain transmission, The data were summarized for the 3D movement time characteristics of the shoulder joint, as shown in Table 4.

Table 4. Shoulder joint time difference and peak angular velocity statistics.

Indicators	Joint	Males		Females	
		Average value	Standard deviation	Average value	Standard deviation
Time difference(s)	External rotation → Internal retraction(A→B)	0.05	0.05	0.05	0.07
	Inward → flexion(B→C)	0.22	0.04	0.56	0.09
	Flexion → Abduction(C→D)	0.07	0.03	0.08	0.03
	Abduction → External rotation (D → E)	0.35	0.08	0.56	0.09
	External rotation → internal rotation (A → E)	0.69	0.06	1.19	0.06
	Inward → Outward (B → D)	0.05	0.05	0.05	0.07
Peak angular velocity (°/s)	External rotation (A)	-110.08	4.67	-81.92	3.14
	Inbound (B)	47.08	7.31	37.73	7.54
	Flex(C)	154.89	17.7	119.10	7.69
	Outreach (D)	-58.43	9.01	-66.75	8.22
	Internal rotation (E)	138.30	6.9	107.61	6.48

As can be seen from Table 4, the average time taken by male athletes to go from external to internal rotation was 0.69s, which was 0.50s lower than that by male athletes, who took 1.19s, i.e. the former finished the smash faster than the latter. During the backward lead of the upper arm, the time difference between internal and external rotation was smaller and almost simultaneous, 0.05s for males and 0.07s for females, indicating that the internal and external rotation movements were almost simultaneous. For the shoulder joint movement in all 5 directions, the peak angular velocity of joint flexion was the largest, indicating the higher importance of shoulder joint flexion forward and downward during the action. The peak angular velocity of joint flexion was 154.89°/s for male players, 34.79°/s faster than female player, who took 119.10°/s. This also explained why male athletes could finish the smash in a shorter period of time than their female counterparts.

Characteristics of the relationship between the position of the body's centre of gravity at the moment of initiation and the effect of smash

The distance from the mapping point of the player's centre of gravity on the ground to the support line at the moment of initiation is calculated. A positive value indicates that the mapping point is on the front side of the support line, i.e., the body leans forward at a greater angle, and a negative value indicates that the mapping point is on the back side of the support line, i.e., the body leans back more. The relationship between this distance and the wrist acceleration during the stroke of the kill technique is shown in Figure 8.

The following characteristics can be seen from Figure 8. With the change of the distance between the gravity mapping point and the support line, the smash show regular changes, and the wrist acceleration values are the largest at the 0 point position; to the left of point 0, the acceleration decreases rapidly with increasing distance; and to the right of point 0, the acceleration decreases relatively slowly with increasing distance. In order to further explore the relationship between the position of the centre of gravity and the hitting effect at

the moment of player initiation, Pearson correlation analysis was conducted on the distance and the wrist acceleration at the moment of hitting, and the result is 0.716.

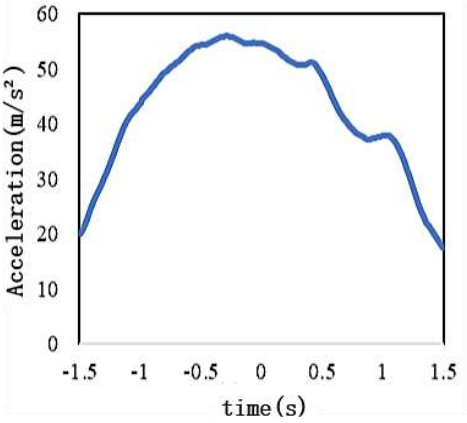


Figure 8. Relationship between mapping point distance and wrist acceleration.

DISCUSSION

Power chain characteristics of badminton players' smash action

Structurally, the human body is connected together by joints to form a complete power chain, and when the end of the power chain is needed to generate maximum speed, the body behaves as a sequential acceleration from the proximal link to the distal link, and this action of making the end link generate maximum speed is also called whipping action (Liu, 2004). The power chain plays a central role in the action process in the field of competitive sports and plays an important role in the completion of action techniques and the monitoring of training quality (Jiang, 2013).

The dynamic chain system of badminton smash action comes from the lower limb muscles doing work to generate torque, which is transmitted up to the elbow and wrist through the knee, hip and shoulder, activating the trunk and upper limb muscles in turn to maximize the angular velocity of the bones, and finally transmitted to the arm to complete the action. The power source during this process comes from the lower limb stirrup turn to make the body produce faster speed, from the lower limb to the upper limb in turn to produce braking, forming the wrist whipping action. The conduction of the dynamic chain allows the joints to twist in a speed that continues to spike to the maximum, and thus the sequence of time is knee - hip - shoulder - elbow - wrist. In previous studies, the order of badminton power chain transmission presents two views, one view that the power source of badminton backcourt technique is in the core area, from which the power is transmitted upwards, driving the shoulder, elbow and wrist joints to accelerate in turn (Lam et al., 2018), the second view that the ankle joint is the power source of badminton backcourt technical movements, from the bottom upwards in order of ankle-knee-hip-shoulder-elbow-wrist, the results of this study support the second view.

The low and high peaks of the shoulder joint represent the external and internal rotation of the shoulder joint during the lead, i.e., the time interval of the high and low peaks of the angular velocity of the shoulder joint represents the movement change of external rotation and then internal rotation of the shoulder joint during the lead. Likewise, the high and low peak angular velocities of the elbow joint represent the change in movement of flexion followed by extension. The preparation phase is composed of four movements: preparation, introduction, hitting and swinging. After preparation, the right foot stirrup turns to generate internal rotation of the knee joint, the hip and above joints produce braking, the dynamic chain is transmitted

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upward, the hip joint starts to accelerate internal rotation, driving the torso to rotate forward, the body weight is transferred from the back foot to the front foot, the power chain is transmitted to the shoulder joint, firstly, the racket is introduced to the lower back, i.e. the shoulder joint is externally rotated, the large and small arms When the head of the racket reaches the bottom, the racket is finished. When the head of the racket reaches the bottom of the racket, the racket is finished. When the ball is hit, the shoulder joint rotates from external to internal rotation, and the racket is swung forward and upward, the elbow joint extends quickly, driving the wrist racket to the highest point, and then the wrist flashes downward quickly to hit the ball. Therefore, according to the sequence of high and low peak, the actions follow the order of knee - hip - shoulder external rotation - elbow flexion - shoulder internal rotation - elbow extension - wrist.

As for the dynamic chain transmission involving knee-hip-shoulder-elbow-wrist, the time difference increased sequentially for both sexes, from 0.09s to 0.56s for males and from 0.15s to 0.94s for females, probably due to the increasing joint movement from the bottom to the top, which required more time, leading to increased time difference between the peaks of different joints. The dynamic chain sequence of male and female athletes was the same, but the peak angular velocity of different joints and the time difference between the peaks were different. Due to different physiques, the explosive power and speed of male athletes were significantly higher than those of female athletes, so the peak angular velocity of joints of male athletes were both greater than those of female athletes, and the time required to complete the movement was shorter than their female counterparts (Pueo & Jimenez-Olmedo, 2019).

Kinematic characteristics of the Upper limb joints in badminton smash action

When the dynamic chain is transmitted to the shoulder joint, it enters the leading phase and the upper arm starts to do the leading loop to the back of the shoulder, and it rotates and accelerates gradually. In the previous dynamic chain analysis, we found that the order of transmission is shoulder, axis, wrist, so the speed of the upper arm external rotation should be the first to reach the fastest, the lower arm and wrist continue to lead the racket to the bottom to reach the fastest speed. Meanwhile, the shoulder joint turned to the inside, so that the racket can reach the bottom. When that happens, the angular speed of the shoulder joint extension reaches the maximum, and the lead phase ends. When entering the hitting phase, the shoulder joint drives the upper and lower arms to swing forward and upward, and they start to change from external rotation and extension to internal rotation and flexion, which drives the elbow joint to turn outward and gain momentum. The peak of forward flexion and internal rotation at the moment of hitting was greater in the kill technique, and this study concluded that the contribution of these two was higher at the time of hitting. This result is similar to the results of Takenori Awatani et al. which correlated shoulder flexion and extension and rotation velocity with racket speed in the backcourt killing technique, respectively, and showed that both shoulder flexion and extension velocity and rotation velocity were significantly correlated with racket speed with correlation coefficients of 0.652 and 0.728 respectively (Awatani et al., 2018).

By comparing the shoulder, elbow and wrist joints longitudinally it can be found that the peak angular velocity of the elbow joint is significantly smaller than that of the shoulder and wrist, a result similar to that of Yuvaraj Ramasamy et al. This study analysed the backcourt technical movements of elite Malaysian players and concluded that greater stirring power and swing speed could speed up the stroke, but at the same time, care should be taken that the elbow joint should not be too fast, otherwise it would lead to a block in velocity transmission (Ramasamy et al., 2021). In the flexion-extension curve, the angular speed of flexion remains relatively high in the lead phase, and the speed drops significantly in the stroke phase, with a downward spike. Analysing the reason, it may be due to the backward and downward lead phase, the need to flex the elbow to drive the small arm and hand downward to lead the racket, to obtain a greater acceleration distance, and the hitting phase to swing forward and upward, from flexion to extension (Hajdu-Szucs et al., 2018).

The results of previous studies concluded that the wrist rotation contributed the most (King et al., 2020). Unlike the results of previous studies, the test results of this study showed that the peak angular velocity of wrist ruler/radial deviation was similar to the peak of internal and external rotation, which means that the ulnar radial deviation also had a higher contribution. The reason for this result mainly lies in the fact that scholars have different opinions regarding the location of the hitting point, some scholars believe that it is above the front of the head, while some studies believe that it is above the front of the right shoulder (Chin et al., 1995).Combined with the badminton grip principle, when the hitting point is above the front of the head, there is no change of ruler and radial deviation, while when the hitting point is above the front of the right shoulder, the wrist is in ulnar deviation posture at the moment of hitting (Qiang, 2001). This study confirms the theory that the hitting point is above the front of the right shoulder.

Therefore, the shoulder joint forward flexion contributes the most, the elbow joint speed should not be too fast, otherwise it will lead to the blockage of speed transmission, and the wrist joint rotation and deviation contribute more.

Characteristics of the relationship between the position of the body's centre of gravity at the moment of initiation and the effect of the killing technique

The implementation of badminton match tactics need to rely on reasonable techniques and footwork to complete, both sides take different tactics according to the situation on the field to maximize the mobilization of the other run, destroy the rhythm of the other side, cause the other side to be passive, and launch an attack when we take the initiative to win (Yu et al., 2008). Each technical action requires four steps: starting, moving, hitting, and returning. Start, move and return are all steps, and the three technical movements analysed above are strikes. At the moment of starting, whether the athlete's gravity line falls on the support surface is an important basis for judging whether the athlete is passive or not. After starting, the athlete moves to the position where the ball is to hit the ball through footwork, and early moving into place and active hitting can achieve better hitting effect. In addition to the technical level, does the hitting effect also have a relationship with the position of the centre of gravity? There are few studies on centre of gravity adjustment and hitting effect at home and abroad. Japanese scholars studied the centre of gravity sway characteristics of players and concluded that athletes with strong centre of gravity adjustment have better sports performance (Masu & Nagai, 2016).

In this study, an attempt was made to investigate the relationship between the position of the player's centre of gravity at the moment of initiation and the effectiveness of the stroke. In terms of the assessment of the stroke effect, since there are many factors that affect the effect of the technique, such as the player's technical level, physical state, and the position of the centre of gravity at the moment of stroke, this paper only discusses the effect of the position of the centre of gravity at the moment of stroke on the effect of the three techniques, using whether the acceleration of the player's hand at the moment of stroke is affected as the basis for judgment. It has been proved that wrist acceleration is highly correlated with racket head acceleration, and the faster the wrist acceleration, the faster the racket head acceleration follows, so the wrist acceleration can be used as a measurement of racket head speed (Kwan et al., 2011).

According to Pearson's critical criteria for correlation, r values between 0.6 and 0.8 are strongly correlated, the acceleration of the racket hand and the position of the centre of gravity are strongly correlated, therefore, a good position of gravity is beneficial for the player to start and move quickly and thus get more active opportunities to hit the ball. The distance has a great influence on the effect of smash.

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Limitations and perspectives

Although the subjects were all national level athletes with a high level of athleticism and stability, there were still individual differences between players, which made it difficult to count our data. In the test of centre of gravity, the difference of athletes' physical fitness and physical condition also has some influence on the test data. Maintaining a good centre of gravity position at the moment of initiation has a facilitating effect on the effectiveness of kills and high balls. It is recommended to increase the practice content of centre of gravity adjustment ability in the training of athletes and to focus on the evaluation of shoulder pronation, elbow flexion, wrist internal rotation and ulnar deviation in the technical evaluation.

CONCLUSION

This study analyses the kinematic parameters of smash actions of high-level badminton players with the aid of motion capture technology. The dynamic chain of smash in badminton is knee → hip → shoulder → elbow → wrist, which can be further divided into knee → hip → shoulder external rotation→elbow flexion → shoulder internal rotation → elbow extension → wrist, with the joint torsion speed increasing gradually with the transmission of the dynamic chain, and upper limb joints contributed significantly more than lower limb joints. The shoulder joint forward flexion contributes the most, the elbow joint speed should not be too fast, otherwise it will lead to the blockage of speed transmission, and the wrist joint rotation and deviation contribute more.

The acceleration of the racket hand and the position of the centre of gravity are strongly correlated, therefore, a good position of gravity is beneficial for the player to start and move quickly and thus get more active opportunities to hit the ball. The distance has a great influence on the effect of smash.

AUTHOR CONTRIBUTIONS

Guo X-P: data collection, formal analysis, methodology, original draft, review and editing. Lin L-W: project administration, supervision, software.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

AVAILABILITY OF DATA AND MATERIALS

All data generated and analysed during this study are included in this published article.

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ORIGINAL ARTICLE

The effect of pyramid method training on increasing the maximal strength: An experimental study in female judo athletes

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ABSTRACT

This study is conducted to examine the preliminary effects of the Pyramid Method training on increasing the maximal strength of female judo athletes, as Judo demands an optimal combination of strength, speed, and endurance. The maximal strength is an important foundation in power ability and the execution of the technique, as in throwing (nage waza), especially in pulling, pushing, and in holding back enemies technique (osaekomi waza). In this quasi-experimental study, the purposive sampling technique is used. We involve 14 female Judo athletes from Persatuan Judo Seluruh Indonesia Kota Surabaya who have experience in training for around three years in a minimum. The experimental study receives Pyramid Training Program for a total of eight weeks, with the focus on the bench press test, power clean, squat, and deadlift. This program is designed for general preparation, according to the strength periodization steps. The experimental result of the Paired T-test and Mixed ANOVA Repeated Measures shows a significant increase and a large within-sample interaction effect between time and experimental group in every strength variable (p < .005). Significant time × group interaction effects with large within-sample effect sizes were observed across all strength variables in the experimental group, while no significant improvements were found in the control group (p < .005). The conclusion from this study is that the Pyramid Training was associated with significant within-sample improvements in the maximal strength of female Judo athletes in the preparation phase by giving optimal stimulus in the neuromuscular systems and is highly relevant for adolescent female athletes who are sensitive to weight variation, which may support physical qualities underlying throwing and grappling techniques. It is suggested that the next study involve bigger samples and a longer duration to evaluate the long-term effect of specific Judo techniques performance.

Keywords: Performance analysis, Pyramid training, Maximal strength, Female athlete, Judo.

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INTRODUCTION

Judo is a martial art that needs all physical components (Da Silva et al., 2021). It needs precise strength, speed, flexibility, balance, agility, and endurance (Kowalczyk et al., 2025). The one component of the main bio motor, which highly determines the ability of the early Judo players foundation, is strength (Krstulović et al., 2006). So that Judo players at least have already had the early model to become the greatest and unstoppable Judo athletes. Strength emerges as a crucial element that has to be followed up on in Judo sport gradually and planned, so that the result will go optimal and minimize the risk of injury (Fernandes Da Costa et al., 2024; Rodríguez et al., 2024), which in turn needs to follow the 7 principles of exercise (Khandelwal, 2019) under every strength exercise phase, which consist of anatomy adaptation phase, hypertrophy, maximal strength, and power (Bompa & Buzzichelli, 2022). This process starts with the anatomy adaptation phase, which functions to prepare muscles to receive heavier weight exercise. After that, the hypertrophy takes part, which enables the muscles to shape into bigger and stronger forms. Next, the maximal strength phase is used to train the nerve system to produce the most optimal force. Last, the power phase is used to change the strength into explosive powers, which is essential in Judo movement technique. However, I will discuss the importance of the maximal strength phase for Judo players. The maximal strength phase is highly important as it becomes the early foundation of power to be more effective and efficient in the throwing technique (nage waza), such as pulling and pushing, also for holding back enemies' techniques (osaekomi waza), so the enemies can't stand up and flee from the holding back position for a certain time.

Some document analysis, such as articles from the research, from Heshmati et al., (2020) discuss that the charge of Pyramid and Reserve Pyramid are effective in increasing the power and muscle mass. Moreover, the study from Cormie et al., (2011) about the importance of increasing and maintaining maximal strength for the athletes' performance success in every branch of sport. The previous study, through analysis, has identified the drawbacks of the study, such as the examined study does not receive special attention in the Strength Pyramid training. The study that examines the linear and non-linear (undulating) periodization of Judo athletes shows a 1RM increase in various exercises (including bench press and squat), but the focus is on the comparison of the periodization model, not on the comparison of the exercise design set, such as Pyramid vs. straight sets (Santos & Franchini, 2021). One study shows a significant increase in maximal strength of the four movements of squat, bench press, pull-up, and clean and jerk after 8 weeks of training. However, it does not show the Pyramid training structure set because it only focuses on the exercise design, which is adjusted with each athlete's goal performance, and does not use the same exercise method for everyone (Harris et al., 2019).

The pyramid method training will produce a different total volume of the set and repetition, compared to the straight sets, which have the same repetitions and sets. Remembering that exercise volume is the important variable in determining the strength adaptation and hypertrophy, the lack of studies that compare the Pyramid training method with other methods for Judo athletes directly, such as straight sets with equated volume, creates a research gap. The main gap is the lack of studies that tested the chronic effects (long-term effects) of Pyramid training towards the increase of the maximal strength (bench press, power clean, barbell squat, deadlift) in Judo athletes. However, due to the limited availability of homogeneous female judo athletes at the club level, the present ones are exploratory in nature, aiming to provide preliminary evidence rather than definitive causal inference. Therefore, small-scale experimental investigations remain relevant as pilot data to inform future randomized controlled trials in combat sports.

As a basis for rationalizing the problem through observation and interview, it turns out that the understanding of physical exercise cannot be stated as adequate for the Judo trainers, if they only taught based on their

experiences. How good it would be if the experiences were supported by sports science to receive an optimal result in minimizing injury risks, because, based on some case studies, which concern in high injury risk in teenagers, especially females, as they are experiencing early maturation in the growth process (Bowerman et al., 2014; Costa e Silva et al., 2017). However, according to PHV, teenagers will experience faster progress because they are more sensitive toward adaptation, which is caused by the given exercise, and also become their investment before becoming elite athletes. In this context, the existence of the gap based on evidences indicate that injury risks for teenage athletes are higher than those of the same age, especially on the elbow and shoulder, which is caused by the wrong throwing, or falling techniques, or even by a sprained knee (Frey et al., 2019), because doing such a spinning technique, changing direction fast, and getting hit repeatedly.

In the branch of Judo sport, it needs a training approach that not only focuses on weightlifting, but also on the neuromuscular stimulus quality, which is received by the muscle. One of the approaches that is commonly used in strength training is the Pyramid training, which involves the increase and decrease of weight in one training session gradually. So, the Pyramid training becomes the most relevant because according to Angleri et al., (2017), it shows that weight variation in the Pyramid training can increase the motor neuron by activating various motor units for increasing muscle contractility, because physiologically it stimulates muscle fibres IIa and IIb types by domain. The combination of high intensity and progressive variation in this method produces maximal strength, explosive power, and neuromuscular coordination. Thus, many kinds of set combinations and repetition can significantly increase the maximal strength. In every aspect, the available information on the effect of Pyramid method training on the maximal strength of female Judo athletes is quite limited. This study examine preliminary responses the strength training exercise using the Pyramid training approach in the 2-month general preparation phase, which consists of bench press, power clean, squat, and deadlift.

METHODS

Participants

The research participants consisted of 14 female Judo athletes of Persatuan Judo Seluruh Indonesia Kota Surabaya, who participated in this study, as shown in the table 2. They should have a minimum of three years of training experience and have participated in various provincial and national championships. All athletes who participated must be in the early period of general preparation and not had any injuries. We received approval from every athlete to participate in this study, and they promised to train by following the instructions from the researcher and trainer. This study used a quasi-experimental design by purposive sampling technique. This design was selected due to practical constraints in elite female judo populations and is consistent with exploratory or pilot experimental studies commonly used in applied sport science to examine feasibility and direction of training effects. There are two groups in this study, which are the experimental group and the control group. The control group followed a conventional resistance training approach using fixed-load straight sets without systematic pyramidal load variation. The training program takes 8 weeks, with 3 sessions per week (Monday, Wednesday, and Friday) at 14.00 -16.00 WIB, as shown in the table 1. No a priori power analysis was conducted, as the study was designed as a feasibility-oriented exploratory investigation rather than a confirmatory trial.

Training load and volume

To minimize confounding effects related to training exposure, both experimental and control groups followed identical weekly training frequency (three sessions per week) and identical exercise selection. The primary difference between groups was the load progression structure (pyramid versus conventional loading), while rest intervals and session duration were kept constant. Although total volume load was not mathematically

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equated, this approach reflects real-world judo training practices and supports ecological validity in applied settings.

Table 1. Training program.

Week	Meeting	Training item	Training dose
1-3	1-9	Warming up. Animal movement (bear crawl forward, bear crawl backward, inchworm forward, and backward) 20 meters with each movement. Bench press, power clean, squat, and deadlift (85% of each athlete's 1RM). Cooling down.	Frequency: 5 Intensity: High Set: 3 Interval: 2-5 Minutes Recovery: 3-5 Minutes
4-6	10-18	Warming up. Animal movement (bear crawl forward, bear crawl backward, inchworm forward, and backward) 20 meters with each movement. Bench press, power clean, squat, and deadlift (90% of each athlete's 1RM). Cooling down.	Frequency: 4 Intensity: High Set: 3 Interval: 2-5 Minutes Recovery: 3-5 Minutes
7-8	19-24	Warming up. Animal movement (bear crawl forward, bear crawl backward, inchworm forward, and backward) 20 meters with each movement. Bench press, power clean, squat, and deadlift (95% of each athlete's 1RM). Cooling down.	Frequency: 3 Intensity: High Set: 3 Interval: 2-5 Minutes Recovery: 3-5 Minutes

Procedures

In this study, the instrument used to measure the height of participants is the Stature meter, and for the weight, the Tanita BC-545N is used. After that, all participants perform the Bench Press, Power Clean, Squat, and Deadlift tests. Before the intervention, every participant must fill out the written agreement letters to show their willingness to participate in this study. Here are the following procedures that were received by participants:

The bench press test

In this study, the baseline data collection groups were conducted one day before the intervention. Before testing, the researcher explained the purpose and the procedure of the correct bench press test. Then, participants warmed up by performing certain animal movements to prevent injury during the test (McGiguan, 2017).

1. Lie supine on a bench in a five-point body contact position: feet on the floor, head on the bench, buttocks on the bench, and shoulders and upper back in contact with the bench. Optimally, the feet should be as close to the centre of the body as possible to facilitate leg drive.
2. Grip the bar with the hands slightly wider than shoulder width.
3. A spotter should help untrack the bar and position it over the centre of the chest.
4. Hold the bar with the elbows fully extended above the centre of the chest.
5. Lower the weight straight down to the centre of the chest (between the nipple line and xiphoid process).
6. At the bottom of the movement, the elbows should be slightly tucked toward the body without being perpendicular to the shoulders or close to the body.
7. Without bouncing the bar off the chest, extend the elbows and press the weight straight up.
8. Maintain the five-point body contact position during the exercise.
9. The spotter should aid in racking the bar once the exercise is completed.

The power clean test

The early data collections were also conducted one day before the intervention. The researcher

explained the purpose and the correct procedure of the power clean test. Then, participants warmed up by performing certain animal movements to prevent injury during the test (McGiguan, 2017).

1. Using a slightly wider than shoulder-width pronated or hook grip, begin by taking hold of a loaded barbell in a lifting rack (or set of blocks) that is set at mid-thigh height.
2. Position the heels approximately shoulder-width apart, with the feet facing slightly outward.
3. Bend at the knees slightly and flex at the hips to lean the torso forward, allowing the barbell to move down the thighs to a starting position that is just above the knees. At this position, the shoulders should be over the barbell, the elbows pointing out, and the head facing forward and in line with the spine.
4. Begin the upward movement by rapidly extending the hips, knees, and ankles while maintaining the shoulder position over the barbell.
5. Allow the barbell to slide up the thighs to ensure it remains as close to the body as possible.
6. As the joints of the lower body reach full extension, rapidly shrug the shoulders.
7. When the shoulders reach their highest elevation, flex the elbows to enable the barbell to remain close to the body as it rises in the vertical plane. The explosive nature of this phase may cause the feet to lose contact with the floor.
8. Rapidly move the feet and legs into a quarter-squat position while forcefully pulling the body under the barbell.
9. As the body moves under the barbell, rapidly thrust the elbows forward to catch the barbell on the front of the shoulders.
10. In the catch position, the torso is nearly erect, the shoulders are slightly in front of the hips and the head remains in a neutral position.
11. Recover to a standing position with the barbell on the front of the shoulders.
12. In a controlled fashion, lower the elbows to untrack the barbell from the shoulders, and then slowly lower the barbell to the thighs.

The squat test

The early data collections were also conducted one day before the intervention. The researcher explained the purpose and the correct procedure of the squat test. Participants warmed up by performing certain animal movements to prevent injury during the test (McGiguan, 2017).

1. Begin by gripping the bar with a shoulder-width pronated grip and placing it on the upper back and shoulders (high-bar or low-bar position can be used). The toes point slightly outward, the chest is out, and the head is tilted slightly upward.
2. Descend by flexing the hips and knees while maintaining a neutral back position until the desired position is reached. This is usually when the thighs are parallel to the floor.
3. Return to the starting position by extending the hips and knees while maintaining a neutral back position.

The deadlift test

The early data collections were also conducted one day before the intervention. The researcher explained the purpose and the correct procedure of the deadlift test. Participants warmed up by performing certain animal movements to prevent injury during the test (McGiguan, 2017).

1. Using a slightly wider than shoulder-width pronated or hook grip, begin by taking hold of a loaded barbell in a lifting rack (or set of blocks) that is set at mid-thigh height.
2. Position the heels approximately shoulder-width apart, with the feet facing slightly outward.
3. Bend at the knees slightly and flex at the hips to lean the torso forward, allowing the barbell to move down the thighs to a starting position that is just above the knees. At this position, the shoulders

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should be over the barbell, the elbows pointing out, and the head facing forward and in line with the spine.
4. Begin the upward movement by rapidly extending the hips, knees, and ankles while maintaining the shoulder position over the barbell.
5. Allow the barbell to slide up the thighs to ensure it remains as close to the body as possible.
6. As the joints of the lower body reach full extension, rapidly shrug the shoulders.
7. When the shoulders reach their highest elevation, flex the elbows to enable the barbell to remain close to the body as it rises in the vertical plane. The explosive nature of this phase may cause the feet to lose contact with the floor.
8. Rapidly move the feet and legs into a quarter-squat position while forcefully pulling the body under the barbell.
9. As the body moves under the barbell, rapidly thrust the elbows forward to catch the barbell on the front of the shoulders.
10. In the catch position, the torso is nearly erect, the shoulders are slightly in front of the hips and the head remains in a neutral position.
11. Recover to a standing position with the barbell on the front of the shoulders.
12. In a controlled fashion, lower the elbows to untrack the barbell from the shoulders, and then slowly lower the barbell to the thighs.

Materials

The materials used in this study included standard resistance training equipment consisting of an Olympic barbell and calibrated weight plates for bench press, power clean, squat, and deadlift exercises. Anthropometric measurements were obtained using a stature meter for body height and a Tanita BC-545N bioelectrical impedance analyser for body mass assessment. All strength testing and training sessions were conducted in an indoor training facility under standardized environmental conditions, supervised by certified coaches to ensure correct technique execution and participant safety throughout the intervention period.

Statistical analyses

Statistical analysis was conducted using IBM SPSS (Version 22.0). Shapiro-Wilk Test ($p < .05$) applied, and pre-test and post-test data from every group were compared using the paired sample T-test. The data was shown as mean and standard deviation. The data was tested for its normality using the Shapiro-Wilk test. Moreover, the data was tested using a T-test to determine the significance of the difference in the same data after the different measurements. Then, it continued by determining which groups were different from the others to find out which specific groups are different using a paired sample T-test. Given the exploratory nature of the study and the small sample size, statistical outcomes should be interpreted with caution. Effect sizes were reported to describe the magnitude of observed changes rather than to support population-level inference. The mixed ANOVA results are therefore presented as indicators of within-sample interaction patterns, not as definitive evidence of causal superiority. Given the small group sizes, assumptions underlying parametric interaction models may be partially violated; therefore, inferential statistics are complemented by effect size interpretation.

RESULTS

All participants in this study, whose characteristics are shown in Table 2, regularly follow the training and participate in the training program according to each group's training programs. These findings reflect substantial within-sample improvements following the intervention and should be interpreted as preliminary evidence within the studied cohort.

Table 2. Players data.

Groups	Jumlah	Age (year)	Weight (kg)	Height (cm)
Experimental group	7 participants	19.1 ± 4.3	48.5 ± 8.1	153.2 ± 6.1
Control group	7 participants	18.4 ± 4.0	57.6 ± 14.1	158.2 ± 8.5

Table 3. shows the test results of the paired sample T-test (pre-test and post-test). Those tables show a significant difference in the experimental groups statistically, because the sig. value is < .05 and the control groups do not show any difference because of sig. > .05.

Table 3. Test result of paired T-Test (pre-test – post-test)

Test	Groups	Mean ± SD	Sig.
Bench press	Experimental	12.1 ± 4.0	.000
	Control	0.3 ± 0.5	.172
Deadlift	Experimental	16.4 ± 4.8	.000
	Control	0.7 ± 1.0	.106
Power clean	Experimental	8.2 ± 2.4	.000
	Control	2.2 ± 4.0	.184
Squat	Experimental	41.4 ± 12.9	.000
	Control	1.9 ± 2.0	.052

Table 4. shows the result of the mixed ANOVA repeated measures analysis, which shows the presence of a very strong interaction between time and groups in the increase of the strength capability in all measurement variables. In the bench press test, the experimental groups receive a bigger increase than the control groups, as it is reflected in the value $F(1,12) = 60.08$, $p < .001$, $\eta^2p = .834$, which indicates very big interaction effects. In the deadlift test, where the experimental groups show a better increase than the control groups, as shown in the value $F(1,12) = 72.20$, $p < .001$, $\eta^2p = .857$. This interaction pattern suggests larger within-sample changes following the applied training program. In the power clean test, it also shows a significant difference in increase between groups, in the value of $F(1,12) = 11.97$, $p < .005$, $\eta^2p = .499$, which indicates a medium to large interaction effect. Meanwhile, the squat test gives a value of $F(1,12) = 64.70$, $p < .005$, $\eta^2p = .844$, which indicates a very big interaction effect. All of these findings show that the training program that was given to the experimental groups demonstrated larger improvements in increasing the strength performance in various lifting exercises, rather than the control groups, which showed minimal increase and were not significant.

Table 4. Test result of repeated measures.

Test	Df	F	Sig.	Partial Eta Squared.
Bench press	1.12	66.08	.000	.834
Deadlift	1.12	72.20	.000	.857
Power clean	1.12	11.97	.005	.499
Squat	1.12	64.70	.000	.844

DISCUSSION AND CONCLUSIONS

The participants' data during the physical training program during the preparation period shows an increase in the maximal strength through the Pyramid training in the female Judo athletes, which is the main finding of this study. This method is also linear with the periodization principle and overload progressive training, which emphasize neuromuscular adaptation and muscle hypertrophy optimally (Bompa & Buzzichelli, 2022;

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Cormie et al., 2011); moreover, the other studies also show that resistance training with Pyramid and traditional methods is likely the same for its effectiveness to increase the positive adaptation in muscle strength and hypertrophy for elderly women (Ribeiro et al., 2017).

While these strength improvements are theoretically relevant to judo performance, no direct inference regarding competitive or technical outcomes can be made from the present data. The previous study shows that the Pyramid training is effective in increasing 1RM maximal strength in bench press, squat, and deadlift, whether in general or even in trained athlete populations. It also increases specific neuromuscular ability, which supports muscle torque production constantly in the knee joint and shoulder, as well as strengthening core muscle stability, such as the rectus abdominis, obliquus externus and internus, erector spinae, and transversus abdominis to work co-ordinately, so that the body becomes more stable to lift maximal weight, which means that this method is relevant to a functional strength program and training periodization (Greco et al., 2019; Liu et al., 2024). In addition, specific Judo training manipulation, which focuses on the lower muscle strength and endurance, must be maximized to increase competitive performance, because the high heart rate has not been proven to be a training intensity level that is accurate in all modalities of Judo training (Franchini et al., 2014; Harris et al., 2020). However, unlike large-scale randomized studies, the present findings should be viewed as hypothesis-generating, providing direction for future controlled trials rather than confirmatory conclusions.

Across all tested exercises, the experimental group demonstrated consistently larger interaction patterns compared with the control group. These findings support the previous literature, which shows that various variations of progressive weight are able to increase the neuromuscular adaptation (Angleri et al., 2017; Ribeiro et al., 2017; Costa et al., 2021). The significant increase in the squat test shows that Pyramid training provides an optimal stimulus for neuromuscular systems (Campos et al., 2002) due to the increased muscle strength, which will closely link with athletes' performance in general. Numerous studies support the argument that stronger muscle strength can increase performance in general sports ability, such as jumping, sprinting, and changing direction in order to perform throwing techniques (nage waza) and defending techniques (osaekomi waza), those athletes will be able to perform well (Suchomel et al., 2016). This method enables a more specific adaptation for female athletes, which generally more sensitive to weight variation due to physiological development factors during adolescence.

This study did not include retention or transfer tests to assess whether the observed strength gains translated into sustained adaptations or improved judo-specific technical performance. Therefore, the observed improvements likely reflect short-term neuromuscular adaptations rather than stable training-induced performance transfer. The limitations of this study include the small sample size (n = 14), the intervention length is only for 8 weeks, and the focus is only on female athletes in the early phase of general preparation. This limits the generalization result on a larger population, including male athletes or different age groups. Meanwhile, this study does not evaluate the long-term effect of Pyramid training on specific Judo technique performances or injury prevention. Further research should involve larger samples, longer intervention duration, biomechanical measurements, and specific technique performances to evaluate the effectiveness of Pyramid training more comprehensively. Additionally, the absence of randomization and assessor blinding increases the risk of systematic bias. These limitations restrict causal interpretation and reinforce the need to consider the present study as preliminary evidence.

During the preparation phase, the Pyramid training was associated with meaningful improvements in maximal strength within the studied cohort, significantly in female Judo athletes, especially in the bench press, squat, deadlift, and power clean. Where this method is more specific to the sensitive female athletes in weight

variation due to physiological factors during adolescence, as it can push the neuromuscular system and stronger muscle strength, which may contribute to the development of physical qualities underlying throwing (nage-waza) and defensive techniques (osaekomi-waza).

This finding is consistent with the previous literature, which shows that a strength training program using the Pyramid method is effective in increasing maximal strength. Further research should involve larger samples, longer duration, biomechanical measurements, and also specific Judo technique performances to be more effective.

AUTHOR CONTRIBUTIONS

Muhamad Fauzi Antoni, S. Pd., M. Kes.: conceptualization, methodology, data collection, and writing original draft. Dr. Dewangga Yudhistira, S. Pd., M. Pd.: data analysis, visualization, and editing draft. Dr. Novadri Ayubi, S. Or., M. Kes.: investigation and data curation. Laily Mita Andriana, S. Pd. M. Fis.: methodology and supervision. Dr. Adi Pranoto, S. Or., M. Kes.: validation and formal analysis. Dr. Ari Wibowo Kurniawan, M. Pd.: resources and project administration. Dany Pramuno Putra, S. Ftr., M. Kes.: supervision and project administration. All authors have participated sufficiently in the work to take public responsibility for its content. All authors have reviewed and approved the final version of the manuscript and agree to its submission and publication in the Journal of Human Sport and Exercise (JHSE).

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ORIGINAL ARTICLE

Empirical analysis of LM-47 students' educational perceptions in informal learning contexts at football academies

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ABSTRACT

Youth sport is increasingly recognised as an informal educational setting that contributes to children's motor, emotional and social development, particularly in the 8-10 age group. In this perspective, football academies represent fundamental learning environments, where the educational role of adults plays a decisive role in shaping children's sporting experiences. However, empirical evidence on the educational perceptions of university students in training, particularly those enrolled in the LM-47 master's degree programme, remains limited. This study aimed to analyse the educational perceptions of LM-47 students working in informal football academy settings, focusing on the importance of movement, motivational factors, operational difficulties and the perceived quality of the educational environment. A sample of 120 LM-47 students completed a structured questionnaire consisting of 14 closed-ended questions. Descriptive statistics and chi-square tests were used to analyse the distribution of responses and associations between the role held and key educational variables ($p < .05$). 80% of participants considered movement to be essential, while 73.3% emphasised the need for a balance between fun and technical learning. Fun games emerged as the main motivational factor (65%), while repetitive or overly difficult activities were identified as the main cause of demotivation (50.8%). Two significant associations were found between the role held and the perceived causes of demotivation ($p = .049$, V = .242) and the evaluation of the football academy environment ($p = .048$, V = .243). The results highlight a shared pedagogical orientation among LM-47 students and confirm the educational value of football academies as informal learning contexts.

Keywords: Physical education, Youth sport education, Football academies, Educational perceptions.

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INTRODUCTION

In recent years, youth sport has been progressively recognised not only as an area of technical and motor skills learning, but also as a genuine informal educational context capable of influencing the overall development of children (Altavilla et al., 2024). From this perspective, youth sport contexts, including football academies, represent complex learning environments in which motor, cognitive, emotional and social dimensions intertwine, assuming a particularly important role in the sensitive stages of developmental growth (Aliberti et al., 2025a; Giardullo et al., 2024). Recent reviews emphasise motor competence as a core element of physical literacy and lifelong engagement in physical activity (Piotrowski, 2025).

Pedagogical and motor-educational literature emphasises how, in the 8–10 age group, children consolidate basic motor patterns, develop relational skills and build their first stable representations of themselves as players and as members of a group (Ceruso et al., 2019a; D'Isanto et al., 2024). Studies on children confirmed significant age-related differences in the development of basic motor skills, highlighting the importance of age-appropriate educational programmes (Hurtado-Almonacid et al., 2024). At this stage, play, intrinsic motivation and the quality of the educational environment are key elements in promoting well-being, active participation and continuity in sporting activities over time (Bailey, 2006; Raiola et al., 2022). Motor competence is strongly associated with physical activity levels and perceived competence in youth (Coe et al., 2024). Several studies show that sporting environments characterised by playful, varied and inclusive activities promote learning, cooperation and emotional engagement in children (Raiola et al., 2025a; Ceruso et al., 2019b). A recent meta-analysis confirms that sport game-based interventions significantly improve children's fundamental motor skills (Li et al., 2022; Sun & Chen, 2024).

The educational value of motor activity has also been documented across different age groups and functional domains (Calandro et al., 2020). Conversely, contexts that are overly focused on performance, early competition or the repetition of standardised tasks can generate frustration and demotivation and increase the risk of children giving up sport (Giardullo et al., 2025; Schlesinger et al., 2018; Harwood et al., 2020). In this sense, football academies can be both powerful educational contexts and critical environments, depending on the quality of relationships, implicit rules and organisational methods adopted. Another key element concerns the role of adults involved in youth sports contexts. The quality of the child's experience depends largely on the educational, communication and methodological skills of the operators, as well as their ability to understand developmental needs and manage group dynamics. Recent studies show that educational style, motivational climate and emotion management have a significant impact on the psychological and physical well-being and participation of young athletes (Aliberti et al., 2025b). In this context, the university education of sports professionals takes on particular importance.

The literature highlights the need for academic programmes that integrate motor, pedagogical and management skills, capable of preparing professionals who can deal with the complexity of informal educational contexts (D'Isanto et al., 2022; D'Elia, 2019). The LM-47 master's degree course fits into this perspective, with the aim of training individuals who can interpret youth sport not only in technical terms, but also in educational and social terms (Esposito et al., 2024a; Raiola, 2025b; D'Elia et al., 2020). Despite the growing attention paid to youth sport as an educational context, the literature still offers little specific evidence on the perceptions of LM-47 graduates who work directly in informal youth football contexts regarding the psychophysical sphere of young footballers, the difficulties encountered on the pitch, the quality of the football school environment and the skills considered necessary to perform their educational role effectively.

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Purpose of study

The aim of this study is to analyse and evaluate the impact of the perceptions of students enrolled in the LM-47 master's degree course who work in informal football contexts, with particular reference to four dimensions: motivation to practise sport, operational difficulties in managing the group, perceived quality of the football school environment and skills considered necessary to work with this age group.

MATERIAL AND METHODS

Study participants

The sample consisted of 120 students enrolled in the LM-47 Master's degree course in Sports and Physical Activity Management at Pegaso Telematic University, selected through convenience sampling. The inclusion criteria were enrolment in the LM-47 course and active participation at the time of the survey in informal sports contexts related to youth football; no specific exclusion criteria were defined. To describe the composition of the sample, the question regarding the role held within the sports context was analysed. The distribution of responses shows that most participants perform operational functions in the field: coaches (30.8%), parents involved in sports activities (28.3%) and educators (16.7%) represent the largest categories. These are followed by figures such as managers, trainers, referees, former practitioners and other minor profiles, which together make up the remainder of the sample (24.2%). This heterogeneous composition allows us to gather perceptions from both technical operators and adults who experience sport in complementary roles. This diversity enriches the analysis of the educational dimensions investigated, allowing us to understand the phenomenon from different points of view.

Participation in the study was voluntary. LM-47 students were sent a link to the online questionnaire, accompanied by a brief information text containing the research objectives, instructions on how to complete the questionnaire and information on data confidentiality. Before starting to complete the questionnaire, participants gave their informed consent. The questionnaire was completed independently, using a computer or mobile device, in an average time of a few minutes. There were no potentially harmful or intrusive questions; the data was collected anonymously and analysed exclusively in aggregate form. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and current regulations on educational research.

Study design

The questionnaire consists of 14 questions (Q1–Q14), organised into macro-areas derived directly from the research problem and objectives. The macro-areas allow information to be collected on the respondent's profile, their perception of the importance of movement, motivational factors, operational difficulties in managing the group and the quality of the educational environment. This structure allows for a systematic and consistent reading of the perceptions of LM-47 students, maintaining a direct link between each question and the educational dimension investigated. All questions are closed-ended, formulated in nominal, ordinal or multiple-choice format, with between one and three options depending on the nature of the question. The absence of open-ended questions ensures uniformity in data collection and allows for clear and immediately comparable quantitative processing, while maintaining a good level of interpretative detail with respect to the participants' experiences. For greater clarity and in order to highlight the consistency between the questions and the theoretical dimensions investigated, the two tables relating to the structure of the questionnaire are presented below. The first contains the complete list of the 14 questions in their entirety; the second organises the same questions into macro-areas of reference, so as to clearly show the alignment between the tool used and the research objectives.

Table 1. List of the 14 complete questions.

N°	Code - Full question
1	Q1. What is your role in the sporting context?
2	Q2. In your opinion, how important is movement in a child's growth?
3	Q3. What motivates a child most during training?
4	Q4. When a child becomes tired or lacks motivation during training, what could be the cause?
5	Q5. What benefits have you noticed (or imagine) that a child gains from physical activity?
6	Q6. What behaviours do you most often observe in children during physical activities?
7	Q7. Have you ever noticed negative behaviour (frustration, arguments, exclusion) during matches or training sessions?
8	Q8. Do you think having fun or learning technique is more important at this age?
9	Q9. When play becomes too competitive, what can happen to children?
10	Q10. How important is it to vary the games during a sporting year?
11	Q11. What do you think is the main difficulty in working with children of this age?
12	Q12. How would you rate the environment at the football academy?
13	Q13. What do you think makes a child happy when playing football?
14	Q14. What values do you think football should convey to children of this age?

To ensure systematic data interpretation and consistency between the research objectives and the survey tool, the questionnaire questions were organised into five macro-areas, as shown in Table 2.

Table 2. Questions by macro thematic areas.

Macro area	Related questions
1. Respondent profile	Q1
2. The importance of movement and educational representations	Q2 – Q5 – Q14
3. Child motivation and factors influencing it	Q3 – Q4 – Q8 – Q9 – Q10 – Q13
4. Operational difficulties in managing the group	Q6 – Q7 – Q11
5. Quality of the educational environment/ football academy	Q12

Statistics analysis

In the first phase, nominal and ordinal variables were summarised using absolute frequencies, percentages and distribution tables, with the aim of outlining a general picture of the educational perceptions expressed by the participants. In a second phase, inferential analyses were conducted using the Chi-square test of independence to examine any association between the role held in the sporting context (Q1) and certain variables considered particularly relevant to the survey, such as the child's motivation, perceived operational difficulties, the quality of the educational environment and the values attributed to sporting practice. This approach made it possible to verify whether different participant profiles showed significantly different response patterns. The analyses were carried out ensuring that the conditions for the applicability of the Chi-square test were met (adequate number of observations per cell, independence of responses). These choices were consistent with methodological recommendations for research in exercise and sport sciences (Aliberti et al., 2023). The level of significance adopted was set at $p < .05$. In addition to the Chi-square test of independence, Cramer's V was calculated to estimate the strength of association between categorical variables. Cramer's V values were interpreted according to conventional thresholds (≈ .10 small effect, ≈ .30 medium effect, ≥ .50 large effect). Effect size estimates were used to support the interpretation of statistically significant associations, while non-significant results were interpreted with caution, especially in the presence of multiple categories and sparse contingency tables. All statistical processing was carried out using JASP

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software (open-source version for statistical analysis), presenting the results in aggregate form in full compliance with ethical standards and data confidentiality.

RESULTS

Table 3 offers a detailed overview of the educational perceptions of LM-47 students working in informal football contexts in the Under-11 category. The descriptive frequencies show a strong convergence of opinions on some key aspects of child development, such as the importance of movement, the central role of play, the need to vary activities and the relevance of the educational environment. At the same time, differences emerge in relation to the roles held in the sporting context, albeit generally limited.

Table 3. Frequencies and percentages of all 14 questions.

Question	**Category / Statistics**	**n**	**%**
Q1. What is your role in the sporting context?	Coach	37	30.8
	Parent	34	28.3
	Other	29	24.2
	Educator	20	16.7
Q2. In your opinion, how important is movement in a child's growth?	Quite	1	0.8
	Very	23	19.2
	Fundamental	96	80.0
	Mean = 2.79; Median = 3; Mode = 3; Standard Deviation = 0.46		
Q3. What motivates a child most during training?	Fun games	78	65.0
	Coach who encourages	22	18.3
	Desire to improve	13	10.8
	Congratulations	7	5.8
Q4. When a child becomes tired or lacks motivation during training, what could be the cause?	Difficult/repetitive tasks	61	50.8
	Coach not very engaging	23	19.2
	Lack of play	22	18.3
	Overly long training sessions	10	8.3
	Too much competition	4	3.3
Q5. What benefits have you noticed (or imagine) that a child gains from physical activity?	Fun + wellbeing + social interaction	55	45.8
	Wellbeing + social interaction	14	11.7
	Wellbeing + social interaction + concentration	17	14.2
	Other combinations	34	28.3
Q6. What behaviours do you most often observe in children during physical activities?	Enthusiasm + cooperation	28	23.3
	Enthusiasm + reassurance	21	17.5
	Enthusiasm + competition	20	16.7
	Enthusiasm	20	16.7
	Other behaviours	31	25.8
Q7. Have you ever noticed negative behaviour (frustration, arguments, exclusion) during matches or training sessions?	Sometimes	81	67.5
	Rarely	28	23.3
	Often	10	8.3
	Never	1	0.8
Q8. Do you think having fun or learning technique is more important at this age?	Both in balance	88	73.3
	Fun	25	20.8
	Technique	4	3.3
	It depends on the child	3	2.5

Q9. When play becomes too competitive, what can happen to children?	Aggression/frustration	63	52.5
	Loss of motivation	36	30.0
	They help each other more	8	6.7
	They have more fun	6	5.0
	Others	7	5.8
Q10. How important is it to vary the games during a sporting year?	Fundamental	102	85.0
	I don't know	9	7.5
	Useful	9	7.5
	Mean = 2.80; Median = 3; Mode = 3; Standard Deviation = 0.50		
Q11. What do you think is the main difficulty in working with children of this age?	Game/technique balance	52	43.3
	Parental pressure	34	28.3
	Group management	21	17.5
	Communication	13	10.8
Q12. How would you rate the environment at the football academy?	So-so	63	52.5
	Quite good	22	18.3
	Very positive	20	16.7
	I don't know	9	7.5
	Not very positive	6	5.0
Q13. What do you think makes a child happy when playing football?	Belonging + fun	30	25.0
	Entertainment + creativity	17	14.2
	Freedom to move around + entertainment	11	9.2
	Belonging + creativity	10	8.3
	Other combinations	52	43.3
Q14. What values do you think football should convey to children of this age?	Loyalty + inclusion + teamwork	30	25.0
	Loyalty + teamwork	11	9.2
	Inclusion + teamwork	8	6.7
	Emotion management + inclusion	8	6.7
	Other combinations	63	52.5

Table 4. Results of Chi-square tests and Cramer's V for associations between Q1 and questionnaire variables.

Association between variables	**χ^2**	**df**	***p*-value**	**Cramer's V**
Q1 – Q2	10.91	6	.091	.213
Q1 – Q3	9.634	9	.381	.164
Q1 – Q4	21.10	12	**.049**	.242
Q1 – Q5	23.55	30	.792	.256
Q1 – Q6	54.20	39	.054	.388
Q1 – Q7	10.59	9	.305	.172
Q1 – Q8	12.00	9	.214	.183
Q1 – Q9	38.64	30	.134	.328
Q1 – Q10	12.34	6	.055	.227
Q1 – Q11	12.72	9	.176	.188
Q1 – Q12	21.20	12	**.048**	.243
Q1 – Q13	125.6	120	.344	.591
Q1 – Q14	72.43	72	.464	.499

Chi-square tests reveal only two significant associations between the respondent's role (Q1) and other items in the questionnaire: Q1–Q4, relating to the causes of the child's tiredness/lack of motivation, and Q1–Q12, concerning the evaluation of the football academy environment. Both statistically significant associations

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showed small-to-moderate effect sizes, as indicated by Cramer's V values (Q1–Q4: V = .242; Q1–Q12: V = .243). A detailed description is shown in Table 4.

DISCUSSION

The results emerging from the descriptive and inferential analysis allow us to outline a clear picture of the educational perceptions of LM-47 students involved in informal football contexts in the Under-11 category, largely confirming what has been highlighted in the reference literature. Firstly, the data relating to the importance of movement in child development (Q2) is particularly significant: 80% of participants consider it "*fundamental*", while a further 19.2% consider it "*very important*". This data indicates an almost total convergence towards a conception of movement as a central element of overall development, in line with contributions that recognise the educational, relational and socio-emotional value of motor activity (Bailey, 2006; Raiola et al., 2022). With regard to children's motivation during training (Q3), 65% of respondents identified fun games as the main motivational factor, followed by encouragement from the coach (18.3%) and the desire to improve (10.8%). This result confirms the centrality of play in youth sports contexts and reinforces the idea that intrinsic motivation is closely linked to the quality of the experience offered rather than to external or performance factors. Higher levels of motor competence have been shown to be associated with greater compliance with physical activity recommendations in school-aged children (Carcamo-Oyarzun et al., 2025; Martínez-López et al., 2024).

An analysis of the causes of fatigue or lack of motivation during training (Q4) shows that over half of the participants (50.8%) attribute this condition to activities that are too difficult or repetitive, while 19.2% point to a coach who is not very engaging and 18.3% to a lack of play. This data highlights how the design of activities and the educational style of the operator have a decisive impact on the child's involvement, confirming the importance of flexible methodological approaches adapted to developmental needs (Guo et al., 2024, 2025). In relation to the benefits of physical activity (Q5), the combinations of responses show a strong recurrence of elements related to fun, physical well-being and socialisation. In particular, 45.8% associate fun, physical well-being and the ability to be with others, while a further 14.2% also add improved concentration. These results reinforce the idea of sport as an informal educational context capable of influencing multiple dimensions of child development. Similar multidimensional benefits have been reported in school-based physical activity interventions, with sustained effects on motor competence and fitness (Bloch et al., 2025). In this perspective, improvements in motor performance are closely related to greater body awareness and functional control (Di Domenico et al., 2024). As for the behaviours observed during physical activities (Q6), enthusiasm and involvement are prevalent, often associated with spontaneous collaboration (23.3%) or the need for reassurance (17.5%). However, there are also signs of attention difficulties and a desire to compete, elements that require careful educational mediation on the part of operators.

The issue of negative attitudes (Q7) shows that 67.5% of participants observe them "*sometimes*", while only 0.8% say they have never encountered them. This suggests that episodes of frustration, conflict or exclusion are part of the youth sports experience and must be managed within a conscious educational project. Regarding the relationship between fun and technique (Q8), 73.3% of respondents believe that the two aspects should be kept in balance, while 20.8% favour fun. This indicates a pedagogically mature view, oriented towards the harmonious development of the child rather than early specialisation. This finding is consistent with constraints-led approaches in youth football, which promote technical learning through play-based and adaptive tasks (D'Isanto et al., 2021). A particularly relevant finding concerns the perception of the effects of overly competitive play (Q9): 52.5% believe that it can generate aggression or frustration, while 30% report a loss of motivation in the event of defeat. These results confirm the critical issues associated

with sports models that focus on performance at an early age (Esposito et al., 2024b). With regard to the variety of activities (Q10), 85% of respondents consider it essential to vary the games during the sporting year, emphasising the importance of novelty and continuous stimulation to maintain high levels of engagement.

The main difficulties in working with children (Q11) mainly concern the balance between play and technical learning (43.3%) and pressure from parents (28.3%), highlighting how the critical issues are not exclusively related to the child, but also to the adult context of reference. The assessment of the football school environment (Q12) is mainly intermediate: 52.5% describe it as "*so-so, could be better*", while only 16.7% consider it very positive. Regarding children's happiness when playing football (Q13), responses predominantly emphasise enjoyment, a sense of belonging and opportunities for creative and autonomous movement, highlighting the importance of an inclusive and emotionally positive climate. With reference to the educational values that football should convey at this age (Q14), participants primarily highlight values related to inclusion, teamwork, loyalty and emotional regulation, confirming the broader educational role attributed to youth sport. This data suggests that there is considerable room for improvement in terms of organisation and education.

Overall, inferential analyses reveal a limited number of statistically significant associations between the role played by respondents in the sporting context (Q1) and the other variables investigated, suggesting a substantial homogeneity of educational perceptions among LM-47 students working in informal football contexts, regardless of the role performed (coach, educator, parent or other). In particular, most of the associations between Q1 and the other questions are not statistically significant ($p > .05$), indicating that the vision of movement, child motivation, the value of the game, competitiveness and the football school environment appears to be widely shared among participants. This data reinforces the hypothesis that LM-47 university training contributes to building a common conceptual framework, oriented towards an educational and not exclusively technical interpretation of youth sport. However, two statistically significant associations emerge that deserve particular attention.

The first concerns the relationship between the role of the respondent (Q1) and the perceived causes of the child's fatigue or lack of motivation during training (Q4), which is significant ($\chi^2 = 21.10$, df = 12, $p = .049$, $V = .242$). This result suggests that the interpretation of the child's attentional and motivational difficulties may vary depending on the direct experience and point of view of the adult involved. For example, those who work in the field on a permanent basis may attach greater importance to the methodological and organisational aspects of training, while those with a different involvement may focus on relational or contextual factors.

The second significant association concerns the relationship between the respondent's role (Q1) and the perceived quality of the football academy environment (Q12) ($\chi^2 = 21.20$, df = 12, $p = .048$, $V = .243$). The data indicate that operational issues are interpreted in a partially differentiated manner depending on the role held: group management, the balance between play and technique, and parental pressure take on different weights depending on the operator's degree of educational and organisational responsibility. This result confirms that, even within a shared value framework, concrete professional experience influences the perception of daily difficulties. Although statistically significant, these associations show small to moderate effect sizes and should therefore be interpreted with caution. Overall, these results suggest that differences between roles do not alter the general educational framework but mainly affect the interpretation of operational issues and field dynamics. This reinforces the idea that the LM-47 course promotes a pedagogically oriented view of youth sport, while leaving room for interpretative nuances linked to specific experience and the role played in informal football contexts.

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Practical implications

The results of the study suggest the need to further strengthen the educational dimension of informal football contexts (Raiola et al., 2023). In particular, it highlights the importance of designing physical activities focused on play, variety and active participation, avoiding repetitive or overly performance-oriented activities. The role of the sports manager and operators trained through the LM-47 course is central in coordinating the various figures involved and ensuring educational consistency between technical objectives and training goals. Specific attention should be paid to the relationship with families, often perceived as a source of pressure, through opportunities for discussion and shared education on the values of sport. In addition, the management of emotions, conflicts and group dynamics appears to be a priority area for intervention, requiring advanced communication and interpersonal skills.

Limitations of the study

This study has some limitations that must be considered when interpreting the results. The use of a self-reported questionnaire exposes the risk of subjective bias and social desirability. The cross-sectional nature of the study does not allow us to capture the evolution of perceptions over time or to establish causal relationships. Finally, the absence of observational or qualitative data limits the possibility of exploring the educational dynamics that emerged in a more detailed manner.

CONCLUSION

This study analysed the educational perceptions of LM-47 students involved in informal football contexts in the Under-11 category, highlighting how university education contributes to developing a shared pedagogical vision of youth sport. The results confirm the importance of movement and play as privileged tools for development and show the centrality of the educational figure, called upon to manage complex dynamics, motivation, emotional climate and relationships with families. Football academies emerge as educational contexts with high potential, but they require competent coordination capable of balancing technical and recreational-relational dimensions. The few significant associations identified suggest that the role played affects some specific interpretations of the sporting experience but does not alter the overall educational vision. In summary, the study confirms the value of the LM-47 course in preparing professionals who are able to critically interpret contexts, design appropriate educational interventions and promote a sporting environment geared towards the well-being and growth of the child.

AUTHOR CONTRIBUTIONS

All co-authors have contributed to the published work equally and agree to its publication in JHSE.

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ORIGINAL ARTICLE

Didactic unit based on goalball: Effects on balance and reaction time in schoolchildren without visual impairment

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ABSTRACT

Para-sports as a core component of educational content constitute a key space for motor development and the promotion of inclusive practices within the school context. In this context, adapted sports such as goalball have emerged as pedagogical tools that foster participation and raise awareness of disability; however, scientific evidence regarding the development of motor skills in students without disabilities remains limited. To evaluate the effect of a goalball-based didactic unit on static balance, dynamic balance, and reaction time in secondary school students simulating a visual impairment. A quantitative quasi-experimental study was conducted. The sample consisted of 22 school students (mean age = 16.83 ± 0.54 years) from an educational institution in south-central Chile. The intervention was eight weeks in duration and comprised nine sessions, applied under two conditions: with visual restriction (blindfolded) and without visual restriction. Static balance was assessed using the Flamingo Balance Test, dynamic balance using the Y Balance Test, and reaction time using the Plate Tapping Test. Significant improvements were observed in static balance (p = .008; η^2 = .16), with large effect sizes in both conditions and a greater magnitude of improvement in the blindfolded condition. Dynamic balance showed slight increases, reaching significance only in the non-blindfolded condition, while reaction time did not exhibit significant changes. The goalball-based didactic unit primarily enhances static postural control and proprioceptive stimulation in students without visual impairment, confirming its value as a pedagogical resource in physical education.

Keywords: Physical education, Goalball, Static balance, Dynamic balance, Reaction time, Inclusive education, School students.

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INTRODUCTION

In Chile, the integration of students with disabilities into the school system is supported by a regulatory framework that promotes access, participation, and educational equity (Law Decree 170, 2009; Law Decree 83, 2015; Law 20,422, 2010; Law, 20,845, 2015). Nevertheless, progressing from integration toward effective inclusion remains a challenge, particularly in the field of physical education (PE), where pedagogical practices must simultaneously address motor, social, and educational objectives (Muñoz-Hinrichsen et al., 2024). In this context, sport is not just seen as a physical or recreational activity, but also as a social phenomenon and a powerful pedagogical tool with significant formative potential. It has the ability to contribute to students' holistic development and foster the creation of educational environments that promote inclusivity as a personal experience (Corrales, 2010; Gamonales & Campos Galán, 2017; Hernández-Beltrán et al., 2024; Nogueda, 1995).

Adapted sport has emerged as a key pedagogical strategy within PE, as it allows students to experience conditions of functional diversity (e.g., visual restriction). This strategy can contribute to the development of positive attitudes toward disability, value education, and provide equal opportunities (Abellán, Sáez-Gallego, & Carrión, 2018; Abellán, Sáez-Gallego, & Reina, 2018; Campos-Campos et al., 2023; Hernández-Beltrán et al., 2017). As such, for us, inclusive education involves more than the mere coexistence of students with and without disabilities in the same space (Haegele, 2019). Following Haegele (2019), inclusion entails an intersubjective experience of belonging, acceptance, and appreciation, in which each student constructs meaning within the shared educational environment. Accordingly, the implementation of adapted sports in school contexts has demonstrated benefits in promoting healthy lifestyles and improving participation and peer interaction among students with and without disabilities (Hernández-Beltrán et al., 2017).

Within this framework, goalball, as an adapted sport, has become established as a sporting modality that promotes participation under equal conditions through the restriction of vision using blindfolds (International Blind of Sports Federation, 2024). Although goalball is specifically designed for individuals with visual impairments, its use as a pedagogical tool in educational contexts, involving students without disabilities, has shown positive effects (Gamonales et al., 2023). For example, at the socio-emotional level, goalball has been shown to enhance cooperation, empathy, respect for diversity, and peer interaction (Gamonales et al., 2023; Laughlin & Happel, 2016). At the motor level, although there is evidence reporting benefits associated with its practice, the available empirical evidence remains limited (Ojeda-Troncoso & Campos-Campos, 2025). Thus, goalball can be positioned as a relevant pedagogical tool for integrated PE –where students with and without disabilities are educated in the same environment– by providing an intervention context that combines social sensitization experiences with motor challenges that remain underexplored empirically, particularly among students without disabilities.

Goalball practice is characterized by high demands on postural control and motor responses to non-verbal stimuli (Santos et al., 2018). Balance, understood as the ability to maintain the centre of gravity within the base of support, depends on the integration of visual, vestibular, and somatosensory systems (Cohen, 2013; Grace-Gaerlan et al., 2012). Diverse studies have shown that visual restriction significantly affects balance, increasing postural sway and reducing stability, both in individuals with visual impairments and in individuals without visual impairments subjected to visual restriction (Zetterlund et al., 2019; Bataller-Cervero et al., 2022). In this context, simulating a visual impairment through goalball practice forces a reorganization of postural control, enhancing the use of proprioception and other sensory channels as compensatory strategies (Bednarczuk et al., 2017).

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Alongside balance, reaction time constitutes another key capacity in goalball, as it determines defensive and offensive effectiveness in response to rapid and unpredictable auditory stimuli (Morales & Torres, 2016; Muñoz-Jiménez et al., 2021). The absence of visual information increases reliance on auditory and proprioceptive cues, requiring faster and more precise motor responses (Ince, 2021). In this regard, visual restriction has shown to increase demands on motor control reorganization processes, directly impacting response speed to external stimuli (e.g., sound) (Bataller-Cervero et al., 2022; Gökşen & İnce, 2024). Likewise, adapted sports such as goalball can promote neural plasticity and the use of alternative perceptual channels, consolidating reaction time as a relevant capacity at both sporting and educational levels (Silva et al., 2010).

From a social and educational perspective, the relevance of this study is particularly significant in the Chilean context. National reports demonstrate that 17.01% of the Chilean population presents some type of disability (Encuesta Nacional de la Discapacidad [ENDISC], 2022). Moreover, a substantial proportion of children and adolescents with disabilities attend primary (92.9%) and secondary education (81.2%), respectively, reinforcing the need for inclusive, evidence-based pedagogical practices in integrated educational settings (ENDISC, 2022). However, scientific evidence regarding the effects of goalball, for example, on school-aged populations without visual impairments remains limited, particularly concerning specific motor variables such as balance and reaction time.

While previous studies have incorporated adapted sport into PE classes with a predominantly sensitization-oriented focus and with value-based and participation-related outcomes, their impact on the development of motor skills and abilities has been limited (Abellán, Sáez-Gallego, & Reina, 2018; Campos-Campos et al., 2023; Hernández-Beltrán et al., 2017) Therefore, the present study focuses exclusively on the analysis of motor outcomes. As such, the aim of this study was to evaluate the effect of a goalball-based didactic unit on static balance, dynamic balance, and reaction time in secondary school students simulating visual impairment.

METHODS

Study design

This study followed a quantitative approach using a quasi-experimental design without a control group, with pre- and post-intervention measurements and a descriptive scope.

Participants

Using a non-probabilistic convenience sampling method, 22 secondary school students (female and male) from an educational institution located in south-central Chile participated in this study. The mean age of the participants was 16.83 ± 0.54 years. Participation was voluntary and required both student assent and informed consent from their parents or legal guardians prior to the start of the intervention. In addition, the necessary approvals were obtained from the school management team where data collection took place. This study was approved by the Scientific Ethics Committee of the Universidad Adventista de Chile (Adventist University of Chile) under approval number 2025-002.

Inclusion criteria

The inclusion criteria were: (a) enrolment in the elective PE course entitled "*Promotion of Active and Healthy Lifestyles*" and (b) submission of signed informed consent and assent, as applicable.

Exclusion criteria

The exclusion criteria were: (a) failure to complete all assessments during the pre- and post-test phases and (b) medical leave or health-related justifications that prevented full physical participation in the implemented activities

Instruments

Static balance

Static balance was assessed using the Flamingo Balance Test, whose validity and test–retest reliability were demonstrated by Tsigilis et al. (2002), reporting an intraclass correlation coefficient (ICC) of .73. The test was performed barefoot, with the participant standing on one foot on a non-slip beam measuring 50 cm in length, 4 cm in height, and 3 cm in width (Ünal et al., 2024), while the free leg was flexed at the knee and held with the hand on the same side. Timing began once the initial position was released and was stopped each time the participant lost balance. If the participant lost balance 15 times within the first 30 seconds, the test was terminated and assigned a score of 31 (Groselj et al., 2019). The test outcome corresponded to the number of attempts rather than the number of errors; therefore, a lower score indicated better static balance performance.

Dynamic balance

Dynamic balance was assessed using the Y Balance Test (YBT). During testing, participants stood barefoot in a single-leg stance on a central platform connected to three pipes oriented in the anterior, posteromedial, and posterolateral directions. Using the free limb, participants pushed a reach indicator that slid along the pipe. The trial was discarded and repeated if: (1) the stance foot was lifted from the platform or crossed the marked line, (2) the participant kicked, pushed, or stepped on the reach indicator, (3) the reaching limb touched the ground, or (4) balance was lost before returning to an upright position (Alkhathami, 2023).

For each direction, one practice trial was performed followed by three valid trials. The greatest reach distance (in centimetres) recorded in each direction was used for analysis. A composite score was calculated and expressed as a percentage of limb length using the formula:

$$[(\text{Anterior} + \text{Posteromedial} + \text{Posterolateral}) / (3 * \text{Limb length}) * 100].$$

Limb length was measured in centimetres from the anterior superior iliac spine to the most distal portion of the medial malleolus (Foldager et al., 2023; Plisky et al., 2021).

Reaction time

Reaction time was assessed using the plate tapping test (Ince, 2021). Participants were positioned in front of a table equipped with a board containing two circular metal plates (20 cm in diameter) separated by 80 cm between their centres. The non-dominant hand was placed on a rectangular plate (30 × 20 cm) located in the centre of the board. Participants were instructed to perform 25 consecutive taps with the dominant hand on the circular plates as quickly as possible. Timing stopped when a total of 50 taps had been completed (Council of Europe, 1983). A shorter completion time indicated better reaction time performance. The procedure was repeated twice, and the best recorded time was used for analysis.

Intervention

The intervention followed a self-developed protocol lasting 8 weeks, distributed across nine sessions of 60 to 90 minutes each (Table 1). It was implemented within the elective PE course *"Promotion of Active and*

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Healthy Lifestyles", addressing learning objectives numbers 1, 2, and 5 established by the Chilean Ministry of Education (Ministerio de Educación, 2019).

The activity design was based on guidelines from the *Goalball Manual* (Gómez & Tosim, 2016) and the *Paralympic Sport Initiation Manual: Goalball* (Aparecido de Oliveira & Pereira da Silva, 2022), which were adapted to the school context of the study. Sessions included individual, paired, and group-based tasks, predominantly using blindfolds to simulate visual impairment, thereby promoting static and dynamic balance as well as reaction speed. This approach aligned with the pedagogical model proposed by the Chilean Ministry of Education, which emphasizes the development of motor skills and adaptation to diverse contexts within PE classes. Additionally, medicine ball throws, locomotor tasks, and authentic goalball game situations were incorporated.

Table 1. Intervention program.

Session	Objective	Activities	Use of blindfolds	Duration
1	• To become familiar with the Paralympic sport of Goalball. • To strengthen motor and sensory coordination.	▪ Presentation on the history of the sport, its objectives, equipment, defensive and offensive fundamentals, and rules, supported by audiovisual materials. ▪ Discussion on the differences between Paralympic sport and adapted sport. ▪ Familiarization with the equipment used in Paralympic Goalball. ▪ Practical demonstration of basic rules.	No No No No	90 minutes
2	• To develop strength and accuracy in throwing. • To apply basic game rules in practical situations.	▪ Specific warm-up: guided jogging and joint mobility exercises. ▪ Throwing and reaction speed stations: chest passes, overhead throws, and hip rotation throws. ▪ Target throwing using different techniques. ▪ Defensive movement drills. ▪ Application in real game situations.	Yes No No Yes Yes	90 minutes
3	• To improve reaction speed to auditory stimuli. • To refine defensive movements in game-like conditions.	▪ Specific warm-up: guided jogging and joint mobility exercises. ▪ Auditory reaction exercises: rapid throws with immediate defensive response; tracking the ball after rebounds or directional changes. ▪ Defensive circuit: lateral movements and zone blocking. ▪ Fast passing in pairs with changes of direction. ▪ Mini-games (1 vs. 1) emphasizing reaction speed in both defence and offense.	Yes Yes Yes Yes Yes	90 minutes
4	• To enhance strength and speed in Goalball throwing. • To improve coordination and application in real game situations.	▪ Specific warm-up: guided jogging and joint mobility exercises. ▪ Throws using a medicine ball. ▪ Throwing and receiving drills in lines (two groups). ▪ Guided coordination circuit. ▪ Game-like situations.	Yes Yes Yes Yes Yes	90 minutes

5	• To improve strength and postural control for Goalball throwing. • To improve balance and spatial orientation during movement.	▪ Specific warm-up: guided jogging and joint mobility exercises. ▪ Workstations: medicine ball throws against a wall; balance exercises on a BOSU with auditory instructions combined with guided straight-line running; rapid blocking following auditory signals (auditory stimulation and reaction). ▪ Small-sided games (1 vs. 1 and 2 vs. 2) emphasizing balance maintenance and control during offensive and defensive actions.	Yes Yes Yes	60 minutes
6	• To improve coordination and orientation through auditory stimuli. • To enhance balance and teamwork in adapted activities.	▪ Specific warm-up: guided jogging and joint mobility exercises. ▪ Group game: collecting materials guided by auditory cues within a set time. ▪ Balance station: obstacle course on a BOSU with guidance, performed in teams (the fastest team wins). ▪ Line movements: forward movement, turn, and return following auditory guidance. ▪ Applied final game: paired reaction speed dynamics using auditory stimuli and movement.	Yes Yes Yes Yes Yes	60 minutes
7	• To strengthen accuracy and power in Goalball throws. • To improve reaction speed and blocking in real game situations.	▪ Joint mobility exercises. ▪ Frontal throws using medicine balls. ▪ Throws performed from a BOSU (balance and body control training). ▪ Reaction to auditory stimuli, rapid movements, and blocking drills. ▪ Game-like situation (3 vs. 3).	Yes Yes Yes Yes	90 minutes
8	• To promote cooperation and spatial orientation through auditory stimuli. • To apply passing techniques and gameplay in reduced Goalball situations.	▪ Specific warm-up: guided jogging and joint mobility exercises. ▪ Cooperative sound maze: obstacle course with one guide, transporting the group from one side to the other. ▪ Goalball passing drills: zig-zag dynamics with back-and-forth movement; the group completing the task in the shortest time wins. ▪ Small-sided game applying passes, blocks, and auditory orientation.	Yes Yes Yes Yes	60 minutes
9	• To integrate the skills learned into real Goalball situations. • To promote reflection on learning, inclusion, and teamwork.	▪ Cooperative warm-up: activation game in pairs (with and without auditory stimuli). ▪ Integrative circuit of stations: precision throwing to targets; auditory reaction with movement and blocking; dynamic balance in an obstacle course. ▪ Goalball match. ▪ Group discussion reflecting on learning outcomes achieved during the intervention.	Yes Yes Yes No	60 minutes

Procedures

First, the educational institution was visited to present the voluntary intervention plan to students enrolled in the elective course "*Promotion of Active and Healthy Lifestyles*." All participants received assent and informed

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consent forms, which were required to be signed by both the students and their parents or legal guardians. Once the signed consent and assent forms were obtained, baseline data collection (pre-test) was conducted.

Assessments were carried out in the school gymnasium during regular class hours, under the supervision of the principal investigator and with PE teacher support. Each student was assessed under two experimental conditions: a non-blindfolded condition (without blindfold; WOB), representing normal visual input, and a blindfolded condition (with blindfold; WB), simulating visual impairment. All assessments were conducted following the standardized protocols established for each test. After completion of the assessments, an 8-week intervention was implemented (Table 1). At the end of the intervention, physical assessments (post-test) were repeated in the school gymnasium. For the analysis of results, only students who completed both the pre-test and post-test were included.

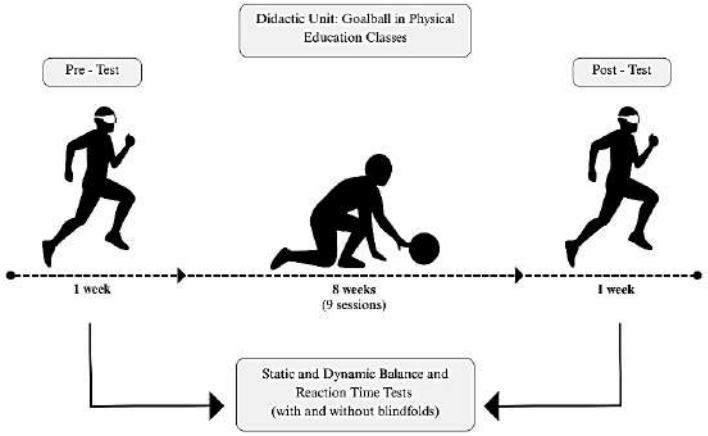


Figure 1. Intervention overview.

Statistical analysis

Sample size was estimated a priori using G*Power version 3.1.9.7, assuming a large effect size (f = 0.40), based on previous evidence reporting moderate to large effects (Bednarczuk et al., 2019; Zetterlund et al., 2019). The analysis considered a significance level of α = .05, a desired statistical power of 0.80, two measurements, and a moderate correlation between repeated measures (r = 0.50), with a sphericity correction of ε = 1. Under these assumptions, the minimum required sample size was 15 participants. In this context, the final sample of 22 students was considered adequate and sufficient to meet the study objectives.

Descriptive data were presented using means and standard deviations for static balance (n), dynamic balance (%), and reaction time (s), given that the data showed a normal distribution according to the Shapiro–Wilk test.

Subsequently, to compare outcomes, a repeated-measures ANOVA with two within-subject factors (time: pre vs. post; condition: with blindfold vs. without blindfold) was applied to evaluate main effects and interactions between the study variables. When the time × condition interaction was significant, post hoc comparisons with Bonferroni corrections were conducted to identify differences between assessment moments (pre vs. post) and between conditions (with and without blindfold).

The effect size of the interaction was estimated using partial eta squared (ηp^2), interpreted as small (.01), medium (.06), and large (.14) (Pallant, 2011). For multiple comparisons, effect size was calculated using

Cohen's d, with the following qualitative thresholds: trivial (<.20), small (.21 – .49), moderate (.50 – .79), and large (>.80) (Cohen, 1992).

As a complementary analysis, the individual relative delta was calculated for each variable and condition. For variables in which an increase in post-intervention scores represented improved performance (e.g., dynamic balance), the relative delta was calculated using the equation: [(Post value – Pre value) / Pre value) * 100]. Conversely, for variables in which a decrease in post-intervention scores indicated improved performance (static balance and reaction time), the relative delta was calculated using the equation: [(Pre value – Post value) / Pre value) * 100]. Based on these values, the absolute change by condition and the difference between conditions (ΔWB − ΔWOB) were estimated, along with their 95% confidence intervals, which were displayed using a forest plot. Positive values indicated greater improvement in the WB (with blindfold) condition, whereas negative values reflected a relative advantage of the WOB (without blind fold) condition.

Statistical analyses were performed using RStudio V 4.5.0. Statistical significance was set at $p < .05$.

RESULTS

The results of the repeated-measures ANOVA for static balance, dynamic balance, and reaction time under the WB and WOB conditions, comparing pre- and post-intervention time points, are presented in Table 2.

Regarding the time × condition interaction, a significant effect was observed only for static balance ($F_{(1,42)} = 7.80$, $p = .008$, $\eta p^2 = .157$, *large effect*). In contrast, no significant interactions were found for dynamic balance ($F_{(1,42)} = 0.00$, $p = .973$, $\eta p^2 = .000$) or reaction time ($F_{(1,42)} = 0.01$, $p = .920$, $\eta p^2 = .000$).

With respect to between-condition effects, a significant main effect of condition was identified for static balance ($F_{(1,42)} = 49.29$, $p < .001$, $\eta p^2 = .540$, *large effect*), indicating overall differences between the WB and WOB conditions across both measurement time points. No significant between-condition differences were observed for dynamic balance ($F_{(1,42)} = 1.77$, $p = .191$). For reaction time, a significant main effect of condition was found ($F_{(1,42)} = 4.39$, $p = .042$, $\eta p^2 = .095$, *medium effect*); however, given the absence of a time effect and a significant interaction, this result reflects a general difference between conditions rather than an intervention-related effect.

Table 2. Repeated-measures ANOVA results.

Variable	Effect	$F_{(df)}$	*p* - Value	η^2 partial
Static balance (n)	Condition	$F_{(1,42)} = 49.29$	<.001	.540
	Time	$F_{(1,42)} = 182.55$	<.001	.813
	Interaction	$F_{(1,42)} = 7.80$	.008	.157
Dynamic balance (%)	Condition	$F_{(1,42)} = 1.77$	.191	.040
	Time	$F_{(1,42)} = 15.53$	<.001	.270
	Interaction	$F_{(1,42)} = .00$	.973	.000
Reaction time (s)	Condition	$F_{(1,42)} = 4.39$	.042	.095
	Time	$F_{(1,42)} = .07$	.790	.002
	Interaction	$F_{(1,42)} = .01$	.920	.000

Regarding within-condition effects, intervention analyses revealed a significant improvement in static balance for both the WB condition ($p < .001$, $d = 2.34$, *large effect*) and the WOB condition ($p < .001$, $d = 1.53$, *large effect*). For dynamic balance, a significant improvement was observed only in the WOB condition ($p = .045$, $d = 0.31$, *small effect*). Finally, no significant improvements were observed in reaction time.

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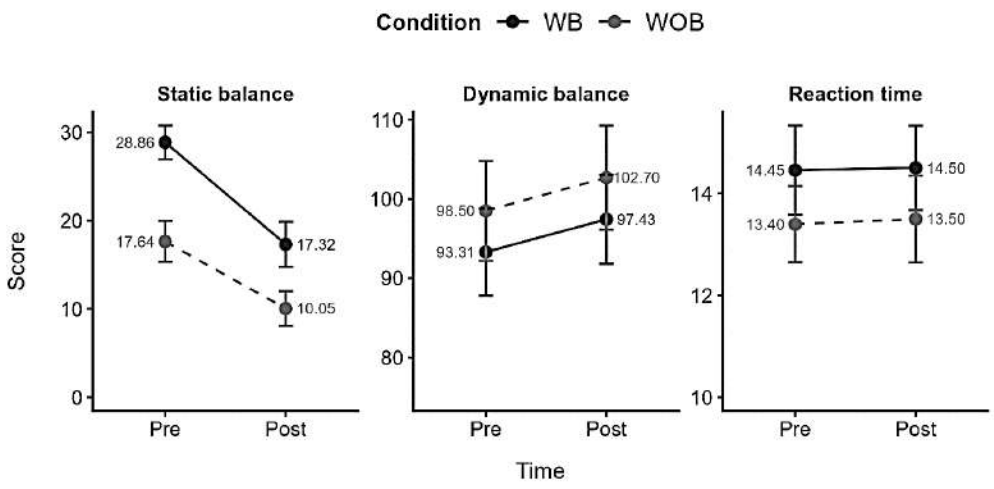


Figure 2. Changes in motor performance following the intervention under conditions with and without visual restriction.

Figure 3 illustrates the between-condition differences (WB − WOB) in absolute change for the analysed variables. For static balance, the point estimate and its 95% confidence interval were entirely located to the right of the null value, indicating a significantly greater improvement in the WB condition compared with WOB. For reaction time, the estimate was close to the null value and the confidence interval crossed zero, indicating no differences between conditions. For dynamic balance, high variability was observed in the estimate, with a wide confidence interval that included the null value, precluding the identification of a clear advantage of one condition over the other.

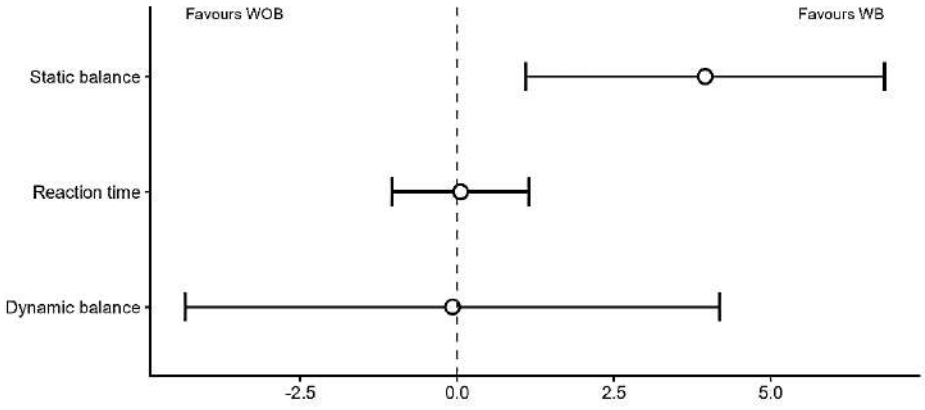


Figure 3. Between-condition difference in absolute change (WB − WOB).

DISCUSSION

The aim of this study was to evaluate the effect of a goalball-based didactic unit on static balance, dynamic balance, and reaction time in secondary school students simulating visual impairment. The main finding was that a goalball-based instructional unit significantly improved static balance and produced modest gains in dynamic balance in students without visual impairment, with a differential effect favouring the blindfolded condition (WB) observed exclusively for static balance.

Effective inclusion in PE requires strategies that level opportunities for participation while challenging the perceptual–motor capacities of all students. In this regard, goalball emerges as a particularly valuable pedagogical tool. According to Lieberman et al. (2019), adapted sport can be implemented as a strategy that engages all students in equivalent motor demands, facilitating the development of physical capacities through shared participation, regardless of disability status. The findings of the present study support this premise by demonstrating that participation in adapted sports increases the demand on compensatory systems, resulting in improvements in both static and dynamic balance.

The significant time × condition interaction observed for static balance ($\eta p^2 = .157$) suggests that systematic Goalball practice under visual restriction enhances postural control mechanisms, likely through increased reliance on proprioceptive and vestibular information. This finding is consistent with previous studies describing postural adaptations associated with visual deprivation during static balance tasks (Akinoğlu & Kocahan, 2018; Gökşen & İnce, 2024).

In line with these sensory reweighting mechanisms, the complementary forest plot analysis showed a point estimate shifted toward positive values in the between-condition contrast, indicating a greater magnitude of pre–post improvement in the WB condition. Although the confidence interval was wide (reflecting interindividual variability and limited precision) the direction of the effect was consistent with the hypothesis that visual restriction through adapted sport practice increases somatosensory and vestibular demands during postural control (Akinoğlu & Kocahan, 2018; Zetterlund et al., 2019). For example, research conducted with athletes with visual impairment has shown that individuals with low vision (B3) perform lower on balance tests with eyes closed than blind athletes (B1), suggesting that residual vision may interfere with the sensory integration required for postural control (Gökşen & İnce, 2024).

Accordingly, the findings in this study are coherent with prior evidence indicating that the complete absence of visual information may foster more efficient somatosensory and vestibular compensatory strategies than those observed in individuals with partial visual impairment. In this context, Juodzbaliene and Muckus (2006) reported that totally blind adolescents exhibited postural control comparable to that of sighted individuals with eyes open, and superior to that of individuals with residual vision. This suggests that residual vision may interfere with the sensory integration required for static balance. Therefore, compensatory strategies may emerge from the specific motor demands inherent to sport practice (Bednarczuk et al., 2019).

One of the most critical contributions of these findings is the insight they provide into visual restriction in individuals with low vision. As noted by Quevedo et al. (2014), knowledge of functional classifications and the impact of residual vision is essential for teachers. The observation that students with partial vision may display less efficient postural control than their blind peers highlights the pedagogical relevance of blindfold use in PE classes. This tool not only equalizes performance conditions but also, as described by Brian & Haegele (2014), allows students without disabilities to "*experience the barriers that students with visual impairments must overcome to participate in activities*" (p. 44), fostering cognitive empathy grounded in the sensory reality of others.

With respect to dynamic balance, the observed changes were moderate. Although dynamic balance has been shown to be influenced by visual status —where individuals without visual impairment typically outperform blind athletes—, it has also been reported that blind athletes who practice goalball once or twice per week demonstrate better dynamic balance than sedentary blind individuals (Aydoğ et al., 2006). In the present study, although no significant global differences were found ($p = .973$), a significant improvement was observed in the WOB condition following the intervention ($p = .045$; $d = 0.31$, *moderate effect*),

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suggesting a positive trend that may depend on longer and more specific training exposure (Bednarczuk et al., 2019).

Although improvement was observed only in the WOB condition, this variation may be explained by the technical demands of the Y Balance Test, which requires highly specific dynamic stability and a greater transfer of acquired skills to elicit significant changes (Plisky et al., 2021; Plisky et al., 2009). Additionally, psychological factors such as fear of falling may limit movement amplitude and confidence during reaching tasks (Erden & Güner, 2018). Consequently, these results should be interpreted in light of the limited duration of the intervention and the absence of a control group, both of which may have constrained the magnitude of observed changes in dynamic balance.

Regarding reaction time, the findings of the present study were more moderate than those reported by Ince (2021), which may be attributed to factors such as the characteristics of the sample, age range, training intensity, and number of sessions. The literature indicates that age influences responsiveness to training stimuli, with younger participants being more susceptible to improvement (Hardwick et al., 2022). Moreover, longer training programs with higher session frequency are associated with greater improvements in reaction time (Balkó et al., 2017), and training specificity and experience are key determinants of these adaptations (Luo et al., 2025). Overall, these findings extend the evidence supporting the use of adapted sport in PE by demonstrating that systematic practice under visual restriction can induce measurable postural adaptations in students without visual impairment, thus extending beyond its traditionally sensitization-focused role.

In summary, the goalball-based didactic unit demonstrated a positive impact primarily on static balance, confirming that participation in this adapted sport stimulates proprioception and strengthens postural control in school-aged students without visual impairment. This finding aligns with previous research highlighting the importance of non-visual stimuli in postural stability (Akinoğlu & Kocahan, 2018; Zetterlund et al., 2019). Although changes in dynamic balance and reaction time were smaller, these results suggest that longer or more targeted programs may further enhance these capacities (Bednarczuk et al., 2019; Ince, 2021; Plisky et al., 2021). Taken together, the present study provides evidence of the pedagogical value of goalball, not only for its motor benefits but also for its inclusive potential to promote body awareness and sensitivity toward diversity within school contexts.

Limitations

This study has several limitations that should be acknowledged. First, differences in the physical spaces where pre- and post-test assessments were conducted may have influenced student performance due to uncontrolled environmental factors. For example, sessions were conducted while sharing the gymnasium with another group, resulting in a constant level of background noise that may have affected the silence required for goalball play and for activities relying on auditory stimuli. Second, the duration of the intervention (8 weeks, 9 sessions) represents another limitation, as longer and more frequent exposure may be necessary to support familiarization and conscious gameplay. Additionally, the absence of a control group limits causal inference regarding the intervention effects.

Future research

Future studies are encouraged to increase sample size, implement longer interventions with higher inter-session frequency, and include a control group to enable more robust comparisons. Furthermore, it would be valuable to explore the impact of this didactic approach in relation to other adapted sports in order to determine the comparative effectiveness of different modalities for developing motor, physical, and cognitive skills in students without visual impairments.

CONCLUSION

The aim of this study was to evaluate the effect of a goalball-based didactic unit on static balance, dynamic balance, and reaction time in secondary school students simulating a visual impairment. In relation to this, it can be concluded that the intervention produced significant improvements in static balance, with large effect sizes in both conditions, but with a greater positive trend in the WB condition. Dynamic balance showed small increases, reaching statistical significance only in the WOB condition, whereas reaction time did not exhibit significant changes. Therefore, the Goalball-based didactic unit appears to be an effective pedagogical strategy for strengthening static postural control and proprioceptive stimulation, even in students without visual impairment, confirming its potential as a valuable instructional resource within PE classes.

AUTHOR CONTRIBUTIONS

CVP: project administration, conceptualization, methodology, data collection, writing-original draft, software, investigation. PR: infrastructure resource management, supervision, investigation. FMH: conceptualization, writing-review, validation. FAR: conceptualization, writing-review, visualization. CLR: methodology, visualization, investigation. KCC: investigation, software, formal analysis, methodology, writing-original draft, editing, supervision.

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AI STATEMENT

Artificial intelligence software was used exclusively for translation and language editing purposes in order to improve the English expression and readability of the text. The scientific content of the manuscript (including the study design, data collection, analysis, interpretation of results, and academic writing) was entirely developed by the authors. No artificial intelligence tools were used to generate the research content, results, or conclusions presented in the manuscript. The authors assume full responsibility for the originality, integrity, and accuracy of the work submitted.

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ORIGINAL ARTICLE

Dance-exercise and dietary habits impact on physical parameters in female college students

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ABSTRACT

This study aimed to compare the physical characteristics, body composition, and dietary preferences of female college students majoring in dance and those from non-dance disciplines, in order to identify potential differences linked to their distinct lifestyles and training backgrounds. This cross-sectional study analysed multiple parameters, including anthropometric measurements (height and BMI), body composition (BFM, VFL, VFA, BAI, WHR, and PBF), and foundational body components (TBW, protein, minerals, SLM, FFM, SMM, and BMR). Dance training history and weekly hours of physical activity were recorded. Dietary preferences were assessed through FFQ, focusing on the consumption of fruits, vegetables, dairy products, beverages, and alcohol. Dance majors were significantly taller (168.75 ± 3.83 cm) than non-dancers (165.03 ± 6.04 cm; p = .0033) and had lower BMI values (19.81 ± 1.69 vs. 21.96 ± 3.66; p = .0029). They also exhibited significantly lower values in fat-related indices compared to their non-dancer counterparts. No significant differences were found in foundational body composition measures between the two groups. Regarding dietary habits, dancers reported a frequent intake of yogurt, fruits, and vegetables, and preferred carbonated drinks, while consuming minimal amounts of alcohol. Non-dancers more commonly drink milk on a weekly basis, as well as a high intake of carbonated beverages, but similarly low alcohol consumption. Female dance majors differed significantly from non-dance majors in terms of height, fat-related indices, and dietary patterns. These discrepancies likely reflect the impact of long-term dance training and associated lifestyle factors on physical and nutritional profiles.

Keywords: Sport medicine, Dance students, Body composition, Dietary habits, Exercise training.

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INTRODUCTION

In contemporary college populations, the interplay among dietary behaviours, body composition (including metrics such as body fat percentage and muscle mass), and overall health has garnered considerable attention (Rosselli et al., 2021; Zhou et al., 2024). Among these people, female undergraduates represent a key demographic whose eating patterns and body composition could offer valuable insights into the general health profile of the student body. However, it is noted that these patterns are not uniform, which are shaped by various factors like academic specialty, daily habits, and cultural food practices (Lees et al., 2017; Robbeson et al., 2015).

Specifically, female students majoring in dance are subject to unique professional demands that usually result in remarkable differences in dietary choices and physical characteristics compared to their non-dance peers. The rigorous training, performance expectations, and aesthetic ideals inherent in dance education necessitate a tailored approach to nutrition and body management (Brown et al., 2020). Consequently, any discrepancies between daily dietary preferences and physiological needs among these students can significantly influence their physical fitness and overall well-being.

Such discrepancies can have profound implications for health, with persistent deviations from normal weight ranges or excessive body fat levels potentially leading to heightened health risks (Ballarin et al., 2021; Leal et al., 2019). Accordingly, a comparative analysis of the dietary habits and body shape indicators of female non-dance undergraduates against those of dance majors not only provides empirical data but also offers insights for developing health education strategies and targeted interventions (Ballarin et al., 2021; Friesen et al., 2011).

This study recruited 35 female dance majors and 35 female non-dance majors. Through administering a Food Frequency Questionnaire (FFQ) (Liu et al., 2022) and employing InBody measurements, we conducted a comprehensive analysis of the participants' dietary habits, seeking to elucidate potential effects of both nutrition and dance-specific training on body composition parameters.

METHODS

Participants

A total of 70 healthy female undergraduate students were recruited through an on-campus online platform. Participants were evenly divided into two groups: 35 dance majors with regular dance training (dancer group) and 35 non-dance majors without formal dance training or established physical activity habits (non-dancer group). Eligibility criteria included the absence of chronic illnesses, metabolic disorders, or recent use of medications that could potentially influence metabolism or body composition.

Food Frequency Questionnaire (FFQ)

Dietary intake over the preceding six months was evaluated using a semi-quantitative FFQ in this study, which was adapted from the NHANES Food Questionnaire (Liu et al., 2022) and modified to reflect local dietary characteristics with several items being revised or excluded. The final version of the FFQ comprised 36 items, organized into six major categories: Dairy Products, Grains and Staple Foods, Vegetables, Fruits, Non-Alcoholic Beverages, and Alcoholic Beverages. Each food item was presented with a standard portion size, with food models provided to assist participants in estimating their typical intake. Participants were requested to report both the frequency and approximate quantity of each food item consumed over the past

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six months. The FFQ was administered by trained personnel to ensure clarity and completeness of the responses.

InBody measurements

Body composition was assessed using the InBody 970 multi-frequency bioelectrical impedance analysis system, which applies high-frequency currents to measure various physiological components.

The assessed parameters included InBody Score, Weight Control, Body Fat Mass (BFM, kg), BFM Control, Visceral Fat Level (VFL), Visceral Fat Area (VFA, cm^2), Fat Mass Index (FMI), Body Adiposity Index (BAI), Obesity Degree, Skeletal Muscle Mass (SMM, kg), SMM/Weight ratio (SMM/WT), Soft Lean Mass (SLM, kg), Fat-Free Mass (FFM, kg), Total Body Water (TBW, L), TBW/WT, protein (kg), minerals (kg), Basal Metabolic Rate (BMR, kcal/day), Skeletal Muscle Mass–Visceral Fat Area Ratio (SVR), segmental lean mass and fat mass in arms, legs, and trunk, as well as circumference measures (arm, neck, chest, abdomen, waist, hip, thigh), and standardized T- and Z-scores of BMI, SMM/WT, FMI, PBF, VFA, TBW/WT, and WHR. All measurements were conducted under standardized conditions. Participants were instructed to fast for at least two hours and to refrain from vigorous physical activity for 12 hours prior to the measurement session. These precautions were taken to enhance measurement accuracy and reliability.

Training records

Participants in the dancer group completed an additional questionnaire to document their training background, including the total number of years of formal dance experience and the average weekly hours dedicated to dance training and other forms of physical exercise over the past three months.

Correlation analysis

Pearson correlation analysis was performed to examine the association between dance training and InBody parameters. Independent variables include age, hours of sleep per night, years of dance training, weekly hours of dance training, weekly hours of non-dance physical activity, and total training hours. Dependent variables covered the parameters of InBody, such as InBody Score, SMM/WT, BFM, PBF, VFA, FMI, SVR, segmental lean and fat distribution, circumference measures, and relevant T- and Z-scores, and so on. This allowed a comprehensive assessment of how different aspects of training are associated with body composition and proportional indices.

Statistical analysis

Data analysis was performed using independent samples *t*-tests to compare physical characteristics, body composition, and dietary patterns between the two groups. A *p*-value of less than .05 was considered statistically significant. All data are presented as mean ± standard deviation unless otherwise specified.

RESULTS

Basic characteristics

As shown in Table 1, female dance students had a significantly greater height compared to non-dance students (168.75 ± 3.83 cm vs. 165.03 ± 6.04 cm, $p = .0033$) and a lower BMI (19.81 ± 1.69 vs. 21.96 ± 3.66, $p = .0029$), these baseline differences were consistent with the inherent anthropometric characteristics of dance-major students. Regarding weight distribution, 88.24% of female dance students had a normal weight, 11.76% were underweight, with 82.35% categorized as moderate BMI and 17.65% as low BMI. In contrast, 14.29% of non-dance female students were underweight, 60.00% had a normal weight, and 25.71% were overweight, with 62.86% having a moderate BMI, 20.00% low BMI, and 17.14% high BMI (Fig. 1). The

dancer students report a mean dance training duration of 8.80 ± 4.08 years, on average, dancer students devote 16.76 ± 12.51 hours per week to dance classes or self-directed practice, reflecting considerable variability in training commitment (Table 2). Some students invest substantial weekly hours in professional practice, whereas others may train less frequently. Moreover, the mean weekly time spent on non-dance athletic activities is 2.26 ± 2.41 hours, indicating that although these students primarily focus on dance training, they also engage in other forms of physical exercise to some degree.

Table 1. Basic characteristics of female college students majoring in dance and non-dance (Mean ± SD).

	Dancer (n = 35)	**non-Dancer (n = 35)**	***p*-value**
Age (year)	19.34 ± 0.83	19.60 ± 0.80	.1967
Height (cm)	168.75 ± 3.83	165.03 ± 6.04	.0033
Current weight (kg)	56.38 ± 5.03	60.04 ± 11.72	.0969
BMI (kg/m^2)	19.81 ± 1.69	21.96 ± 3.66	.0029

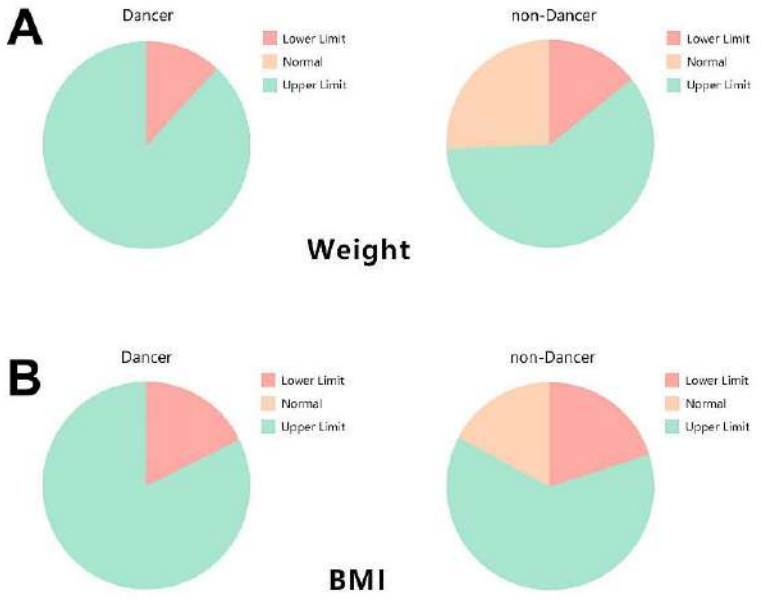


Figure 1. Comparison of weight (A) and BMI (B) distribution in dancer and non-dancer.

Table 2. Training records of dance students.

	Mean(n = 34*)	**SD**
Dance training(year)	8.80	4.08
Dance classes or self-training (hours/week)	16.76	12.51
non-Dance athletic training (hours/week)	2.26	2.41

*Note. *: One dancer student InBody data and training records were missing, resulting in n = 34.*

Human body characteristic

As shown in Table 3, Dancers had a significantly greater height, measuring 168.75 ± 3.83 cm compared to 165.03 ± 6.04 cm in non-dancers (p = .0033). However, there was no statistical difference in body weight, with dancers averaging 56.38 ± 5.03 kg and non-dancers averaging 60.04 ± 11.72 kg (p = .0982). Correspondingly, the BMI was notably lower in dancers at 19.81 ± 1.69, compared to 21.96 ± 3.66 in non-dancers (p = .0027), indicating that dancers tend to have a leaner physique.

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Regarding overall body composition, dancers achieved a higher InBody Score of 73.24 ± 3.72, versus 70.06 ± 4.05 for non-dancers (p = .0012). Additionally, dancers exhibited significantly better Weight Control scores (3.62 ± 4.92 vs. –1.66 ± 8.44, p = .0023) and BFM Control (-1.00 ± 2.62 vs. –5.93 ± 5.50, p < .0001). Although there were no noteworthy differences in BMR, protein, minerals, FFM, SMM, or SLM, the SMM/WT was considerably higher in dancers, measuring 39.99 ± 1.93 compared to 36.93 ± 2.49 in non-dancers (p < .0001). This underscores the greater proportion of lean mass in dancers relative to their body weight.

Segmental analysis demonstrated clear advantages in the dancer group. The lean mass percentages of both legs were significantly higher in dancers, with values of 108.55 ± 5.21% for the right leg compared to 99.14 ± 7.91% for the control group (p < .0001), and 108.31 ± 5.23% for the left leg versus 99.10 ± 7.82% (p < .0001). In contrast, fat mass percentages were consistently lower across all body regions. For example, dancers exhibited significantly lower body fat mass percentages in the arms (69.56 ± 12.83% for the right arm compared to 98.61 ± 29.12% for the control group, p < .0001; 70.15 ± 12.37% for the left arm vs. 98.23 ± 28.71%, p < .0001), trunk (120.34 ± 24.30% vs. 175.35 ± 58.66%, p < .0001), and legs (83.08 ± 11.42% for the right leg vs. 98.40 ± 18.52% for the control, p = .0042; 83.21 ± 11.28% for the left leg vs. 98.49 ± 18.62%, p = .0045). These findings reinforce that dancer exhibit significantly reduced segmental adiposity and improved lean mass distribution.

Additionally, dancers showed consistently lower indices of central adiposity. Their VFL was significantly lower at 5.47 ± 1.24 compared to 8.49 ± 3.33 in the control group (p < .0001). The visceral fat area was also lower in dancers, measuring 59.46 ± 11.45 cm² compared to 89.28 ± 33.33 cm² in the control group (p < .0001). PBF was lower as well, with values of 26.16 ± 3.23% versus 31.65 ± 4.94% (p < .0001). Derived indices, including FMI (5.20 ± 0.92 vs. 7.09 ± 2.09, p < .0001), BAI (23.50 ± 1.84 vs. 25.77 ± 2.99, p = .0003), Obesity Degree (94.21 ± 8.11 vs. 104.54 ± 17.40, p = .0025), and SVR (0.39 ± 0.07 vs. 0.27 ± 0.08, p < .0001), all indicate better body composition in dancers.

In terms of TBW content, there was no significant difference in absolute litres between the groups (30.4 ± 2.61 vs. 29.74 ± 4.74, p = .482). However, the TBW/WT was significantly higher in dancers (53.98 ± 2.38% vs. 49.98 ± 3.67%, p < .0001), indicating a more favourable body water proportion relative to body weight. Dancers also exhibited greater segmental TBW in both legs, with the right leg showing 5.46 ± 0.46 litres compared to 5.01 ± 0.84 litres in the other group (p = .0079) and the left leg showing 5.45 ± 0.47 litres compared to 5.01 ± 0.85 litres (p = .0101). Differences in TBW for the arms and trunk were not significant: right arm (1.43 ± 0.20 vs. 1.47 ± 0.35, p = .4976), left arm (1.42 ± 0.19 vs. 1.46 ± 0.35, p = .5030), and trunk (13.84 ± 1.13 vs. 14.00 ± 2.19, p = .6966). Additionally, T- and Z-scores for TBW/WT were also higher in dancers, with T-scores of 0.67 ± 0.55 compared to −0.26 ± 0.86 (p < .0001) and Z-scores of 0.23 ± 0.45 compared to −0.15 ± 0.65 (p = .0057).

Circumference measurements further supported the finding of reduced central adiposity in the dancer group. Neck circumference was lower in dancers (30.97 ± 1.22 cm vs. 32.38 ± 2.44 cm, p = .0035), as was chest circumference (83.02 ± 3.29 cm vs. 86.96 ± 7.23 cm, p = .0051), and abdominal/waist circumference (74.19 ± 3.64 cm vs. 81.84 ± 9.39 cm, p < .0001). However, hip circumference did not show any significant difference. This is consistent with the significantly lower WHR (0.82 ± 0.02 vs. 0.88 ± 0.05, p < .0001) and waist-to-height ratio (0.44 ± 0.02 vs. 0.50 ± 0.05, p < .0001) observed in the dancer group.

Finally, standardized T- and Z-scores confirmed these findings. Dancers consistently displayed lower scores related to adiposity (e.g., BMI, FMI, PBF, VFA, and WHR) and higher scores related to lean mass (e.g., SMM/WT). These consistent differences across absolute values, segmental distribution, circumference

measures, and standardized indices collectively demonstrate that female dance students maintain a significantly leaner and more favourable body composition profile compared to their non-dance counterparts.

Table 3 Human body characteristic parameters in dancer and non-dancer (Mean ± SD).

Item	Dancer (n = 34)	non-Dancer (n = 34)	*p*-value	*q*-value
Height	168.75 ± 3.83	165.03 ± 6.04	.0033	.0123
Weight	56.38 ± 5.03	60.04 ± 11.72	.0982	.0107
BMI	19.81 ± 1.69	21.96 ± 3.66	.0027	.0142
InBody Score	73.24 ± 3.72	70.06 ± 4.05	.0012	.0098
Weight Control	3.62 ± 4.92	-1.66 ± 8.44	.0023	.0123
BFM Control	-1 ± 2.62	-5.93 ± 5.5	<.0001	.0017
BMR (Basal Metabolic Rate)	1268.26 ± 77.44	1248.71 ± 140.88	.4793	.2278
Protein	8.12 ± 0.72	7.96 ± 1.29	.5336	.2387
Minerals	3.07 ± 0.27	2.97 ± 0.5	.3226	.2219
FFM (Fat Free Mass)	41.59 ± 3.58	40.68 ± 6.52	.4779	.2289
SMM (Skeletal Muscle Mass)	22.54 ± 2.15	22.04 ± 3.9	.5172	.2320
SMM/WT	39.99 ± 1.93	36.93 ± 2.49	<.0001	.0001
SLM (Soft Lean Mass)	39.03 ± 3.37	38.19 ± 6.12	.4852	.2278
Lean Mass of Right Arm	1.83 ± 0.25	1.89 ± 0.45	.4891	.8913
Lean Mass (%) of Right Arm	89.44 ± 7.21	91.17 ± 10.56	.4283	.9534
Lean Mass of Left Arm	1.82 ± 0.24	1.88 ± 0.46	.5055	.8855
Lean Mass (%) of Left Arm	88.75 ± 6.76	90.32 ± 10.98	.4803	.9901
Lean Mass of Trunk	17.74 ± 1.46	17.99 ± 2.81	.6571	.9893
Lean Mass (%) of Trunk	95.6 ± 3.88	96.56 ± 4.6	.3541	.7619
Lean Mass of Right Leg	7.02 ± 0.6	6.44 ± 1.09	.0081	.0107
Lean Mass (%) of Right Leg	108.55 ± 5.21	99.14 ± 7.91	<.0001	.0001
Lean Mass of Left Leg	7 ± 0.6	6.44 ± 1.09	.0102	.0107
Lean Mass (%) of Left Leg	108.31 ± 5.23	99.1 ± 7.82	<.0001	.0001
PBF (Percent Body Fat)	26.16 ± 3.23	31.65 ± 4.94	<.0001	.0001
BFM (Body Fat Mass)	14.8 ± 2.57	19.37 ± 6.03	.0001	.0076
BFM% of Whole Body	111.34 ± 28.78	171.51 ± 66.49	<.0001	.0014
BFM of Right Arm	0.98 ± 0.19	1.39 ± 0.51	<.0001	.0022
BFM% of Right Arm	97.31 ± 19.24	144.47 ± 50.27	<.0001	.0006
BFM of Left Arm	1 ± 0.19	1.41 ± 0.5	<.0001	.0019
BFM% of Left Arm	98.78 ± 19.45	146.82 ± 50.3	<.0001	.0006
BFM of Trunk	6.77 ± 1.36	9.48 ± 3.34	<.0001	.0037
BFM% of Trunk	120.34 ± 24.3	175.35 ± 58.66	<.0001	.0013
BFM of Right Leg	2.55 ± 0.42	3.03 ± 0.8	.0032	.0144
BFM% of Right Leg	99.74 ± 16.67	123.16 ± 30.86	.0002	.0077
BFM of Left Leg	2.56 ± 0.42	3.02 ± 0.8	.0038	.0164
BFM% of Left Leg	99.75 ± 16.7	123.15 ± 31.04	.0002	.0087
Arms/Legs Fat	7.08 ± 1.2	8.86 ± 2.6	.0005	.0107
VFL (Visceral Fat)	5.47 ± 1.24	8.49 ± 3.33	<.0001	.0006
VFA (Visceral Fat Area)	59.46 ± 11.45	89.28 ± 33.33	<.0001	.0008
FMI (Fat Mass Index)	5.2 ± 0.92	7.09 ± 2.09	<.0001	.0014
BAI (Body Adiposity Index)	23.5 ± 1.84	25.77 ± 2.99	.0003	.0049
Obesity Degree	94.21 ± 8.11	104.54 ± 17.4	.0025	.0124
SVR(Skeletal Muscle Mass-Visceral Fat Area Ratio)	0.39 ± 0.07	0.27 ± 0.08	<.0001	<.0001
TBW (Total Body Water)	30.4 ± 2.61	29.74 ± 4.74	.482	.2278
TBW/WT	53.98 ± 2.38	49.98 ± 3.67	<.0001	.0001
TBW of Right Arm	1.43 ± 0.2	1.47 ± 0.35	.4976	.8970
TBW of Left Arm	1.42 ± 0.19	1.46 ± 0.35	.503	.8745
TBW of Trunk	13.84 ± 1.13	14 ± 2.19	.6966	1.0000
TBW of Right Leg	5.46 ± 0.46	5.01 ± 0.84	.0079	.0107
TBW of Left Leg	5.45 ± 0.47	5.01 ± 0.85	.0101	.0107

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AC (Arm Circumference)	26.16 ± 1.36	27.85 ± 3.05	.0043	.0141
AMC (Arm Muscle Circumference)	22.71 ± 1.06	23.53 ± 2.19	.0512	.0894
Measured Circumference of Neck	30.97 ± 1.22	32.38 ± 2.44	.0035	.0107
Measured Circumference of Chest	83.02 ± 3.29	86.96 ± 7.23	.0051	.0180
Measured Circumference of Abdomen	74.19 ± 3.64	81.84 ± 9.39	<.0001	.0014
WC (Waist Circumference)	74.19 ± 3.64	81.84 ± 9.39	<.0001	.0014
Measured Circumference of Hip	90.91 ± 2.89	92.73 ± 6.5	.1398	.3629
Measured Circumference of Right Arm	26.28 ± 1.39	28.04 ± 3.05	.0031	.0128
Measured Circumference of Left Arm	26.16 ± 1.36	27.85 ± 3.05	.0043	.0141
Measured Circumference of Right Thigh	49.75 ± 2.27	50.14 ± 4.5	.655	.9538
Measured Circumference of Left Thigh	49.8 ± 2.26	50.14 ± 4.56	.702	.9053
WHR (Waist-Hip Ratio)	0.82 ± 0.02	0.88 ± 0.05	<.0001	<.0001
WHtR (Waist-Height Ratio)	0.44 ± 0.02	0.5 ± 0.05	<.0001	.0001
ABSI (A Body Shaped Index)	0.08 ± 0	0.08 ± 0	<.0001	.0001
Conicity Index	1.18 ± 0.03	1.25 ± 0.05	<.0001	<.0001
BMI_T score	-0.71 ± 0.62	0.09 ± 1.36	.0026	.0146
SMI(SMM/Wt) T score	0.71 ± 0.61	-0.24 ± 0.78	<.0001	.0001
SMI(SMM/Wt) Z score	0.25 ± 0.5	-0.16 ± 0.6	.0032	.0350
FMI_T score	-0.72 ± 0.46	0.21 ± 1.04	<.0001	.0017
PBF_T score	-0.7 ± 0.56	0.25 ± 0.84	<.0001	.0001
VFA_T score	-0.54 ± 0.4	0.49 ± 1.15	<.0001	.0006
VFA_Z score	-0.2 ± 0.35	0.3 ± 0.93	.0044	.0472
TBW/WT_T Score	0.67 ± 0.55	-0.26 ± 0.86	<.0001	.0001
TBW/WT_Z Score	0.23 ± 0.45	-0.15 ± 0.65	.0057	.0292
WHR_T score	-0.5 ± 0.52	0.86 ± 1.01	<.0001	<.0001
WHR_Z score	-0.18 ± 0.34	0.46 ± 0.83	.0001	.0031

Food frequency analysis

Based on the six-month FFQ (Table 4), dancers more frequently reported weekly yogurt (51% vs 37%) and melon (29% vs 20%), whereas non-dancers more often consumed milk (71% vs 32%), bananas (21% vs 12%), onions (46% vs 24%), and cucumbers (32% vs 0%). Both groups relied on rice as a staple (97% vs 94%) and toast/bread (70% vs 64%), with oatmeal uncommon (≤6%). Cooked greens were prevalent (77% vs 88%), while raw greens were less frequent among dancers (12% vs 34%); broccoli and cauliflower were similar (broccoli: 40% vs 48%, cauliflower: 29% vs 32%), with dancers reporting more corn (40% vs 29%). Carbonated beverages were reported weekly by a notable minority in both cohorts but were higher in non-dancers (43% vs 35%); fruit juices were generally infrequent (each ≤24%). Alcohol intake was low overall (beer 3% vs 6%; wine 0% vs 6%; liquor 0% in both). Synthesizing across categories, dancers tended toward fermented dairy and selected fruits/vegetables perceived as lighter, alongside markedly lower frequencies of certain raw/pungent items and slightly lower carbonated-drink prevalence; non-dancers showed higher milk, banana, and carbonated-drink frequencies.

Table 4. Food frequency survey in dancer and non-dancer.

Items	**Dancer (35)**		**non-Dancer (35)**	
	≥1 time/week	<1 time/week	≥1 time/week	<1 time/week
Dairy products				
Yogurt	51%	49%	37%	62%
Milk	32%	69%	71%	28%
Grains and staple foods				
Oatmeal	3%	98%	6%	94%
Rice	97%	3%	94%	6%
Toast (bread)	70%	32%	64%	38%

Vegetables				
Cooked green	77%	24%	88%	12%
Raw green	12%	88%	34%	65%
Carrots	24%	76%	24%	77%
String beans	15%	86%	21%	79%
Peas	12%	89%	20%	81%
Corn	40%	60%	29%	71%
Broccoli	40%	60%	48%	52%
Cauliflower	29%	72%	32%	68%
Onions	24%	77%	46%	54%
Cucumbers	0%	80%	32%	68%
Tomatoes	23%	77%	18%	83%
Summer squash	9%	92%	9%	92%
Fruits				
Apple	18%	83%	21%	80%
Pear	12%	88%	12%	88%
Banana	12%	88%	21%	80%
Pineapple	12%	88%	9%	91%
Peach	12%	88%	12%	89%
Grape	9%	91%	12%	89%
Melon	29%	71%	20%	80%
Strawberry	20%	80%	20%	80%
Orange	29%	72%	35%	65%
Grapefruit	6%	94%	6%	94%
Non-alcoholic beverages				
Tomato juice	6%	94%	9%	91%
Orange juice	20%	80%	24%	77%
Apple juice	9%	91%	12%	88%
Grape juice	6%	94%	12%	89%
Meal replacement drink	6%	95%	6%	94%
Carbonated beverage	35%	66%	43%	57%
Alcoholic beverages				
Beer	3%	98%	6%	94%
Wine	0%	100%	6%	95%
Liquor	0%	100%	0%	100%

Effects of dance training on body composition

Within the Dancer group, Pearson correlation analysis (Fig. 2) showed that Age was significantly positively associated with Lean Mass (%) of Left Arm ($p < .05$), significantly negatively associated with WHR Z score ($p < .05$), and highly positively associated with SMM/WT Z Score and TBW/WT Z Score (both $p < .001$). Age also demonstrated a highly significant positive association with VFA Z score ($p < .001$). Moreover, Years of dance training was significantly positively correlated with WHR, WHtR, Measured Circumference of Right Arm, Measured Circumference of Chest, Measured Circumference of Abdomen, WC, and VFL ($p < .05$). The results suggest that within dancer group, higher age is linked to proportional gains in muscle and body-water indices but also to greater visceral adiposity, and that longer training duration relates positively to several indices of central adiposity and upper-torso/upper-limb circumferences.

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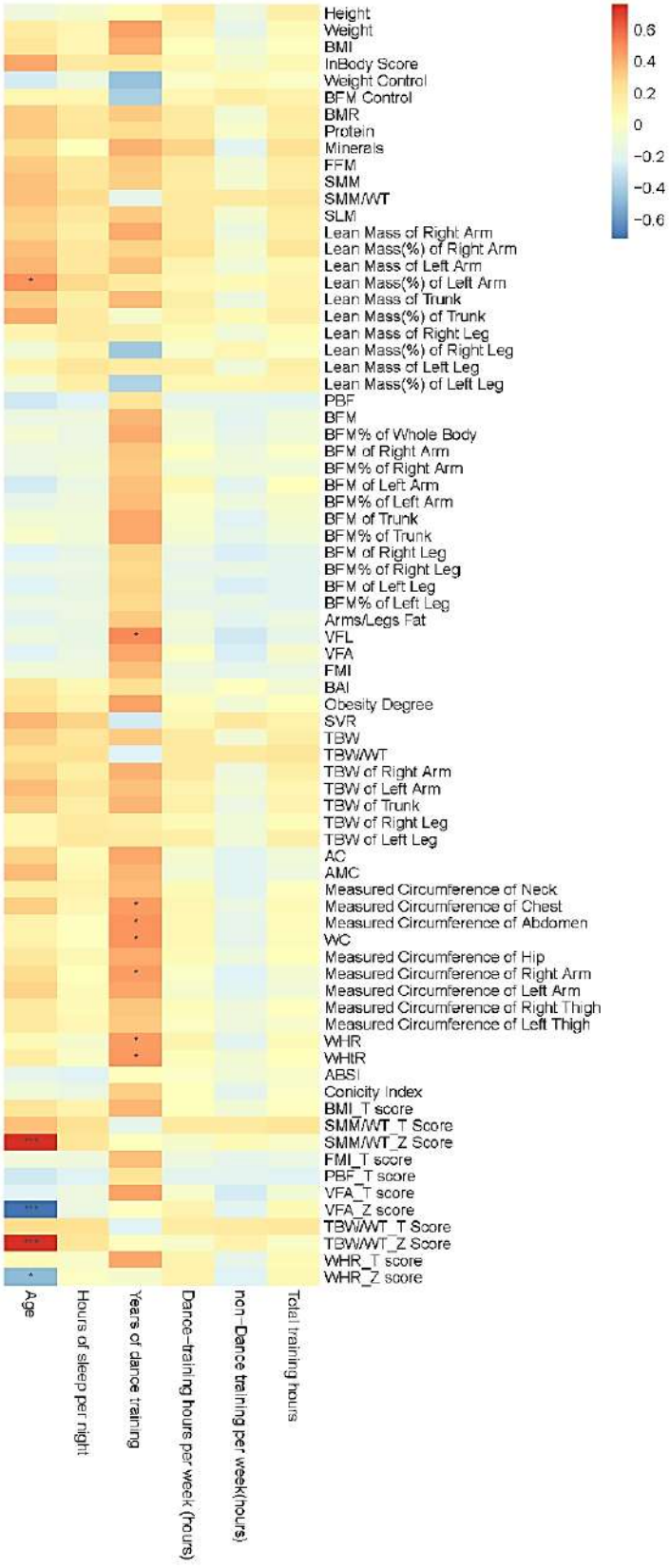


Figure 2. Correlation analysis of training duration of dancer students and InBody parameters.

DISCUSSION AND CONCLUSIONS

Dance training influences body composition in various ways. It includes both aerobic and anaerobic elements, which increase metabolic demands and help maintain a lean physique (Brooks et al., 2023; Chaikali et al., 2023; Lu et al., 2020). This study found that dancers had lower levels of body fat and more favourable fat distribution compared to non-dancers, highlighting how rigorous practice can improve body composition. Although dance students showed significant differences in fat-related measures, they did not differ substantially from their non-dancing counterparts in terms of total body water, protein content, mineral density, skeletal muscle mass, or basal metabolic rate (Lu et al., 2020). One possible explanation for this is that the increased intensity of their training is often balanced by a corresponding dietary intake, which helps preserve overall lean tissue (Challis et al., 2020; Deng et al., 2024; Duarte et al., 2023; Gammone & D'Orazio, 2020). Additionally, fundamental factors like skeletal mass tend to remain relatively stable after skeletal maturity is reached, indicating a point of balance that dance training may not significantly alter (Kim et al., 2019; Lambert et al., 2020).

On average, participants in dance majors had 8.80 years of specialized dance experience and practiced about 16.76 hours per week, demonstrating a high level of commitment. Extended and intense training regimens can result in significant improvements in musculoskeletal function and cardiorespiratory efficiency, which may help explain their advantages in managing body fat and maintaining physical form (Leal et al., 2019; Lim et al., 2015; Milanese et al., 2022; Wang et al., 2023). The results of this study revealed that dancers often consumed yogurt, a variety of fruits (such as melon, orange, strawberry, and apple), and certain cooked vegetables. This may indicate a preference for foods that are considered light or nutrient-rich. However, their inclination toward carbonated beverages should be approached with caution due to potential metabolic implications. In contrast, non-dancers preferred milk, bananas, onions, and other produce, which might reflect their usual choices or sociocultural influences. These differing preferences emphasize how lifestyle and personal taste can influence dietary habits and, consequently, energy balance.

For dancers, maintaining low body fat can enhance aesthetics and performance, but it also poses the risk of inadequate energy availability if nutritional needs are not met. Non-dancers with higher body fat face different concerns, particularly increased risks for cardiometabolic disorders. Preventive strategies for both groups should include balanced meal plans, mindful hydration, and personalized workout prescriptions. Monitoring energy intake and expenditure is crucial for dancers to protect their bone density and hormonal health, while non-dancers may benefit from gradual exercise regimens and reduced consumption of sugary beverages (Saenz et al., 2024).

Our study compares the dietary behaviours, body composition, and training durations of dance students with non-dance students. The findings provide valuable guidance for promoting nutritional well-being among the wider student population and offer critical insights into optimizing training management and nutrition support for dance students. Future research could adopt longitudinal or interventional designs to systematically track how dance training affects body composition, dietary habits, and health outcomes over extended periods. Such studies could inform evidence-based strategies that encourage both dancers and non-dancers to adopt healthier lifestyles.

AUTHOR CONTRIBUTIONS

Caifang Qiu conceived and designed the study, drafted the manuscript, conducted data collection, and performed the data analysis. Juanmin Gao was responsible for revising the thesis and providing research funding.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

AVAILABILITY OF DATA AND MATERIALS

Data will be available by the author upon reasonable request.

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ORIGINAL ARTICLE

Effects of mini-trampoline exercise on neck and knee muscle strength, range of motion, and health-related fitness in sedentary adults

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ABSTRACT

Sedentary behaviour is increasingly prevalent among young adults and is associated with poorer musculoskeletal health and physical function. Mini-trampoline exercise is low-impact, but its effects on neck and knee function and cardiac autonomic modulation in sedentary adults remain unclear. This study examined the effects of an eight-week mini-trampoline programme. Twenty sedentary adults were randomised to trampoline training or control. The training group completed supervised sessions three times per week for eight weeks; controls maintained usual activities. Outcomes pre/post included knee muscle strength (primary outcome) and neck strength, cervical and knee range of motion, pain, dynamic balance (Star Excursion Balance Test (SEBT)), and heart rate variability (HRV). Neck strength and pain were significantly better than controls, whereas knee strength increased within the training group without a significant between-group difference. Selected measures of knee and cervical range of motion and selected SEBT outcomes favoured training. HRV indices showed favourable between-group differences: root mean square of successive differences (RMSSD), standard deviation of normal-to-normal intervals (SDNN), and high-frequency power (HF) increased and the low-frequency/high-frequency ratio (LF/HF) decreased. An eight-week mini-trampoline exercise programme was associated with improvements in neck strength, balance, pain, and cardiac autonomic modulation in sedentary adults.

Keywords: Sport medicine, Physical inactivity, Rebound exercise, Cervical musculature, Joint mobility, Heart rate variability, Dynamic balance.

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INTRODUCTION

Modern technology has reshaped daily routines, with many adults spending prolonged periods sitting at work, at home, and during transportation. Sedentary behaviour (SB), commonly defined as any waking behaviour with an energy expenditure of ≤1.5 metabolic equivalents (METs) performed in a sitting, reclining, or lying posture (Mansoubi et al., 2015), is now highly prevalent worldwide (Park et al., 2020). A twenty-country study reported that adults aged 18–65 typically sat for 3–8 h/day (median 5 h/day), and 25% sat for ≥8 h/day (Bauman et al., 2011). Sitting for ≥7.5 h/day has been used to indicate a high level of SB (Goyal & Rakhra, 2024), with younger adults tending to report longer sitting times than those aged ≥40 (Bauman et al., 2011).

A growing body of evidence has identified prolonged SB as a major risk factor for all-cause mortality and a wide range of chronic diseases, including cardiovascular disease, type 2 diabetes, hypertension, and several types of cancer (Shibata et al., 2025). Consequently, SB has emerged as a critical public health concern. In response, the World Health Organization has emphasised the importance of reducing sedentary time and increasing physical activity across the lifespan, highlighting the urgent need for feasible and effective interventions targeting the sedentary population (Organization, 2020).

Beyond metabolic and cardiovascular consequences, SB is increasingly recognised as a contributor to musculoskeletal dysfunction. Systematic reviews have shown that prolonged sitting is associated with a higher incidence of musculoskeletal pain, reduced muscle strength, and impaired joint function, particularly affecting the cervical spine and lower extremities (Dzakpasu et al., 2021). Office workers and individuals with prolonged screen exposure report substantially higher prevalences of neck pain, with annual estimates ranging from 42% to 63% (Guduru et al., 2022). Similarly, prolonged sitting has been linked to knee pain, joint stiffness, and an increased risk of knee osteoarthritis (Ehsani et al., 2017). Notably, recent research has demonstrated a strong association between prolonged sitting behaviour and knee osteoarthritis (Ma et al., 2024). Mechanistically, extended sitting may increase intra-articular knee pressure and contribute to muscle atrophy and joint stiffness (Lee et al., 2015).

Exercise-based interventions are widely regarded as a cornerstone strategy for mitigating the adverse effects of SB. Evidence from systematic reviews suggests that regular physical activity can improve musculoskeletal function, reduce pain, and enhance physical performance in sedentary adults (Bull et al., 2020). However, identifying exercise modalities that are safe, engaging, and feasible for individuals with prolonged sitting habits remains challenging.

Among various exercise modalities, trampoline-based exercise has gained increasing attention as a low-impact and accessible form of physical activity. Previous studies have shown that trampoline or rebound exercise can improve cardiorespiratory fitness, enhance balance and motor performance, increase bone density, and promote psychological well-being (Brea-Fernández et al., 2023; Kong et al., 2018; Posch et al., 2019; Schöffl et al., 2021). A recent narrative review further suggests that rebound exercise provides repetitive elastic loading and dynamic postural challenges, which may stimulate neuromuscular activation while minimising joint impact, making it particularly suitable for individuals with limited exercise tolerance (Okemuo et al., 2023).

Mini-trampoline exercise represents a structured, moderately intense form of rebound exercise that may be especially appropriate for sedentary populations (Iannaccone et al., 2020). Despite its potential benefits, existing research has predominantly focused on balance, lower-limb performance, and cardiovascular outcomes, whereas the effects of mini-trampoline exercise on cervical and knee musculoskeletal function in

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sedentary adults remain largely unexplored. Moreover, high-quality randomised controlled trials specifically addressing these outcomes are scarce.

Therefore, the objective of this randomised controlled trial is to investigate the effects of an eight-week mini-trampoline exercise programme on musculoskeletal and physical fitness outcomes in sedentary adults, with particular focus on neck and knee muscle strength, as well as the knee and cervical joint range of motion.

MATERIALS AND METHODS

Participants

This study was designed as a pilot randomised controlled trial to investigate the preliminary effects and feasibility of an eight-week mini-trampoline exercise programme in sedentary adults. Participants were recruited through announcements posted on the official platform of Heilongjiang Institute of Technology and included sedentary adults aged 18–35 years. Sedentary behaviour was defined as spending at least six hours per day engaged in sedentary activities (e.g., sitting during work, study, screen use, or transportation) during the previous week, assessed using self-reported daily activity records. Inclusion criteria were: aged between 18 and 35 years; sedentary time ≥6 h/day; and no regular participation in structured aerobic or trampoline-related exercise during the previous three months. Exclusion criteria comprised: recent participation in trampoline exercise within the last week; the presence of cardiovascular, respiratory, neurological, or other severe systemic diseases; pregnancy or breastfeeding; a current diagnosis of severe psychiatric disorders; and the inability to commit to at least three training sessions per week. As this was a pilot trial, no formal a priori sample size calculation was performed, and a total of 20 participants (10 per group) was considered sufficient to assess feasibility, refine measurement procedures, and estimate preliminary effect sizes for future large-scale randomised controlled trials. Participants were randomly allocated in a 1:1 ratio to either the trampoline or control group using a computer-generated random sequence prepared by an independent researcher not involved in recruitment or outcome assessment, with group allocation concealed using sealed, opaque envelopes opened only after completion of baseline assessments. Due to the nature of the intervention, the blinding of participants and exercise instructors was not feasible; however, outcome assessors and data analysts were blinded to group allocation throughout data collection and analysis. The participant recruitment and allocation process is shown in Figure 1.

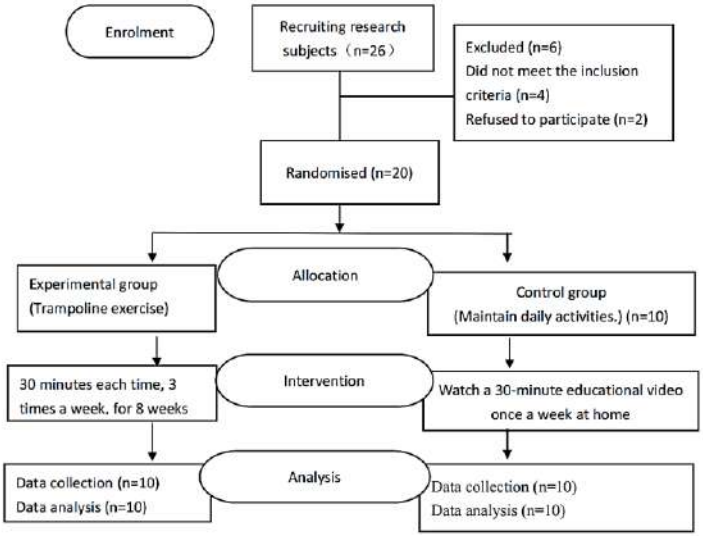


Figure 1. Participant recruitment flowchart.

Measures

The primary outcome of this pilot trial was knee muscle strength. Secondary outcomes included neck muscle strength, joint range of motion, pain intensity, dynamic balance, body composition, flexibility, knee cartilage thickness, handgrip strength, and heart rate variability (HRV). All outcome measures were assessed at the baseline and repeated after the eight-week intervention period. All measurements were conducted by the same trained assessor, who received standardised training and was blinded to group allocation, following standardised procedures in a climate-controlled laboratory maintained at 26 °C. Participants were instructed to rest in a seated position for 10 minutes before baseline assessment.

HRV was assessed using short-term recordings obtained during 3–5 minutes of seated rest, in accordance with established recommendations for resting HRV assessment (Electrophysiology, 1996). RR intervals were recorded using a Polar H10 heart rate sensor chest strap, which has been previously validated for accurate and reliable RR interval acquisition in HRV analysis (Schaffarczyk et al., 2022). Neck flexor and extensor muscle strength was measured during maximal voluntary isometric contractions using a handheld dynamometer (Nscing ES-SH-II, Germany) (Selistre et al., 2021). In contrast, knee muscle strength was assessed using an electronic dynamometer (BCS-400, Beijing Huafu Technology Co., Ltd., China), previously used in studies assessing lower-limb muscle strength using dynamometry (Najiah et al., 2021). Three trials were performed for each muscle strength measurement. The highest value was recorded for analysis.

Cervical range of motion (ROM), including flexion, extension, left and right rotation, and left and right lateral flexion, was assessed using the WE-CAP device, which has demonstrated high reliability and validity for cervical ROM measurement (ICC = 0.89–0.98) (Panngooluema & Eungpinichpong, 2021). Participants were seated upright and performed active movements to the maximum pain-free range; each movement was measured three times, and the mean value was used for analysis. Knee joint ROM, including flexion and extension, was measured using a standard goniometer (Takei 12–1412) following standardised goniometric procedures, with three repetitions recorded for each movement and the mean value used for statistical analysis (Norkin & White, 2016).

Health-related physical fitness was evaluated using standardised field tests. Handgrip strength was assessed using a grip strength dynamometer (GRIP-D, Takei, Japan), with three trials performed for each hand and the maximum value recorded for analysis. Pain intensity was evaluated using a 100-mm visual analogue scale (VAS), and scores were converted to a 0–10 scale for statistical analysis. Dynamic balance was assessed using the Star Excursion Balance Test (SEBT), which has demonstrated good reliability and validity for assessing dynamic postural control (Gribble et al., 2012). Flexibility was assessed using the sit-and-reach test, with the best value from three trials used for analysis. Body composition, including skeletal muscle mass and body fat mass, was measured using a Flycat Body Composition Analyzer 280 (China), based on bioelectrical impedance analysis. Knee cartilage thickness was assessed using a standard ultrasonographic technique with an ultrasound diagnostic instrument (Konted C10, China) in a fully knee-bent, supine position, a method previously validated for the reliable in vivo measurement of femoral cartilage thickness. Three consecutive measurements were obtained for each knee, and the average value was used for analysis (Naredo et al., 2009).

Procedures

This study was reviewed and approved by the Ethics Committee of Khon Kaen University, Thailand (Approval No. HE682018), and conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants prior to the start of the study.

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Participants assigned to the trampoline group completed an eight-week supervised mini-trampoline exercise programme, performed three times per week, with each session lasting 30 minutes and at least 48 hours between sessions. All training sessions were conducted in a supervised indoor exercise facility at the School of Physical Education and overseen by trained personnel with a background in sports science to ensure adherence to the correct technique and participant safety. A standard mini-trampoline was used for all sessions (diameter: 100 cm; height: approximately 22 cm). Training was performed individually, with each participant exercising on a separate trampoline within a supervised group setting. Each session consisted of a five-minute warm-up, a 20-minute main exercise phase, and a five-minute cool-down. The main exercise phase included a series of progressive rebound-based movements such as jumping in place, single-leg hopping, forward and backward jumps, and jumping jacks. A detailed description of the exercise content and weekly progression is provided in Table 1. Exercise intensity was prescribed at a moderate level and monitored using heart rate, with the target training intensity maintained at 60–80% of the estimated maximum heart rate. Each exercise bout lasted approximately two minutes, followed by a rest interval of 30 seconds to one minute. Training difficulty was gradually progressed according to individual tolerance and performance to maintain safety and adherence. Training adherence was monitored through attendance records, and participants were regularly asked about fatigue, pain, or discomfort during the intervention period. No serious adverse events were reported.

Table 1. Detailed mini-trampoline exercise programme (Eight-week intervention).

Week 1	Stand on both legs with heels raised Single-leg stance Move forward and backward in small steps Jog Jump in place Single-leg hop	Week 5	Standing high jump High leg lift Scissors (“paper-scissors”) bounce Single-leg forward and backward jump Jumping jacks Back kick
Week 2	Jump in place Jump forward and backward with a small amplitude Jump left and right Jump on one leg Jog Jumping jacks	Week 6	Standing high jump Squat jump Run in place Scissors (“paper-scissors”) bounce back and forth Single-leg forward and backward jump Back kick
Week 3	Jump in place (clap legs with both hands) Jump forward and backward (raise arms) Jump left and right Hop on one foot Jumping jacks High leg raises	Week 7	Standing high jump Squat jump Scissors (“paper-scissors”) bounce Single-leg forward and backward jump High leg lift Jumping jacks
Week 4	Jump in place (cross arms) Jogging Scissors (“paper-scissors”) bounce Single-leg hop Jumping jacks Back kick	Week 8	Standing high jump High knee lift Scissors bounce back and forth Single-leg forward and backward jump Jumping jacks Back kick

Participants in the control group were instructed to maintain their usual daily lifestyle and did not engage in any structured exercise programme during the study period. To provide basic health support and reduce attrition, the control group received a weekly 30-minute health education video addressing sedentary behaviour and general physical activity recommendations. After completion of all outcome assessments, participants in the control group were offered access to the same mini-trampoline training protocol in accordance with ethical considerations.

Analysis

Data were analysed using SPSS version 29.0 (SPSS Inc., Chicago, IL, USA). Data normality was assessed using the Shapiro–Wilk test. Normally distributed variables are presented as mean ± standard deviation, and non-normally distributed variables as median (interquartile range). Within-group comparisons were performed using paired t-tests or Wilcoxon signed-rank tests, and between-group comparisons were conducted using independent-samples t-tests or Mann–Whitney U tests, as appropriate. Given the exploratory nature of this pilot study and the relatively small sample size, no formal adjustment for multiple comparisons was applied, and statistical significance was set at $p < .05$; therefore, the results should be interpreted cautiously.

RESULTS

A total of 20 sedentary adults completed the study. The trampoline group (TG) consisted of seven men and three women with a mean age of 28.25 ± 4.94 years, while the control group (CG) included six men and four women with a mean age of 29.60 ± 4.03 years. No significant between-group differences were observed at the baseline in age, sex distribution, anthropometric variables, or any outcome measures, indicating comparable baseline characteristics between the two groups (all $p > .05$).

For muscle strength outcomes (Table 2), within-group analyses demonstrated significant post-intervention increases in neck flexor, neck extensor, and knee muscle strength in the TG ($p < .001$), whereas no significant changes were observed in the CG ($p > .05$). No significant between-group differences were detected at the baseline for these variables. At post-intervention, neck flexor and extensor muscle strength were significantly greater in the TG compared with the CG (both $p < .001$). Knee muscle strength was also higher in the TG than the CG; however, this between-group difference did not reach statistical significance ($p = .086$).

Table 2. Changes in neck and knee muscle strength before and after the intervention.

Outcome	Group	Before (Mean ± SD)	After (Mean ± SD)	Within-group t	*p*-value	Between-group t (After)	*p*-value
Neck flexor muscle strength (N)	CG	98.59 ± 3.06	99.32 ± 2.60	−1.05	.319	−8.23	<.001
	TG	97.37 ± 4.03	103.76 ± 4.46	−9.98	<.001		
Neck extensor muscle strength (N)	CG	122.61 ± 6.59	121.61 ± 7.07	1.61	.142	−4.59	<.001
	TG	119.70 ± 3.67	134.28 ± 5.12	−15.65	<.001		
Knee muscle strength (N)	CG	438.1 ± 69.3	453.7 ± 81.8	−1.30	.227	−1.82	.086
	TG	442.0 ± 48.8	515.0 ± 68.6	−5.97	<.001		

Note. Values are presented as mean ± standard deviation. Within-group comparisons were performed using paired t-tests. Between-group comparisons were performed using independent-samples t-tests. Statistical significance was set at p < .05. CG = control group; TG = trampoline group.

Regarding the knee and cervical range of motion (Table 3), no significant within-group changes were observed in the CG for any knee or cervical range of motion variables (all $p > .05$). In the TG, significant within-group improvements were observed for the knee range of motion, including left knee flexion and extension (both $p < .001$), right knee flexion ($p < .001$), and right knee extension ($p = .027$). Similarly, the cervical range of motion in the TG showed significant within-group increases, with improvements observed in lateral flexion ($p = .002$), rotation ($p < .001$), extension ($p < .001$), and flexion ($p = .015$). Between-group comparisons showed no significant baseline differences in any knee or cervical range of motion measures. After the intervention, the TG demonstrated significantly greater left knee flexion ($p < .001$), left knee extension ($p = .013$), and right knee extension ($p = .001$) than the CG, whereas no significant between-group difference was detected for right knee flexion ($p = .144$). At post-intervention, a significant between-group difference was observed for cervical lateral flexion ($p = .045$); however, no significant differences were detected for other cervical range of motion variables (all $p > .05$).

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Table 3. Changes in knee and neck range of motion before and after the intervention.

Outcome	Group	Before (Mean ± SD)	After (Mean ± SD)	Within-group t	*p*-value	Between-group t (After)	*p*-value
Left knee flexion (°)	CG	122.74 ± 5.69	122.32 ± 7.01	0.65	.534	−4.29	<.001
	TG	123.52 ± 8.97	139.88 ± 10.89	−15.73	<.001		
Left knee extension (°)	CG	2.83 ± 1.05	2.26 ± 1.36	1.75	.113	−2.76	.013
	TG	3.21 ± 1.70	4.32 ± 1.93	−7.12	<.001		
Right knee flexion (°)	CG	119.87 ± 8.77	119.67 ± 9.67	0.15	.883	−1.53	.144
	TG	120.82 ± 11.13	127.55 ± 13.15	−7.66	<.001		
Right knee extension (°)	CG	3.11 ± 0.94	2.74 ± 1.51	1.32	.220	−3.88	.001
	TG	3.51 ± 1.11	4.70 ± 0.52	−2.64	.027		
Neck lateral flexion (°)	CG	42.05 ± 4.57	41.28 ± 4.19	0.84	.421	−2.15	.045
	TG	42.03 ± 2.92	45.33 ± 4.22	−4.44	.002		
Neck rotation (°)	CG	64.65 ± 6.34	65.37 ± 7.02	-0.96	.361	-1.66	.115
	TG	65.51 ± 4.94	70.08 ± 5.60	-13.39	<.001		
Neck extension (°)	CG	42.27 ± 11.34	42.33 ± 11.90	−0.08	.937	−1.57	.134
	TG	44.72 ± 9.17	50.11 ± 10.22	−5.89	<.001		
Neck flexion (°)	CG	54.33 ± 4.15	55.73 ± 3.88	−1.86	.096	1.68	.110
	TG	48.05 ± 5.87	51.04 ± 7.91	−3.00	.015		

Note. Values are presented as mean ± standard deviation. Within-group comparisons were performed using paired t-tests. Between-group comparisons were performed using independent-samples t-tests. Statistical significance was set at p < .05. CG = control group; TG = trampoline group.

Table 4. Changes in body composition, knee cartilage thickness, and dynamic balance before and after the intervention.

Outcome	Group	Before (Mean ± SD)	After (Mean ± SD)	Within-group t	*p*-value	Between-group t (After)	*p*-value
Left knee cartilage thickness (mm)	CG	2.89 ± 0.43	2.86 ± 0.40	1.41	.193	−0.76	.460
	TG	2.94 ± 0.32	2.98 ± 0.30	−1.50	.168		
Right knee cartilage thickness (mm)	CG	3.08 ± 0.21	3.04 ± 0.25	1.07	.309	−0.71	.487
	TG	3.10 ± 0.20	3.11 ± 0.18	-0.26	.798		
Sit-and-reachtest (cm)	CG	14.70 ± 4.41	14.99 ± 5.08	−0.45	.666	−0.43	.674
	TG	14.84 ± 5.33	16.14 ± 6.81	−1.40	.194		
Skeletal muscle mass (kg)	CG	26.60 ± 4.37	27.37 ± 4.51	−0.54	.602	0.16	.871
	TG	26.67 ± 5.10	27.02 ± 4.97	−2.26	.050		
Body fat mass (kg)	CG	19.85 ± 1.04	19.85± 0.88	−0.00	1.000	-0.83	.422
	TG	20.91 ± 2.19	20.40 ± 1.90	2.63	.027		
SEBT Left – Anterior (cm)	CG	78.20 ± 7.77	78.30 ± 7.29	−0.13	.899	−1.33	.201
	TG	74.40 ± 8.11	82.90 ± 8.20	−9.22	<.001		
SEBT Left – Posteromedial (cm)	CG	66.60 ± 8.68	66.80 ± 9.80	−0.23	.820	−0.94	.357
	TG	65.40 ± 9.51	71.20 ± 11.00	−6.41	<.001		
SEBT Left – Posterolateral (cm)	CG	68.00 ± 6.25	68.30 ± 7.13	−0.35	.734	0.00	1.000
	TG	63.40 ± 4.14	68.30 ± 5.38	−7.65	<.001		
SEBT Composite score – Left	CG	0.81 ± 0.05	0.82 ± 0.05	−0.47	.652	−1.22	.236
	TG	0.78 ± 0.07	0.85 ± 0.08	−14.35	<.001		
SEBT Right – Anterior (cm)	CG	72.80 ± 6.78	72.40 ± 7.71	0.39	.705	−3.51	.003
	TG	73.20 ± 4.96	83.40 ± 6.24	−8.25	<.001		
SEBT Right – Posteromedial (cm)	CG	69.20 ± 6.39	69.30 ± 7.33	−0.16	.876	−1.60	.126
	TG	68.50 ± 8.81	76.00 ± 10.99	−9.15	<.001		
SEBT Right – Posterolateral (cm)	CG	60.90 ± 6.84	61.00 ± 6.99	−0.36	.726	−2.58	.019
	TG	62.90 ± 3.90	67.40 ± 3.57	−7.73	<.001		
SEBT Composite score – Right	CG	0.78 ± 0.05	0.77 ± 0.06	0.22	.831	−3.77	.001
	TG	0.78 ± 0.05	0.87 ± 0.05	−16.72	<.001		

Note. Values are presented as mean ± standard deviation. Within-group comparisons were performed using paired t-tests. Between-group comparisons were performed using independent-samples t-tests. Statistical significance was set at p < .05. CG = control group; TG = trampoline group.

For knee cartilage thickness, body composition, and dynamic balance outcomes (Table 4), no significant within-group or between-group differences were observed for knee cartilage thickness or sit-and-reach performance (all $p > .05$). In terms of body composition, the TG demonstrated a significant reduction in body fat mass ($p = .027$) , whereas the increase in skeletal muscle mass approached but did not reach statistical significance ($p = .050$). No significant changes in body composition variables were observed in the CG (all $p > .05$). However, no significant between-group differences were detected for body composition variables at post-intervention (all $p > .05$). Regarding dynamic balance, significant within-group improvements were observed in all Star Excursion Balance Test (SEBT) directions and composite scores for both limbs in the TG (all $p < .001$), while no significant changes were detected in the CG. Post-intervention between-group comparisons showed significant differences for right anterior reach ($p = .003$), right posterolateral reach ($p = .019$), and right composite score ($p = .001$), whereas other SEBT variables did not differ significantly between groups (all $p > .05$).

Table 5. Changes in pain intensity, handgrip strength, and heart rate variability before and after the intervention.

Outcome	Group	Baseline	Post-intervention	Within-group Z	*p*-value	Between-group Z (Post)	*p*-value
VAS	CG	7.00 (6.25, 7.00)	7.00 (7.00, 8.00)	0.246	.792	−2.993	.003
	TG	7.00 (7.00, 7.00)	5.50 (4.25, 6.00)	−2.859	.004		
Left handgrip (kg)	CG	30.97 (30.43, 31.57)	31.03 (29.33, 31.39)	−1.326	.185	−0.605	.545
	TG	30.98 (28.89, 31.64)	30.35 (28.66, 31.38)	−0.700	.484		
Right handgrip (kg)	CG	29.60 (27.56, 31.33)	29.98 (28.36, 31.39)	0.949	.343	1.097	.273
	TG	31.38 (30.22, 31.47)	31.33 (31.21, 31.62)	1.887	.059		
RMSSD (ms)	CG	43.01 (41.27, 45.88)	43.73 (40.96, 50.78)	0.459	.646	1.965	.049
	TG	39.70 (36.76, 47.63)	53.19 (50.49, 55.80)	2.701	.007		
LF/HF	CG	2.13 (1.71, 2.27)	2.09 (1.71, 2.29)	0.051	.959	−2.043	.041
	TG	1.87 (1.67, 2.40)	1.49 (1.12, 1.86)	−2.805	.005		
SDNN (ms)	CG	45.00 (44.25, 45.75)	45.00 (44.25, 46.75)	0.318	.750	3.791	<.001
	TG	44.50 (43.00, 45.00)	63.50 (61.25, 64.75)	2.807	.005		
HF (ms^2)	CG	420.00 (413.25, 421.75)	406.50 (396.25, 419.50)	−0.867	.386	−3.781	<.001
	TG	414.50 (400.75, 429.50)	973.00 (956.75, 984.50)	2.803	.005		

Notes: Values are presented as median (25th – 75th percentiles). Within-group comparisons were performed using the Wilcoxon signed-rank test. Between-group comparisons were performed using the Mann–Whitney U test. Z values correspond to the Wilcoxon signed-rank test (within-group) and the Mann–Whitney U test (between-group). CG = control group; TG = trampoline group.

Pain intensity, handgrip strength, and autonomic nervous system indices are presented in Table 5. Pain intensity, assessed using the VAS, decreased significantly in the TG after the intervention ($p = .004$), whereas no significant change was observed in the CG ($p = .792$). A significant between-group difference in VAS scores was observed at post-intervention ($p = .003$). No significant within-group or between-group differences were found for left or right handgrip strength (all $p > .05$). For heart rate variability indices, the TG exhibited significant post-intervention increases in RMSSD, SDNN, and HF, along with a significant reduction in the LF/HF ratio (all $p < .01$), whereas no significant changes were observed in the CG. Between-group comparisons at post-intervention demonstrated significant differences for RMSSD ($p = .049$), LF/HF ratio ($p = .041$), SDNN ($p < .001$), and HF ($p < .001$).

DISCUSSION

This study evaluates the short-term effects of an eight-week mini-trampoline exercise programme on musculoskeletal function, pain, body composition, dynamic balance, and autonomic regulation in sedentary

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adults. Overall, the findings suggest an association between the intervention and improvements in neck and knee muscle strength, selected knee and cervical range-of-motion outcomes, reduced pain intensity, and favourable changes in HRV. In contrast, no measurable changes in knee cartilage thickness or sit-and-reach flexibility were observed during the intervention period. These findings support the feasibility and potential functional benefits of mini-trampoline exercise in sedentary adults.

Improvements in neck flexor and extensor strength were among the most consistent findings, with clear between-group differences observed after the intervention. These strength gains are consistent with the postural control demands of rebound exercise, which requires continuous head–trunk stabilisation and may enhance the neuromuscular recruitment of cervical stabilising muscles. This interpretation aligns with previous reports linking sedentary behaviour to altered cervical mechanics and studies indicating that trampoline-based training can improve neck-related function (Jeon et al., 2012; Liu et al., 2015; Mekhora et al., 2000).

Knee muscle strength also increased significantly within the trampoline group. However, the absence of a statistically significant between-group difference at post-intervention suggests that this pilot study may have been underpowered to detect moderate group effects. Given prior evidence supporting the effects of trampoline-based training on knee-related performance (Tay et al., 2019), the observed within-group improvements are biologically plausible and warrant confirmation in larger trials designed to detect between-group differences.

Mini-trampoline training was further associated with improvements in several knee and cervical range of motion measures, whereas no meaningful changes were observed in the control group. Between-group advantages were most evident for left knee flexion and extension, right knee extension, and cervical lateral flexion and rotation, while other range-of-motion outcomes did not differ significantly between groups. These selective improvements suggest that repeated low-impact movement cycles and continuous postural adjustments may preferentially enhance mobility in movement directions most engaged during training, which is consistent with task-specific adaptations reported following balance- and movement-based exercise interventions (Pagan et al., 2024). Given the exploratory nature of this pilot trial, these findings should be interpreted cautiously and hypothesis-generating rather than confirmatory.

Pain intensity decreased significantly following the intervention, with lower post-intervention pain levels observed in the trampoline group compared with controls. This reduction may reflect non-specific exercise-related mechanisms, such as improved neuromuscular control and altered pain modulation, as suggested in previous studies (Rathi et al., 2024; Sarelius & Pohl, 2010; Shiro & Matsubara, 2017). In contrast, consistent with the principle of training specificity, handgrip strength did not change, as the intervention primarily targeted lower-limb loading and balance-related tasks.

With respect to body composition, the trampoline group demonstrated a reduction in body fat mass, whereas the increase in skeletal muscle mass did not reach statistical significance, with no significant between-group differences observed at post-intervention. These findings may indicate early metabolic or compositional adaptations but do not support definitive group-level effects within the constraints of this small pilot sample (Thyfault & Bergouignan, 2020) (Kolnes et al., 2021). Similarly, no changes in knee cartilage thickness were detected. This is plausible given the short intervention duration and the slow structural adaptation of cartilage tissue, which likely requires longer-term mechanical exposure to produce detectable morphological changes (Welhaven et al., 2022).

Dynamic balance improved substantially within the trampoline group across Star Excursion Balance Test outcomes, while between-group differences were limited to selected right-sided measures. Such limb- and direction-specific effects may be influenced by factors such as sample size, limb dominance, and baseline variability and should therefore be interpreted as preliminary. In contrast, sit-and-reach performance did not change, a finding consistent with the training characteristics of mini-trampoline exercise, which emphasise dynamic postural control and functional movement rather than sustained end-range stretching. Without targeted flexibility-oriented stimuli, improvements in static flexibility may be limited, as reported previously (Rathi et al., 2024).

Finally, coordinated improvements were observed in HRV indices, including increases in RMSSD, SDNN, and HF, alongside a reduction in the LF/HF ratio, with significant post-intervention differences in comparison to controls. Collectively, these changes are consistent with enhanced parasympathetic modulation and improved sympathovagal balance, suggesting that mini-trampoline exercise may exert beneficial effects on autonomic regulation in sedentary adults, in line with previous evidence demonstrating improvements in cardiac autonomic modulation following regular exercise interventions.

Importantly, no exercise-related adverse events or safety concerns were reported throughout the intervention period, indicating that the mini-trampoline programme was well tolerated by sedentary participants (Sánchez-Delgado et al., 2023). The present pilot findings support the feasibility and potential multi-domain benefits of mini-trampoline exercise. However, larger, prospectively registered randomised controlled trials with longer intervention and follow-up periods are required to confirm these preliminary observations and to characterise dose–response relationships and adherence effects.

Several limitations should be acknowledged. The small sample size of this pilot study limited its statistical power. Although the eight-week intervention was sufficient to induce functional and physiological adaptations, it may have been insufficient to capture slower structural changes, such as alterations in knee cartilage thickness or more pronounced body composition remodelling. In addition, the findings are limited to sedentary young adults, which may restrict generalisability. Although outcome assessors were blinded to group allocation (single-blinded design), participant blinding was not feasible due to the nature of the exercise intervention, which may have introduced performance or expectation bias.

CONCLUSIONS

An eight-week mini-trampoline exercise programme was associated with improvements in musculoskeletal function, balance, pain, and autonomic regulation in sedentary adults. These preliminary findings support the feasibility of mini-trampoline exercise and warrant confirmation in larger, long-term randomised controlled trials.

AUTHOR CONTRIBUTIONS

Yuan Xie conceived the study, coordinated participant recruitment and data collection, delivered the intervention, performed the statistical analyses, and drafted the manuscript. Prof. Dr. Wichai Eungpinichpong supervised the study, contributed to the study design and methodology, guided interpretation of the findings, and critically revised the manuscript for important intellectual content. Asst. Prof. Dr. Nichanun Panyaek contributed to the study design and intervention planning, supported data interpretation, and reviewed and revised the manuscript. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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ORIGINAL ARTICLE

Reactance as a possible predictor of better rehydration strategy of combat sport athletes

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ABSTRACT

Rapid weight loss is a widespread practice in combat sports, intended to meet weight-class requirements while preserving an anatomical advantage. These strategies primarily reduce extracellular and intracellular fluid volumes by manipulating carbohydrate, sodium, and water intake, followed by rapid weight gain after the official weigh-in. This study analysed the association between raw bioelectrical impedance variables measured immediately after weigh-in and competitive outcome in amateur combat athletes. A cross-sectional analytical design was conducted with 54 athletes from boxing, Mixed Martial Arts, and Muay Thai. Measurements of resistance (R), reactance (Xc), and phase angle (PhA) were obtained under standardized conditions using a tetrapolar device. Descriptive statistics characterized the sample, and logistic regression evaluated predictors of winning or losing. Mean values for R/H (height), Xc/H, PhA/H, and Z/H reflected a dehydrated profile consistent with recent weight cutting. Only Xc/H met the regression model's entry criteria. Higher Xc/H values were associated with lower odds of winning (OR = 0.857), suggesting that athletes with lower post-weigh-in reactance/height — potentially reflecting more effective rehydration and extracellular volume restoration — were more likely to achieve victory. These findings highlight the physiological relevance of bioelectrical markers for assessing recovery and their promise as indicators of competitive readiness in combat sports.

Keywords: Sport medicine, Bioelectrical impedance analysis, Reactance-to-height ratio, Phase angle, Combat sports, Athlete monitoring.

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INTRODUCTION

Combat sports are defined as disciplines in which the competitive objective is to overcome an opponent through striking, takedowns, holds, chokes, or joint locks. Given that performance in these sports is inherently linked to one athlete exerting physical dominance over another. That force equals mass multiplied by acceleration. Weight-class systems were developed to promote fairness in competition. These systems require athletes to meet a particular yet physiologically atypical condition: presenting an exact body mass at the official weigh-in (Mohamad et al., 2016).

Although initially designed to safeguard athlete welfare and competitive equity, weight-class regulations have historically motivated many athletes to seek ways to retain anatomical advantages such as greater size or mass relative to their opponents. This has led to the widespread practice known as rapid weight loss (RWL), commonly referred to as "*weight cutting*." RWL strategies involve the accelerated reduction of total body mass, typically within less than two weeks, followed by an equally rapid regain of body weight (rapid weight gain, RWG). Over time, these practices have become deeply embedded in the culture and competitive logic of combat sports (Wilbraham et al., 2024).

Most RWL methods converge on a central physiological aim: reducing total body water by manipulating intramuscular, extracellular, and fundamental physiological fluid compartments (Ricci et al., 2025). Carbohydrate restriction is among the most widely employed strategies, given that glycogen storage in skeletal muscle and the liver contains a substantial water component; approximately 3 grams of water are required for each gram of glycogen stored. Consequently, reducing carbohydrate intake can yield a meaningful decrease in body mass (Melkonian et al., 2022; Mendes-Netto et al., 2023). Nevertheless, misinformation disseminated online has led some athletes to adopt this strategy too early or for unnecessarily long periods. Although a daily intake of nearly 50 g over three days can almost deplete glycogen stores, extended periods of low-carbohydrate availability may increase protein catabolism and contribute to bone demineralization (Greene et al., 2018; Margolis & Pasiakos, 2023; Mountjoy et al., 2023).

Historically, fighters also commonly reduced fluid intake as early as one month before competition. However, current evidence supports a different approach to fluid manipulation. Contemporary protocols typically involve markedly increasing fluid intake in the days leading up to weigh-in, sometimes reaching 80–100 ml/kg, followed by a controlled reduction to approximately 30 ml/kg. This approach promotes a transient rise in urine output while maintaining adequate electrolyte balance, thereby facilitating acute weight reduction without the pronounced risks of prolonged dehydration (Ceylan et al., 2022; Reale et al., 2018).

Sodium, a key electrolyte in sport physiology, plays essential roles in fluid regulation, muscle contraction, and carbohydrate metabolism, and is therefore abundant in plasma (Barley & Harms, 2025; McCubbin, 2022). Its relevance to RWL stems from its direct influence on water retention: reducing sodium intake to below 500 mg per day in the three days preceding weigh-in can increase total body water loss. However, when sodium restriction is combined with increased fluid intake, the risk of exercise-associated hyponatremia becomes salient. This condition can lead to severe, potentially life-threatening consequences, underscoring the need for systematic monitoring of sodium concentration during RWL interventions (Stachenfeld, 2008). Therefore, the present study aimed to identify which factors were associated with the competitive outcome (win/loss) using binary logistic regression with stepwise selection.

MATERIALS AND METHODS

Study design

A cross-sectional observational analytical study was conducted to evaluate the association between raw bioimpedance variables (resistance, reactance, and phase angle) after official weigh-in and competitive outcome (win/loss) in amateur combat athletes. Measurements were recorded at a single point in time, according to a protocol established before the fight.

Participants

The sample comprised 54 athletes from various combat sports (boxing, MMA, and Muay Thai) who participated in a competitive event. The subjects were aged 12-39 years and underwent weight cutting before the official weigh-in.

The inclusion criteria were: (a) voluntarily agreeing to participate, signing an informed consent form, and, in the case of minors, obtaining consent from the responsible guardian; (b) not having any injuries or medical conditions that would prevent bioimpedance measurement; (c) completing the official weigh-in. Athletes who did not complete the rest period before measurement or who had electrical implants were excluded.

Procedure

Upon arrival at the weight-in location, each athlete completed the official weight category verification procedure. Once the weigh-in was complete, they proceeded to the assessment area, where they were weighed again for internal control and measured in accordance with the ISAK protocol. They were then instructed to lie supine on a stretcher.

Participants remained at complete rest for 10 minutes, without speaking or moving, to allow body fluids to stabilize and reduce variability induced by exercise or the stress of weighing.

After the rest period, electrical bioimpedance was measured using an AKERN BIA 101 PRO, a tetrapolar alternating-current device. Following international recommendations for full-body BIA, electrodes were placed at standard anatomical hand-foot sites: distal electrodes on the dorsal surfaces of the hand and foot, and proximal electrodes at the wrist and ankle, with inter-electrode distances respected and adequate skin contact ensured.

During measurement, the athlete was instructed to remain completely still and silent, with limbs slightly apart, to avoid any muscle tension that could interfere with the impedance values.

The equipment recorded the raw variables: resistance (R), reactance (Xc), and phase angle (PhA). Once the recording was complete, the electrodes were carefully removed, the athletes were thanked for their participation, and the athlete continued their pre-fight recovery routine.

Data analysis

A general description of the athletes' characteristics was provided, including anthropometric, bioelectrical, and water-composition variables. These are summarized using means, standard deviations, ranges, and, for competitive results and sports modality, frequencies and percentages.

To explore factors associated with winning or losing the match, a binary logistic regression was performed. Before adjusting the model, each predictor was evaluated individually using the score test. The model was

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estimated using a stepwise procedure. Its contribution was verified using the omnibus test, pseudo-R^2 values, and the Hosmer–Lemeshow test, as well as through the percentage of correctly classified cases. In addition, its coefficient, significance level, odds ratio, and confidence interval were reviewed.

Ethical considerations

This study was conducted in accordance with the Declaration of Helsinki and Resolution 8430 of 1993 of the Colombian Ministry of Health for research involving human subjects. In addition, it was previously approved by the ethics committee in October 2025, as recorded in institutional paper No. 320.02-07-2025. Each participant voluntarily provided their written informed consent before participating.

RESULTS

Participants had a mean age of 21.38 ± 6.09 years, ranging from 12.6 to 39.3 years. Combat time averaged 9.93 ± 2.59 minutes, ranging from 1.75 to 11 minutes. Height averaged 168.98 ± 7.54 cm, with values ranging from 152 to 190 cm.

In bioelectrical measurements, the resistance/height (R/H) ratio had a mean value of 294.45 ± 43.17 ohm/m, with a range of 195.73 to 467.21 ohm/m. Reactance/height (XC/H) recorded an average of 33.88 ± 4.22 ohms/m, with values ranging from 22.11 to 47.40 ohms/m. Phase/height (PhA/H) averaged 6.62 ± 0.46 degrees/m, with a range of 5.6 to 7.8 degrees/m. Standardized impedance (Z/H) averaged 294.10 ± 40.39 ohms/m, with values ranging from 196.90 to 469.60 ohms/m.

Regarding water compartments, total body water (TBW) averaged 42.51 ± 5.15 litres, ranging from 32.6 to 55.9 litres. Intracellular water (ICW) averaged 25.23 ± 3.15 litres, with a range of 19.3-32.9 litres. Extracellular water (ECW) averaged 17.31 ± 1.95 litres, with values between 13.3 and 23.0 litres.

In the analysis of the XC/H variable by match outcome, the losing group recorded an average of 34.93 ± 4.00 ohm/m, with a 95% confidence interval of 33.54-36.33 ohm/m. In the group that won, the mean was 32.59 ± 4.00 ohm/m, with a 95% confidence interval of 30.72-34.46 ohm/m. (Figure 1)

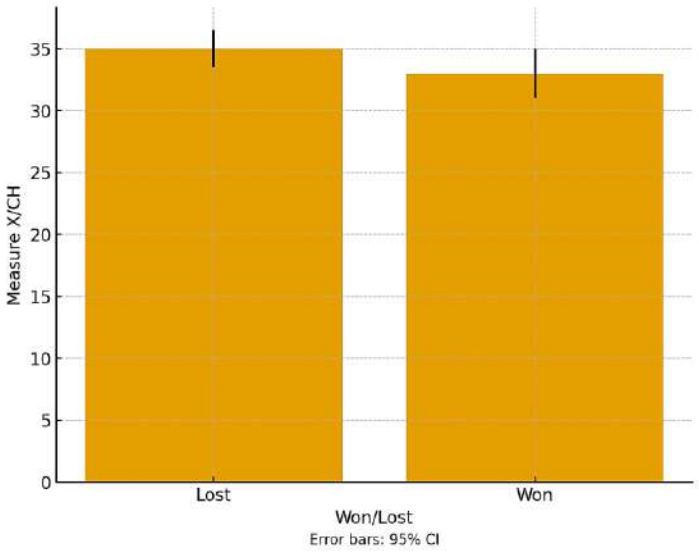


Figure 1. Comparison of XC/H Values by Match Outcome (Xc/H = reactance/height).

In terms of competitive outcomes, 53.7% of athletes lost (n = 29), whereas 46.3% won (n = 25). Regarding the sport, 35.2% were boxers (n = 19), 24.1% MMA fighters (n = 13), and 40.7% Muay Thai fighters (n = 22). (Figure 2)

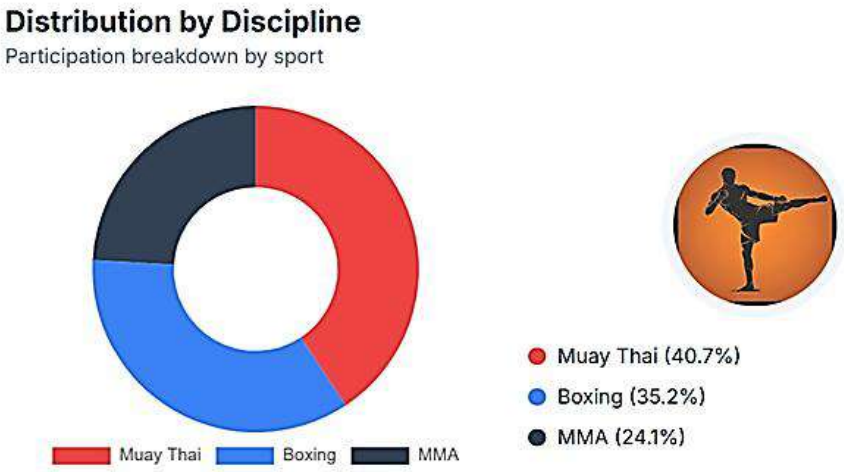


Figure 2. Distribution by Discipline. Participation breakdown by sport (MMA = Mixed Martial Arts).

When initially examining individual associations using the scoring test, most predictors did not show sufficient statistical evidence to be included in the model. However, two variables, height and the reactance-to-height ratio (XC/H), showed significant effects and were therefore considered for selection.

After applying the stepwise procedure, only XC/H was retained in the final equation. The inclusion of this predictor significantly improved model fit, as indicated by the omnibus test ($\chi^2 = 4.535$, df = 1, $p = .033$). The pseudo R^2 showed values of .081 for Cox and Snell and .108 for Nagelkerke. The Hosmer–Lemeshow test indicated an adequate fit between predicted and observed values ($\chi^2 = 12.759$; df = 8; $p = .120$), supporting the model's consistency.

In terms of discrimination capacity, the model correctly classified 66.7% of cases, with a 72.4% accuracy rate for athletes who lost and 60.0% for those who won. The variable retained in the model was XC/H, which showed a negative coefficient (B = –0.155) and a p-value at the threshold of statistical significance ($p = .053$). Its odds ratio (Exp(B) = 0.857) indicates that, for each additional unit in this relationship, the odds of winning decrease by approximately 14.3%. The 95% confidence interval (0.732–1.002) mainly remained below the null value, suggesting a relatively consistent inverse effect, though it was close to the significance threshold. The exclusion test confirmed that removing this predictor would significantly impair model fit ($\chi^2 = 4.535$, $p = .033$), underscoring its contribution to the final equation.

DISCUSSION

The main findings of this study indicate that each 1 Ω/m increase in Xc/H before the fight was associated with a +/-14% decrease in the probability of victory. In contrast, a relatively low Xc/H in the post-weigh-in period is associated with a higher likelihood of winning. This pattern appears to contradict the traditional view that high values of Xc/H and phase angle (PhA) indicate greater cell mass and better muscle quality (Ward & Brantlov, 2023); however, the acute response of reactance to changes in hydration accounts for this pattern in Xc/H.

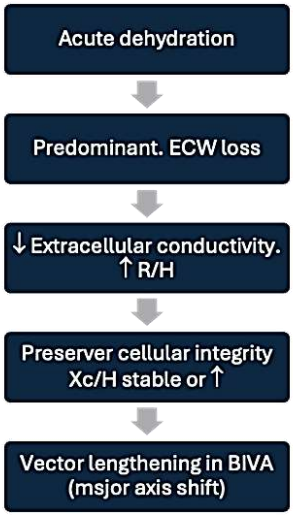
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Physiology of weight cutting

Strategies such as gradually reducing sodium intake affect rehydration physiology in these athletes, potentially leading to a decrease in Xc (Malbarin, et al., 2024). The absence of glycolytic reserves and reduced plasma sodium levels create a gradient that slows fluid entry into the cell, even when the athlete is consuming fluids, given the possible increase in serum potassium levels during the cutting process (Brinkman et al., 2023; Ly et al., 2023).

In weight-cutting among combat athletes, acute fluid loss occurs predominantly from the extracellular water (ECW) compartment, primarily when dehydration is induced by exercise in a hot environment or by fluid and sodium restriction. This pattern extends the Bioimpedance vector analysis on the BIVA graph, as reflected by significant increases in R/H and Xc/H, and its magnitude is proportional to the degree of total water loss. In experimental studies in men subjected to exercise in heat, dehydration produced a shift of the vector along the central axis, without a reduction in Xc/H, indicating that membrane capacitance is preserved despite the volumetric decrease in ECW (Gatterer et al., 2014; Galloway & Maughan, 2000). On the other hand, although it is recognized that glycogen depletion can contribute to changes in intracellular water (ICW), Shiose et al. (2018) demonstrated that, under controlled conditions, a marked reduction in muscle glycogen (≈60% decrease) does not alter the segmental ECW/ICW distribution according to BIS, suggesting that most of the vector displacement observed after acute cutting responds mainly to changes in the extracellular compartment and not to direct changes in glycogen-bound water (Shiose et al., 2000).

Recent evidence supports this interpretation from a physiological and biophysical multicompartmental approach, highlighting that ECW is the primary determinant of conductivity due to its high electrolyte concentration. At the same time, capacitance is primarily associated with cell membrane integrity and body cell mass (BCM) volume. In conditions of acute dehydration, a reduction in ECW decreases conductivity and increases R/H, whereas the preservation of cell membranes and ICW maintains or slightly increases Xc/H (Rosa et al., 2025). The article by Rosa et al. (2025) emphasizes that acute variations in PhA and raw BIA parameters should be interpreted with respect to the differential dynamics of compartments, rather than solely in terms of total body water volume. Thus, the findings reinforce that the vectorial elongation characteristic of weight loss primarily reflects contraction of the extracellular space, with maintenance of cellular integrity, rather than a significant loss of intracellular volume. (Figure 3)



Note. ECW = Extracellular Water; R/H = resistance/height; Xc/H = reactance/height; BIVA = Bioelectrical impedance vector analysis.

Figure 3. Fluid dynamics in weight cutting.

Rehydration and glycogen replenishment after weighing

Immediate rehydration expands extracellular volume (ECV), which increases conductivity and reduces resistance; at the same time, dilution of the extracellular space decreases membrane density per unit volume and reduces reactance (Xc/H); in a second phase lasting 24 to 48 hours, glycogen synthesis and the re-entry of potassium into the cell draw water into the intracellular compartment (ICW), gradually restoring cell mass and reactance (Carrasco-Marginet et al., 2017). Glycogen replenishment can cause increases of 1 to 2 kg in body weight in a matter of hours, because each gram of glycogen stores several grams of water (Murray & Rosenbloom 2018; Dynka et al., 2025). These fluctuations explain the increases of up to 10% in weight observed between weigh-in and competition in mixed martial arts fighters (Burke et al., 2017; Bagot et al., 2024).

Bioelectrical interpretation of resistance and reactance

In combat sports, the interpretation of the BIVA allows for sensitive monitoring of variations in hydration status and cell mass associated with processes such as weight cutting and rehydration. Resistance (R) is inversely related to total body water (TBW) content, so increases in R reflect reductions in body fluids and are valuable indicators of dehydration after weighing. Reactance (Xc), on the other hand, expresses the capacitive properties of cell membranes and is linked to cell mass content and the ICW/ECW ratio; lower Xc values may suggest reduced cell integrity and functionality. Among karate practitioners evaluated under euhydrated conditions, Rossi (2021) observed significant sex differences in R and Xc, highlighting their sensitivity to relevant physiological variations. Therefore, in contexts where body weight is acutely manipulated, the upward and rightward shift of the bioelectrical vector indicates water loss and possible alteration in muscle hydration, making it a key parameter for guiding nutritional and recovery decisions (Rossi, 2021).

R represents opposition to current flow through body fluids (especially ECW) and decreases as the volume of water and electrolytes increases. Xc expresses the capacity of cell membranes and dielectric structures to store charge, increases with the integrity and quantity of membranes, and decreases when extracellular water predominates. The length of the impedance vector in the RXc graph is a continuous indicator of hydration: short vectors (lower R/H) correspond to water overload, while long vectors (higher R/H) reflect dehydration. Lateral shifts (influenced mainly by Xc/H) indicate changes in the dielectric mass of tissues, i.e., in the quantity or quality of cell membranes (Carrasco-Marginet et al., 2017). After a session of exercise with dehydration, the vector lengthens and shifts upward and to the right, whereas after rehydration it shortens and shifts downward and to the left (Gatterer et al., 2014).

At rest and over the long term, higher Xc/H and a larger phase angle are typically associated with greater cell mass and better muscle quality (Carrasco-Marginet et al., 2017). Still, it should be noted that following rehydration, the expansion of the extracellular space reduces Xc/H because there is more water outside the cell and a lower membrane density per unit volume. Therefore, a short vector with lower Xc/H may reflect adequate rehydration rather than a decrease in cell mass. Studies involving exercise in heat show that changes in Xc/H are inversely correlated with variations in plasma osmolarity, suggesting water shifts between the intracellular and extracellular compartments (Gatterer et al., 2014). It is also essential to consider that classic BIVA assumes the body is a uniform cylinder and does not account for segmental geometry; therefore, heavier fighters or those with wider limbs may have lower Xc/H without this indicating poorer cellular condition—methods such as specific BIVA correct for this limitation.

The physiological changes described above help explain why a lower Xc/H before combat was associated with a higher probability of victory in our sample. Fighters who rehydrated and reloaded glycogen more effectively increased their extracellular and total volumes; this results in shorter vectors and lower reactance

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due to membrane dilution (Gatterer et al., 2014; Carrasco-Marginet et al., 2017). In turn, glycogen replenishment brings water into the intracellular compartment, but this process takes several hours. When the measurement is taken 1 to 3 hours before the fight, extracellular expansion is likely to predominate, which is why the winners showed lower Xc/H without negatively affecting their cell mass. This hypothesis is consistent with the findings of Gatterer et al., who observed that, after exercise and subsequent rehydration, the impedance vector shortens, and that changes in Xc/H are inversely related to variations in plasma osmolarity. Another contributing factor may be the efficiency of weight cutting. Fighters who arrive at the weigh-in less dehydrated, or who have more time to rehydrate, may need to reduce glycogen loss less, which reduces intracellular water loss. The literature suggests that changes in Xc/H may reflect the relationship between intracellular and extracellular water loss (Gatterer et al., 2014). Thus, a high Xc/H could indicate that the athlete still has a high osmotic gradient and has not yet fully recovered intracellular water. This condition can decrease strength and endurance during combat.

CONCLUSIONS

From a physiological perspective, weight cutting causes depletion, particularly in the extracellular compartment, thereby lengthening the impedance vector and increasing reactance. Subsequent rehydration and carbohydrate replenishment, especially in the early hours, increase extracellular volume and reduce reactance through dilution. Fighters who achieved lower Xc/H after recovery were more likely to win, suggesting that adequate rehydration status before combat may provide a competitive advantage. However, due to methodological limitations and the exploratory nature of the data, this observation should be interpreted with caution and confirmed in future studies.

AUTHOR CONTRIBUTIONS

MSS & DFG: conceptualization and methodology. JGCh: methodology and formal analysis. MSS, DFG, JGCh & ICR-P: data curation, writing – original draft, preparation, visualization, writing – review and editing. All authors have read and agreed to the final version of the manuscript.

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ORIGINAL ARTICLE

Effects of caffeine ingestion on performance and biomechanical parameters of running: A randomized crossover trial

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ABSTRACT

This study aimed to assess the impact of 6mg/kg of caffeine (CAFF) on running performance and technique. Using a randomized, double-blind, crossover structure, 14 subjects ran 2.5 kilometres on a treadmill, without (PRE) and with (POST) fatigue, under 3 conditions with 7 days as a wash-out: control (CON), placebo (PLA), and CAFF. CON was always assessed first. The results showed that POST, there was less flight time (d = 0.85), more step rate (d = 0.61-0.62) and less stride length in both legs (d = 0.61-0.63), less knee flexion (d = 0.75), and a slower performance (d = 0.72). Compared to CON, PLA increased contact time in both legs (d = 0.70-1.01) while improving performance (d = 1.00), and CAFF reduced step rate (d = 0.85-0.86) and increased stride length in both legs (d = 0.82-0.86) while also enhancing performance (d = 1.01). CAFF PRE showed a faster time compared to CAFF POST, PLA POST, CON PRE, and CON POST (d = 1.17-1.92), and PLA PRE was faster than CON PRE, CON POST, and CAFF POST (d = 1.19-1.50). In conclusion, CAFF improved running performance compared to CON, suggesting a front-loaded strategy, while PLA also enhanced performance relative to CON. Furthermore, CAFF, PLA, and fatigue modified running kinematics. This trial was prospectively registered on Clinical Trials (NCT06039358; September 2023) and supported by "*AGAUR-FI ajuts*".

Keywords: Biomechanics, Ergogenic aids, Injuries, Sports performance, Sports nutrition.

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INTRODUCTION

Caffeine (CAFF) is one of the few supplements that has been classified as an ergogenic aid, with strong evidence supporting its efficacy and safety (Maughan et al., 2018). Its benefits on performance are accepted to be mainly derived from its effect on the central nervous system as an antagonist at the adenosine receptors, although other mechanisms have also been hypothesized (Guest et al., 2021). Moreover, the reduction of perceived exertion or fatigue during exercise and increased alertness and vigilance have also been reported with CAFF ingestion (Guest et al., 2021; Maughan et al., 2018). However, some of the ergogenic effects of CAFF may be attributable to the placebo (PLA) effect (Marticorena et al., 2021). Endurance exercise is the type of effort in which much of the research on CAFF has been conducted, and improvements of 2-4% have been observed with 3-6mg of CAFF/kg (Guest et al., 2021). More specifically, CAFF may enhance performance over different running distances (Schubert & Astorino, 2013). Additionally, CAFF can improve time to exhaustion in running trials and time to complete endurance running time trials (Wang et al., 2023).

In this regard, running is an increasingly popular physical activity, with a variety of distances to compete in (Schubert & Astorino, 2013; Skypala et al., 2023). However, running-related injuries can be common (Skypala et al., 2023). Different kinematic, kinetic, and spatiotemporal variables have been identified as factors that may increase the risk of running-related injuries (Ceyssens et al., 2019; Willwacher et al., 2022). Besides, one of the leading causes of injuries in running may be neuromuscular fatigue (Encarnación-Martínez et al., 2022). While unfatigued running may allow the maintenance of the preferred movement pattern, fatigue can limit the muscular ability to control joint movement (Encarnación-Martínez et al., 2021), generating modifications in the running biomechanics (Encarnación-Martínez et al., 2021; Skypala et al., 2023). Moreover, metabolic acidosis and neuromuscular fatigue are detrimental to performance in middle-distance running (Schubert & Astorino, 2013).

Taken together, the ergogenic role of CAFF in running performance and the relevance of biomechanics for injury risk highlight a gap in the literature, as few studies have thoroughly examined how CAFF influences running biomechanics. Specifically, this effect has been assessed during the development of a 100-metre and 60-metre sprint running, identifying modifications in its execution (Horiuchi & Nagahara, 2024; Matsumura et al., 2023). Different potential processes have been mentioned to physiologically explain some of these modifications, such as CAFF effects on muscle activation (Horiuchi & Nagahara, 2024; Matsumura et al., 2023) or the calcium release from the sarcoplasmic reticulum (Horiuchi & Nagahara, 2024), which in some cases lead to greater force during muscle contractions (Horiuchi & Nagahara, 2024).

Based on this evidence, while the benefits of CAFF are usually judged solely by performance outcomes, its impact on technique execution has not been clearly studied, which may entail adverse consequences. Therefore, assessing the impact of the cognitive and physiological effects of CAFF on running technique and its preservation in fatiguing circumstances may be interesting due to its aforementioned relation with injury risk. The goal of this study is to determine whether CAFF can modify the performance and technical execution of running in fatigued and non-fatigued conditions in naïve-low CAFF consumers, compared to a PLA and a control (CON). We hypothesize that CAFF generates changes in the technical execution of running in fatigued and unfatigued circumstances due to its physiological effects, potentially benefiting performance and neuromuscular patterns.

MATERIALS AND METHODS

Participants

This study's target population consisted of individuals with an advanced training level, defined as an uninterrupted training time of ≥1 year in their regular exercise modality, and a good technique in the assessed exercises - based on a previous classification (Santos Junior et al., 2021). The exclusion criteria were chosen to diminish interindividual differences in the response to CAFF (Pickering & Kiely, 2018): 1) Being <18 or >30 years old; 2) Relevant medical conditions; 3) Pregnancy; 4) Smoking; 5) Regular medication consumption or its consumption during the study; 6) Regular consumption of ergogenic supplements or its consumption during the study; 7) Habitual CAFF ingestion of >25mg/day-0.99mg/kg/day (not naïve-low consumers (Filip et al., 2020)).

Making an a priori power analysis using G*Power (v. 3.1.9.6, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), assuming a within repeated measures ANOVA, an effect size (ES) of the CAFF impact of 0.15 (f) (Grgic, 2022), a significance level of .05, a desired power of 0.80, 1 tested group with 6 measurements, and a correlation among repeated measures of 0.90 (Grgic, 2022), the sample size needed would be 11 participants. This study is within a project that assessed the impact of CAFF on running, jumping, and squatting. The sample size was calculated based on the effect of CAFF on the vertical jump height since this performance outcome leads to a more restrictive measurement (running performance ES = 0.39, and correlation = 0.67 (Hurst et al., 2019)). Considering possible dropouts, we recruited 15 athletes. The promotion of the study for the enrolment process was conducted at the University of Vic and other facilities of the city's sports teams using posters. The recruitment period was from October to November 2023. One participant withdrew from the study between the enrolment and the familiarization sessions, due to an injury unrelated to the study. Therefore, 14 volunteers completed the entire study and were included in all the analyses (Figure 1 and Table 1).

Table 1. Baseline data of the participants, by sequence.

Variable	Sequence control-caffeine-placebo	Sequence control-placebo-caffeine
Sex	Male = 7 (100%) Female = 0 (0%)	Male = 4 (57.14%) Female = 3 (42.86%)
Age (years)	22.00 (3.32)	22.14 (3.08)
Height (m)	1.76 (0.06)	1.69 (0.07)
Body mass (kg)	75.53 (8.06)	62.31 (6.33)
Body fat (%)	19.59 (4.34)	22.26 (8.88)
Habitual caffeine intake from foodstuffs (mg/kg/day)	0.20 (0.35)	0.25 (0.31)
Habitual caffeine intake as an ergogenic aid (mg/kg/day)	0.00 (0.00)	0.00 (0.00)

Note. Sex is reported as frequency and (%), while the rest of the values are the mean and (standard deviation). m = Meters. kg = Kilograms. mg = Milligrams.

Measures

The primary outcomes of this study were the effect of CAFF on performance and biomechanics, compared between the 3 sessions, with and without fatigue. The same researcher assessed all the outcomes. The trial protocol consisted of 2.5km running on a treadmill (RAM, Padua, Italy), adapted from previous studies (Dingenen et al., 2018; García-Pinillos et al., 2019): Participants ran with their usual training shoes for 8 minutes at 10.5km/h with 0% slope, the last 30 seconds of which were recorded for further analysis. The movement was filmed in slow-motion at 240fps using a smartphone (iPhone 11 Pro Max, Apple, Cupertino, USA). It was placed on a portable tripod perpendicular to the sagittal plane, 2.79m from the treadmill, and at

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a height of 1.16m. After this period, they completed the remaining distance at a self-selected velocity as quickly as possible. They manually modified the treadmill velocity and received standardized verbal feedback. The performance modification outcome was the time to complete the remaining 1.1km after the 8 minutes at 10.5 km/h, measured using a stopwatch.

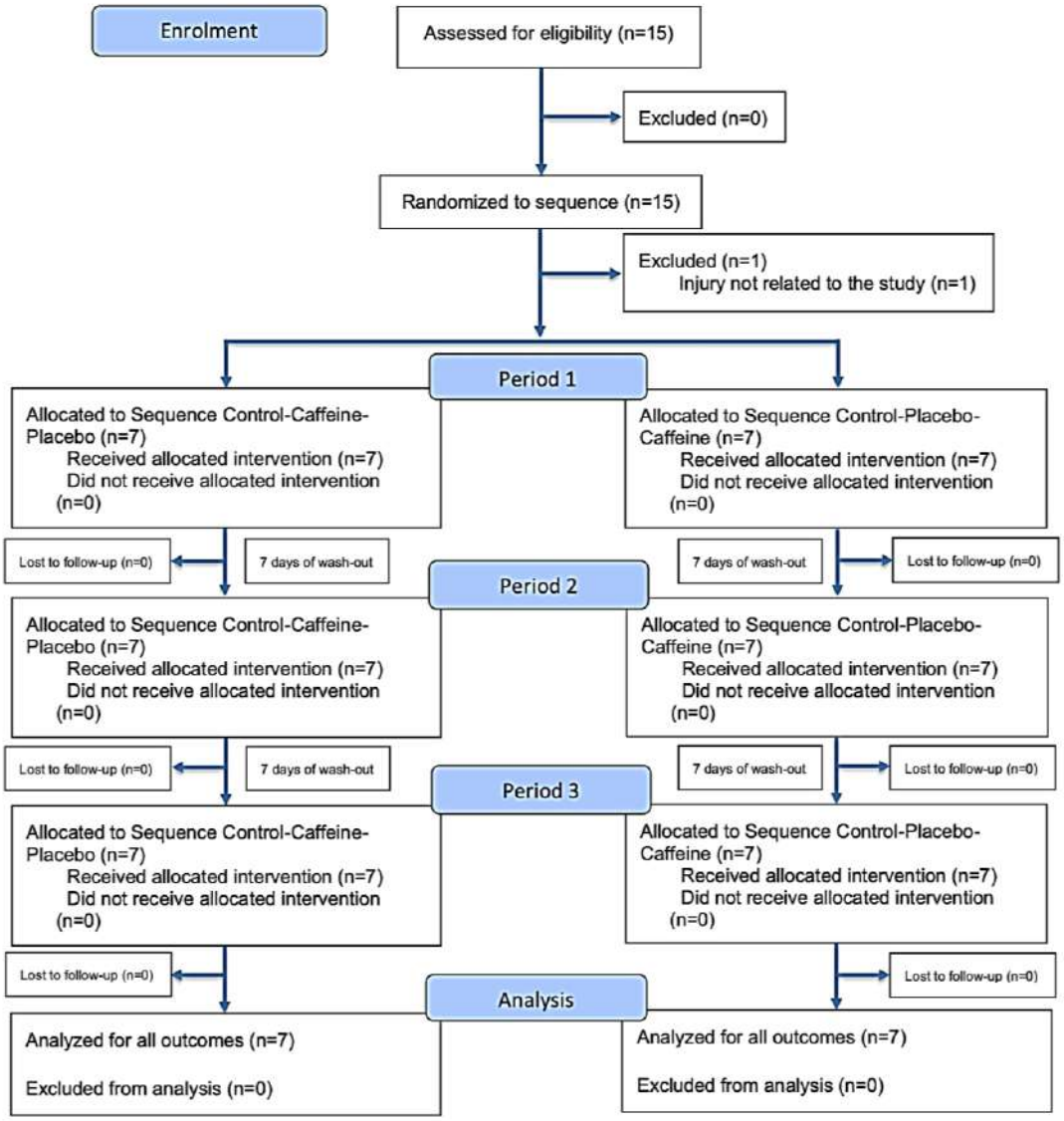


Figure 1. CONSORT flow diagram.

The running technique analysis was conducted using the 30-second recording, performed by a single researcher, and was done using Kinovea (v. 0.9.5), which has shown its validity and reliability (Balsalobre-Fernández et al., 2014; Puig-Diví et al., 2019). The mean values of 10 consecutive strides that did not present remarkable technique abnormalities were analysed. Reflective markers were placed on the participants' right side of the body, always by the same researcher. They were fixed to the greater trochanter (GT), the lateral femoral epicondyle (LFE), the fibular head (FH), and the lateral malleolus (LM). Adhesive spray, tape, and elastic bandages were used to ensure their attachment. The LFE and the FH were localized and marked with the athletes seated with the knee flexed at 90º, while for the other landmarks, they were standing.

The identified variables included two angles measured on the midstance frame (the moment that the knee of the leg not touching the ground is beside the knee of the leg contacting the ground), on the right side of the body. These were the knee angle (angle formed by the GT-LFE line, and the LFE-LM line; ↓ angle - ↑ knee flexion), and the tibial angle (angle formed by a vertical line from the LM and the LM-FH line; ↑ angle - ↑ ankle dorsiflexion). Other spatiotemporal variables were also measured individually for both limbs: step rate (10/duration of the 10 analysed steps), stride length (velocity of the treadmill/step rate), contact time (time from the initial contact to the toe-off (when the foot loses contact from the ground) of the same leg), and flight time (time from the toe-off to the initial contact of the same leg). The feasibility of these variables was tested in a pilot study. Figure 2 presents some of these variables and procedures.

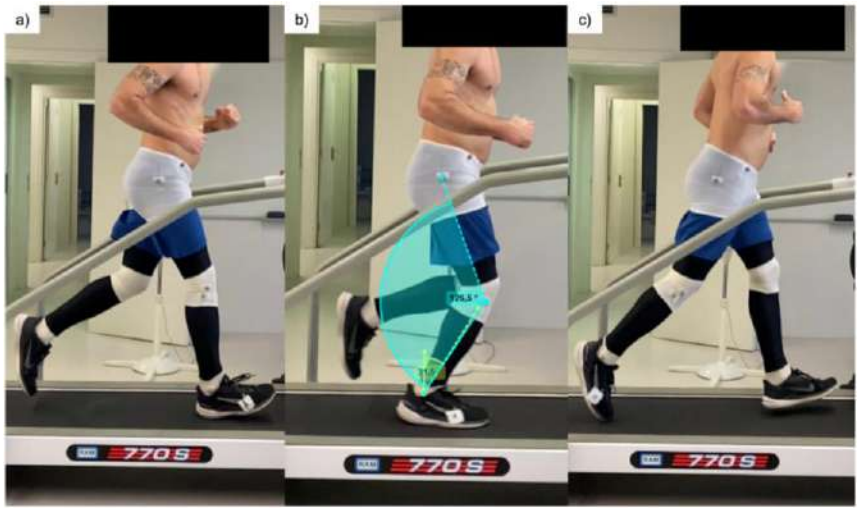


Figure 2. Representative frames showing key time points during running: (a) initial contact, (b) midstance, and (c) toe-off. The midstance frame also illustrates the measurement of knee and tibial angles.

Procedures

Study design

This study is reported under the CONSORT guidelines and their extension for crossover trials (Dwan et al., 2019; Hopewell et al., 2025) (Supplementary Material 1). There was no public or participant involvement in the design, conduct, or reporting of the trial. The structure of the study was a randomized controlled trial, double-blinded, PLA-controlled, with a crossover. The crossover design was chosen to optimize the required sample size (Dwan et al., 2019). This trial registry and protocol were prospectively registered on ClinicalTrials (Identifier: NCT06039358 (https://clinicaltrials.gov/study/NCT06039358); registered September 15, 2023). No important changes were performed from the pre-specified procedures.

In this article, only the results of the running exercise of the study are reported. It is important to mention that for each participant, the order of the exercises was randomized (https://www.random.org) and kept constant across all sessions. The data of the study were collected in the sports sciences laboratories of the University of Vic-Central University of Catalonia (Vic, Spain). No interim analyses were performed or planned. The occurrence of severe side effects from the trial was the only criterion for early stopping the study. The study protocol was reviewed and approved by the University of Vic-Central University of Catalonia Research Ethics Committee (internal code: 238/2022) before its commencement. The study respected the rights of the participants at all times and adhered to the principles outlined in the Declaration of Helsinki and its subsequent amendments.

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The athletes visited the centre individually 5 times during the study. The first one was the enrolment session, in which their eligibility criteria were checked. Afterward, once the athletes were informed about the study procedures, they provided their informed consent before their inclusion in it. Finally, their baseline characteristics were registered: self-reported biological sex, age, height measured using a stadiometer (GIMA, Gessate, Italy), body mass and body fat measured using a bioimpedance scale (Omron, Kyoto, Japan), habitual CAFF consumption from foodstuffs (Bühler et al., 2014), and habitual use of CAFF as an ergogenic aid for training and competitions.

During the following weeks, the other 4 sessions (≈3 hours each) took place: familiarization, CON, CAFF consumption, and PLA consumption. The last two sessions mentioned, which were identical and assessed together with the CON one, were performed in a randomized and double-blind fashion. CON session was always the first one assessed, similar to previous research (Filip-Stachnik et al., 2022; Horiuchi & Nagahara, 2024; Hurst et al., 2019). All the sessions were separated by at least 7 days to allow recovery and a wash-out period to avoid carry-over effects (Magkos & Kavouras, 2005). The follow-up period finished the morning after the assessed sessions.

Each participant performed the assessed sessions at a consistent time of the day. During the 48 hours before each session, the athletes were requested not to undergo fatiguing physical activities nor ingest CAFF. During the 24 hours preceding the sessions, they were also not allowed to consume alcohol and had to ingest a diet as similar as possible. To do so, dietary intake information from 24-hour recalls was recorded and evaluated using the ASA24 Dietary Assessment Tool (v. 2022, National Cancer Institute, Maryland, United States of America). Finally, 2-4 hours before the beginning of the sessions, they had to eat their habitual pre-exercise meal.

As part of the familiarization session, the participants completed the 48-hour CAFF control and the ASA24 assessments, and their records were replicated in subsequent sessions. Afterward, they were informed about the benefits of CAFF for exercise performance to achieve a more consistent PLA effect. Then, they standardized the size of 5 elastic bandages, practiced the warm-up protocol used in the remaining sessions, and adjusted the execution and intensity of the squat movement performed in this study. Finally, the exercises performed in the other sessions were demonstrated, and participants practiced them until an acceptable technique was achieved.

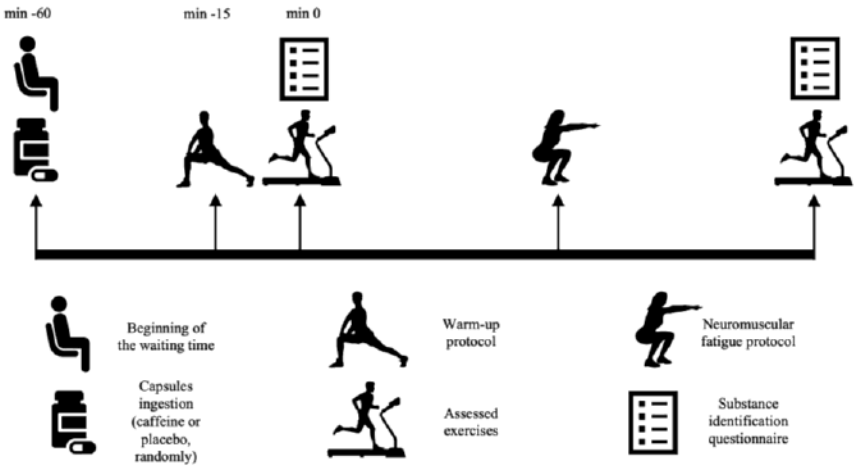


Figure 3. Assessed sessions structure.

The structure of the assessed sessions is outlined in Figure 3. There was no resting period between the exercises or the fatigue protocol. The warm-up protocol consisted of 5 minutes of jogging at 10km/h on a treadmill, 5 minutes of dynamic stretching, and 5 minutes of activity-specific protocols. A Yo-Yo squat protocol was used to generate neuromuscular fatigue, based on previous research (Lesinski et al., 2016). The athletes performed Yo-Yo squats, reaching a 90º knee flexion, until they could not maintain a cadence of 70 beats per minute. They performed as many sets as needed until they could not achieve 60% of the repetitions of the first set, with a 1-minute rest between sets. The participants estimated their perceived exertion after each set using a 6-20 Borg Scale to ensure a high level of effort. During the sessions, environmental characteristics were controlled (mean temperature: 21.50º ± 2.17º, mean humidity: 48.40% ± 10.15%), and the athletes drank water ad libitum.

Caffeine ingestion protocol

In this study, the CON (i.e., no substances consumed), CAFF, and PLA sessions were compared. The format and presentation of PLA and CAFF ingestion protocols were identical. The two conditions involved the oral ingestion of 3 opaque capsules with 200ml of water. Participants consumed 6mg/kg of anhydrous CAFF powder (Harrison Sport Nutrition, Granada, Spain) 60 minutes before exercise, as generally recommended (Maughan et al., 2018), whereas PLA consisted of cellulose (Guinama, Valencia, Spain). CAFF dosage calculations were based on participants' body mass during the enrolment session. Both substances were manually encapsulated (Guinama, Valencia, Spain), and researchers ensured that the athletes consumed the capsules.

Blinding

A random allocation sequence was created by a researcher external to the study using a list of computer-generated random numbers (http://www.randomizer.org), to perform fixed simple randomization without restrictions. To implement the random allocation sequence, the researcher enrolling the participants, who was also present during the rest of the sessions, codified their names in the order in which they were enrolled. This codified data was then sent to the same external researcher, who randomly shuffled its order with a web page (https://www.random.org), and related the randomized order of the participants to the simple randomization sequence of numbers (e.g., first athlete and the first number), and the participants were assigned to a group accordingly (e.g., even numbers - CAFF-PLA sequence; odd numbers - PLA-CAFF sequence). The external researcher saved a copy of the allocation list in a location inaccessible to the other investigators. Half of the 14 participants were assigned to each group (allocation ratio 1:1). Afterward, the external researcher placed the opaque capsules of CAFF and PLA in envelopes, and on their outside part, the codified athlete's name and the session in which they were to be consumed were written. Therefore, the participants and all researchers directly involved in the sessions, data collection and analysis, and outcome assessment, were blinded. The treatment order was revealed after the data analyses and outcome adjudication were completed.

Caffeine identification and side effects

Participants completed an online questionnaire during the CAFF and PLA sessions, in which they reported what they believed they had ingested: immediately before and after the assessed exercises, the athletes selected between the options "*caffeine*", "*placebo*", or "*I don't know*", providing a reason for their answer (Saunders et al., 2017). The morning after these sessions, participants completed another online questionnaire comprised of 8 questions with yes/no answers to evaluate the side effects of CAFF during the hours after the sessions (Muñoz et al., 2020), in which the attribution of events was based on the participant's self-perception. These outcomes were compared between the PLA and CAFF sessions and considered secondary.

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Statistical analysis

For the analysis of the impact of CAFF on technique and performance, the normal distribution of the non-standardized residuals for each variable was assessed using the Shapiro-Wilk test and Q-Q plots, and any outliers were numerically identified. Since all the variables did not have a normal distribution or had outliers, they were analysed non-parametrically. Data are reported as their median and 25-75 centile range (IQR). An Aligned Rank Transform (ART) ANOVA (Wobbrock et al., 2011) was performed for each outcome to assess the disparities between conditions. If any significant differences were found, post-hoc pairwise comparisons were performed with Bonferroni's correction, using the ART-C procedure (Elkin et al., 2021). The relative ES of the ANOVAs was measured using the partial eta squared (η_p^2) and interpreted as small (0.01), medium (0.06), and large (0.14). For the multiple pairwise comparisons, the adjusted simple ES (differences in means of the aligned ranks) and their 95% confidence interval (CI) are reported. In addition, Cohen's D ES is also reported, interpreted as trivial (<0.2), small (0.2-<0.6), moderate (0.6-<1.2), large (1.2-<2.0), very large (2.0-<4.0), and extremely large (≥4). The ES from ART and ART-C are based on the aligned rank-transformed data, so they should be considered cautiously. *P*-value significance was set at .05.

The effectiveness of blinding was measured using the Bang blinding index (BBI) and reported as the estimate and its 95% CI, as well as the number of cases for each circumstance. The McNemar test was used to assess the differences in the frequencies of side effects using its p-value, and the number of cases is reported descriptively too, but ES and their CI were not calculated due to low or null cases in most variables. The ICC(2,1) was measured (two-way mixed effects, absolute agreement, single rater) to assess the reliability of the 2D analysis variables and was interpreted with the 95% CI as poor (<0.50), moderate (0.50-<0.75), good (0.75-0.90), or excellent (>0.90).

All the analyses considered the data at the outcome time point of the 14 participants who completed the study, as randomized. They were performed using R (v. 4.4.2, R Foundation for Statistical Computing, Vienna, Austria) through RStudio (v. 2023.06.0+421, Posit Software, Boston, United States of America) and the add-on packages "*readxl*", "*dplyr*", "*knitr*", "*rstatix*", "*afex*", "*emmeans*", "*effectsize*", "*car*", "*ARTool*", "*BI*", "*rcompanion*", and "*psych*".

RESULTS

Effect of caffeine on technique and performance

The complete data of the analysed performance and biomechanical outcomes can be found in Supplementary Material 2. Table 2 provides a summary of the significant results from the analyses. Figures 4 and 5 also illustrate some of the main findings.

Table 2. Significant results found in the ART ANOVA and the post-hoc comparisons.

Outcome	ART Anova significant results (*p*-value)	Significant post-hoc comparisons (*p*-value)	Effect direction
Knee angle at midstance	Fatigue (p = .0010)	PRE – POST (p = .0010)	↑ knee angle (e.g., ↓ knee flexion) in POST
Contact time of the right leg	Treatment (p = .0016)	PLA – CON (p = .0010)	↑ contact time in PLA
Contact time of the left leg	Treatment (p = .0212)	PLA – CON (p = .0341)	↑ contact time in PLA
Flight time of the right leg	Fatigue (p = .0002)	PRE – POST (p = .0002)	↓ flight time in POST
Flight time of the left leg	Fatigue (p = .0002)	PRE – POST (p = .0002)	↓ flight time in POST
Step rate of the right leg	Treatment (p = .0060) Fatigue (p = .0070)	CAFF – CON (p = .0057) PRE – POST (p = .0070)	↓ step rate in CAFF ↑ step rate in POST
Step rate of the left leg	Treatment (p = .0069) Fatigue (p = .0057)	CAFF – CON (p = .0069) PRE – POST (p = .0057)	↓ step rate in CAFF ↑ step rate in POST

Stride length of the right leg	Treatment (p = .0065) Fatigue (p = .0055)	CAFF – CON (p = .0058) PRE – POST (p = .0055)	↑ stride length in CAFF ↓ stride length in POST
Stride length of the left leg	Treatment (p = .0094) Fatigue (p = .0071)	CAFF – CON (p = .0091) PRE – POST (p = .0071)	↑ stride length in CAFF ↓ stride length in POST
Running performance	Treatment (p = .0003)	PLA – CON (p = .0011) CAFF – CON (p = .0011)	PLA ↓ time than CON CAFF ↓ time than CON
	Fatigue (p = .0015)	PRE – POST (p = .0015)	↓ time in PRE
	Treatment × Fatigue (p = .0089)	CAFF PRE - PLA POST (p = .0413) PLA PRE - CON POST (p = .0027) PLA PRE - CON PRE (p = .0026) PLA PRE - CAFF POST (p = .0380) CAFF PRE - CON POST (p = .0001) CAFF PRE - CON PRE (p = .0001) CAFF PRE - CAFF POST (p = .0011)	CAFF PRE ↓ time than PLA POST PLA PRE ↓ time than CON POST PLA PRE ↓ time than CON PRE PLA PRE ↓ time than CAFF POST CAFF PRE ↓ time than CON POST CAFF PRE ↓ time than CON PRE CAFF PRE ↓ time than CAFF POST

Note. Abbreviations: PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. ↑= More. ↓= Less.

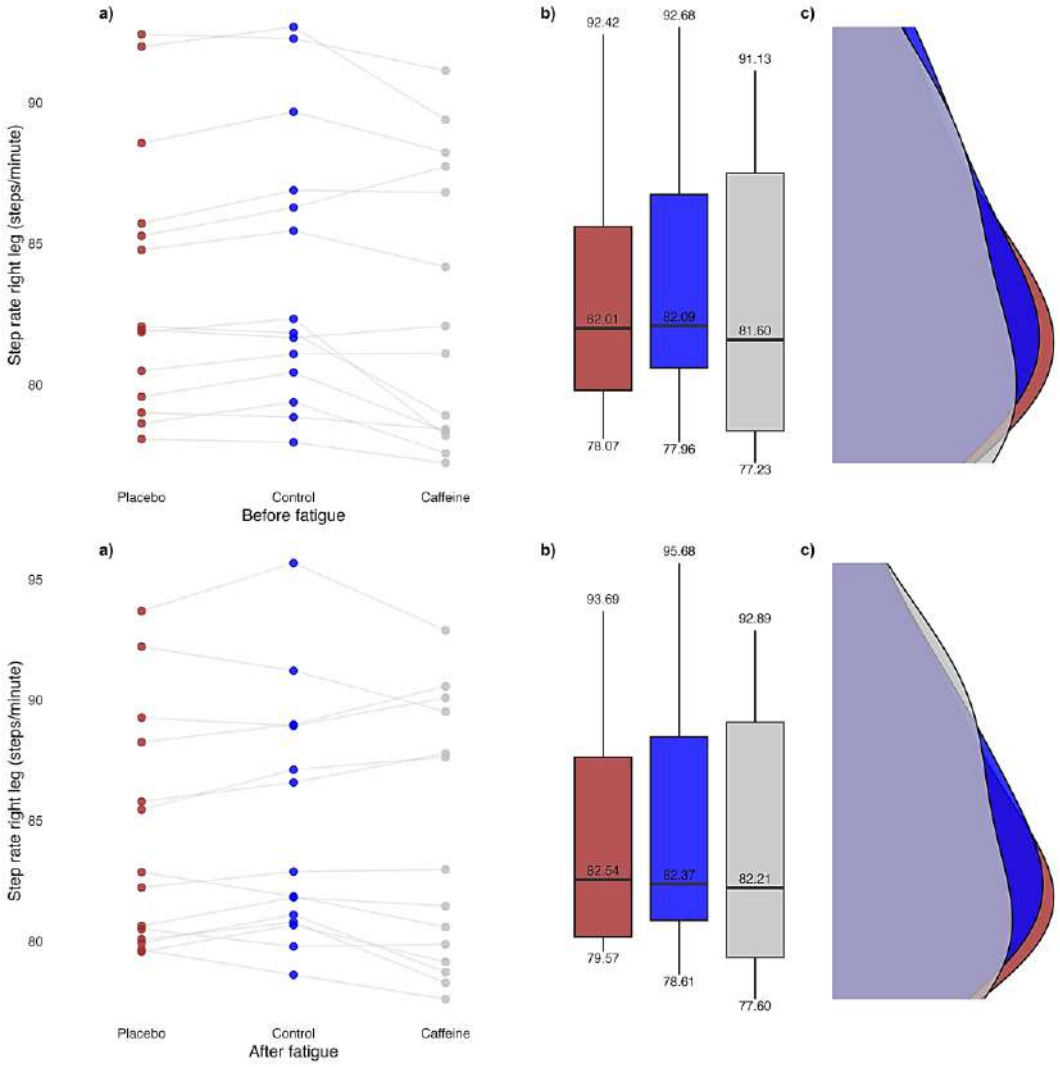


Figure 4. Differences in the step rate of the right leg between the caffeine, control, and placebo sessions, before (top) and after (bottom) the fatiguing protocol. The data for the left leg is not presented due to the similarity in both legs' results. a) Individual data of each participant. b) Box and whisker plot. c) Distribution plot.

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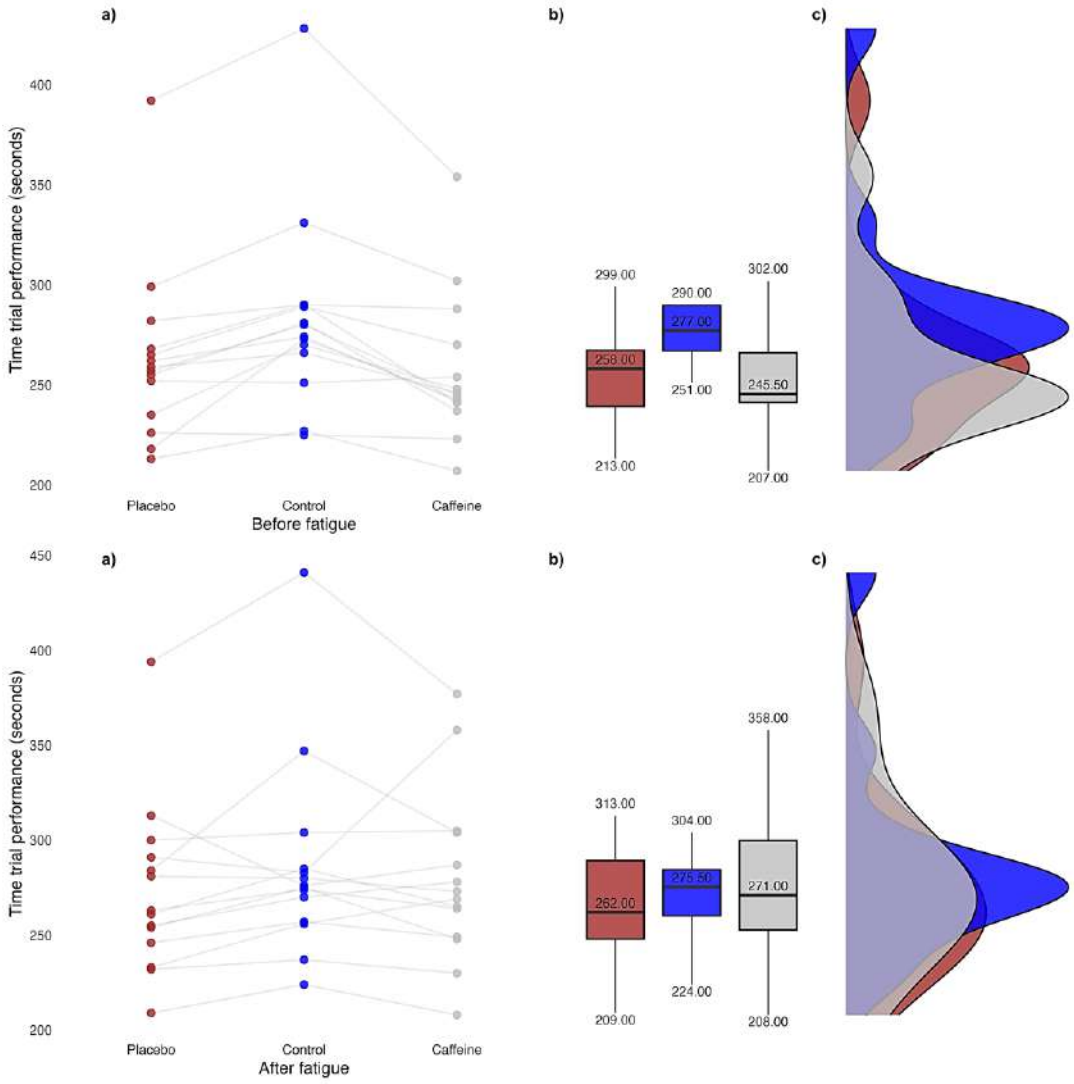


Figure 5. Differences in the running performance between the caffeine, control, and placebo sessions, before (top) and after (bottom) the fatiguing protocol. a) Individual data of each participant. b) Box and whisker plot. c) Distribution plot.

On the other hand, for the tibial angle at midstance, in the ART ANOVA, only a tendency towards significance was found for Treatment (p = .0835) and Fatigue (p = .0513). Likewise, for the flight time of the right leg, only a tendency towards significance was also found for Treatment (p = .0723).

Blinding effectiveness, side effects, and reliability

The complete data of the analysed outcomes for the blinding, side effects, and reliability can be found in Supplementary Material 2. Regarding blinding, when answering before the beginning of the exercises, in the CAFF session, 4/14 participants identified CAFF (BBI = 0.07 [95%CI: -0.30, 0.44]), while in the PLA session, 6/14 athletes identified PLA (BBI = 0.36 [95%CI: 0.04, 0.68]). When answering after the end of the exercises, in the CAFF session, 4/14 athletes identified CAFF (BBI = 0.00 [95%CI: -0.40, 0.40]), while in the PLA session, 4/14 participants identified PLA (BBI = -0.14 [95%CI: -0.58, 0.29]). On the other hand, there were no significant differences in the frequencies of side effects between treatments. Finally, all the 2D variables

showed good to excellent intratester reliability (ICC: 0.91-0.95), except for the knee angle and the tibial angle, for which it was excellent (ICC: 0.97-0.98).

DISCUSSION

The primary objective of this study was to evaluate the impact of CAFF on technique and performance during treadmill running. The results of the trial indicate that: 1) CAFF and PLA reduced the time to complete the time trial, while fatigue had the opposite effect; 2) CAFF, PLA, and fatigue modified the kinematics of running. The impact of some of these effects will be discussed regarding their influence on injury risk and running economy. Because no direct measurements were undertaken for this purpose, this analysis is intended to provide a foundation for future longitudinal and more specific research to determine if these modifications truly have an effect on injuries and running economy. Consequently, no firm conclusions can be drawn in this regard from our results.

Regarding running performance: CAFF without fatigue (PRE) was faster than CAFF with fatigue (POST), PLA POST, CON PRE, and CON POST; PLA PRE was faster than CAFF POST, CON PRE, and CON POST; CAFF was faster than CON; PLA was faster than CON; and PRE was faster than POST. CAFF may enhance running performance (Schubert & Astorino, 2013; Wang et al., 2023) and might modify pacing strategies (Wang et al., 2023). Our results support the performance-enhancing effect of CAFF in time trials, particularly before fatigue and compared to the CON session. They also suggest that CAFF generates a more front-loaded strategy in the effort distribution of exercises with incomplete resting bouts, influenced by the accumulation of fatigue. However, in continuous efforts, this theory may not apply (Rohloff et al., 2022).

It is important to note that PLA performance was also improved. The impression that CAFF has been ingested when knowing its benefits could lead to an improvement in performance (Saunders et al., 2017). Moreover, the belief of having ingested CAFF has been reported to improve performance and affect the pacing (Hurst et al., 2019; Rohloff et al., 2022), and to increase the distance covered while running for a limited time (Valero et al., 2024). Consequently, the CON session is a relevant element to be included in CAFF studies.

As for the biomechanical outcomes, after the fatiguing protocol, there was less knee flexion at midstance. An increased knee range of movement during the stance phase of running has been associated with fatigued conditions (Encarnación-Martínez et al., 2021), and it is unclear whether a larger knee flexion at midstance might enlarge or reduce energetic cost (Van Hooren et al., 2024). In this regard, greater knee flexion during the midstance reduces vertical ground reaction forces and injury risk in the lower extremity, although it could also augment the metabolic cost (Encarnación-Martínez et al., 2021). Besides, both a smaller peak knee flexion angle (Ceyssens et al., 2019) and a more flexed knee in the midstance (Skypala et al., 2023) may be associated with an increased risk of running-related injuries. Therefore, fatigue generated an unexpected strategy that may be energetically efficient, at the expense of more injury risk. However, previous evidence is conflicting in this regard.

On the other hand, PLA generated greater contact time than CON for both legs. Unlike our results, in central fatigue conditions, stance time may be augmented (Encarnación-Martínez et al., 2021), PLA might not be able to modify contact time compared to CON (Valero et al., 2024), and CAFF consumption could decrease support time while sprinting (Horiuchi & Nagahara, 2024). These disparities could be due to differences in the running protocols. Shorter (Ceyssens et al., 2019) and longer (Willwacher et al., 2022) ground contact times have been associated with an increased risk of running-related injuries. Therefore, PLA increased contact time, which has an equivocal impact on injury risk.

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Regarding flight time, in the fatigued state, it was reduced in both legs. As in our study, CAFF consumption did not affect flight time during sprints (Horiuchi & Nagahara, 2024). In this regard, it has been hypothesized that a higher duty factor (e.g., shorter contact time and/or longer flight time) could lead to lower energy cost at slower speeds (Van Hooren et al., 2024), such as that analysed in this study. Consequently, PLA and fatigue may be detrimental to the running economy due to their impact on contact time and flight time, respectively.

We also found a lower step rate in CAFF than in CON and a higher step rate in the fatigued state in both legs. In contrast, a sustained stride frequency has been suggested in fatigue conditions, as long as the running speed remains constant (Encarnación-Martínez et al., 2021). PLA has already been shown not to affect step frequency compared to CON (Valero et al., 2024), while CAFF was unable to modify this variable on 100-meter sprints (Matsumura et al., 2023), but increased it during 60-meter sprints (Horiuchi & Nagahara, 2024). A lower step frequency could increase the risk of running-related injuries (Ceyssens et al., 2019; Mesquita et al., 2025). Additionally, deviating too much from the preferred step frequency may reduce running economy (Bernans et al., 2023), and a higher stride frequency has been associated with a lower energetic cost (Van Hooren et al., 2024). Considering this information, CAFF may increase injury risk by lowering the step rate, while fatigue could have the opposite effect. Besides, CAFF may worsen the running economy.

In addition, both legs showed a greater stride length in CAFF than in CON and a shorter stride length in the fatigued state. Contrary to our study, CAFF was not able to modify this variable during sprints (Horiuchi & Nagahara, 2024; Matsumura et al., 2023), and in fatigued conditions with a constant running speed, a sustained stride length can be expected (Encarnación-Martínez et al., 2021). Since a longer stride length when running at a constant speed may lead to a greater energetic cost of running (Van Hooren et al., 2024), CAFF may lower the running economy, while fatigue may increase it.

Considering these results, our hypothesis is partly confirmed, as CAFF was able to modify some aspects of running technique, although its effects were not beneficial for injury risk or running economy. Future research should continue to assess the impact of sports supplements on technique and performance. It would also be interesting to test it using different systems and circumstances closer to competition movements.

Finally, the blinding was better for CAFF than PLA. In the PLA sessions, almost half of the participants correctly identified PLA before exercise, while the same proportion of participants believed that they had consumed CAFF after the session. This may be due to the more stable performance in PLA sessions. Regarding side effects, although no significant differences were found between CAFF and PLA, insomnia, gastrointestinal problems, and tachycardia or palpitations were only reported with CAFF, and there were no cases of irritability overall. Both CAFF and PLA reported the same number of cases of increased activeness and headache, while for the rest of the side effects, CAFF generated a greater incidence.

Limitations

Despite the familiarization session and the easily identifiable session in which no treatment was administered, the difference between CON measures and the two treatments may be biased, as the CON session was always the first to be assessed. However, since 7 athletes underwent the CAFF-PLA and the PLA-CAFF sequence, respectively, the bias effect may be distributed among both treatments. Additionally, similar situations have happened previously (Filip-Stachnik et al., 2022; Horiuchi & Nagahara, 2024; Hurst et al., 2019). Moreover, any carry-over effect of CAFF was likely neglected due to the time between sessions. On the other hand, it is preferable for a randomized controlled trial to have a limited number of primary outcomes (Hopewell et al., 2025). However, due to the nature of this study and its novelty, we believed it may be

interesting to assess diverse variables as primary outcomes. Another limitation is that no sex-specific analyses were performed due to the low number of women participating in this study; nevertheless, these analyses may not be critical, given that CAFF appears to affect both sexes similarly (Montalvo-Alonso et al., 2024; Papadakis et al., 2025). Finally, the reported results should be interpreted with caution when attempting to extrapolate them beyond the circumstances of this trial.

CONCLUSIONS

CAFF improved performance in running time trials compared to CON, suggesting a front-loaded strategy in efforts with an incomplete rest. PLA also enhanced performance relative to CON, which highlights the importance of including CON sessions in ergogenic aids research. Furthermore, CAFF, PLA, and fatigue were able to modify the kinematics of running, adding another layer of complexity when assessing the appropriateness of CAFF ingestion for each athlete.

AUTHOR CONTRIBUTIONS

ABR: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft, visualization, supervision, project administration, funding acquisition. XBB: conceptualization, methodology, validation, formal analysis, investigation, resources, writing – review & editing, visualization, supervision. JP: conceptualization, methodology, validation, formal analysis, investigation, writing – review & editing, visualization, supervision, funding acquisition.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in CORA.RDR repository at https://doi.org/10.34810/data2401.

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SUPPLEMENTARY MATERIAL 1: CONSORT checklist.

Table 1. CONSORT 2025 checklist item description, adapted using the CONSORT 2010 extension to randomized crossover trials (Dwan et al., 2019; Hopewell et al., 2025).

Section/topic	No	CONSORT 2025 checklist item description, adapted using the CONSORT 2010 extension to randomized crossover trials	Reported on
Title and abstract			
Title and structured abstract	1a	Identification as a randomized crossover trial	Title
	1b	Structured summary of the trial design, methods, results, and conclusions	Abstract
Open science			
Trial registration	2	Name of trial registry, identifying number (with URL) and date of registration	Study design
Protocol and statistical analysis plan	3	Where the trial protocol and statistical analysis plan can be accessed	Study design
Data sharing	4	Where and how the individual de-identified participant data (including data dictionary), statistical code and any other materials can be accessed	Data availability statement
Funding and conflicts of interest	5a	Sources of funding and other support (e.g., supply of drugs), and role of funders in the design, conduct, analysis and reporting of the trial	Supporting agencies
	5b	Financial and other conflicts of interest of the manuscript authors	Disclosure statement
Introduction			
Background and rationale	6	Scientific background and rationale	Introduction / Discussion
Objectives	7	Specific objectives related to benefits and harms	Introduction
Methods			
Patient and public involvement	8	Details of patient or public involvement in the design, conduct and reporting of the trial	Study design
Trial design	9	Rationale for a crossover design. Description of trial design including type of trial (e.g., parallel group, crossover), allocation ratio, the number and duration of periods, duration of wash-out period, consideration of carry over effect, and framework (e.g., superiority, equivalence, non-inferiority, exploratory)	Study design / Blinding
Changes to trial protocol	10	Important changes to the trial after it commenced including any outcomes or analyses that were not prespecified, with reason	Study design
Trial setting	11	Settings (e.g., community, hospital) and locations (e.g., countries, sites) where the trial was conducted	Participants / Study design
Eligibility criteria	12a	Eligibility criteria for participants	Participants / Study design
	12b	If applicable, eligibility criteria for sites and for individuals delivering the interventions (e.g., surgeons, physiotherapists)	Not applicable
Intervention and comparator	13	Intervention and comparator with sufficient details to allow replication, including how and when they were actually administered. If relevant, where additional materials describing the intervention and comparator (e.g., intervention manual) can be accessed	Caffeine ingestion protocol
Outcomes	14	Prespecified primary and secondary outcomes, including the specific measurement variable (e.g., systolic blood pressure), analysis metric (e.g., change from baseline, final value, time to event), method of aggregation (e.g., median, proportion), and time point for each outcome	Introduction / Caffeine identification and side effects / Measures
Harms	15	How harms were defined and assessed (e.g., systematically, non-systematically)	Caffeine identification and side effects
Sample size	16a	How sample size was determined, accounting for within participant variability and including all assumptions supporting the sample size calculation	Participants

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Randomization:	16b	Explanation of any interim analyses and stopping guidelines	Study design
Sequence generation	17a	Who generated the random allocation sequence and the method used	Blinding
	17b	Type of randomization and details of any restriction (e.g., stratification, blocking and block size)	Blinding
Allocation concealment mechanism	18	Mechanism used to implement the random allocation sequence (e.g., central computer/telephone; sequentially numbered, opaque, sealed containers), describing any steps to conceal the sequence until interventions were assigned	Blinding
Implementation	19	Whether the personnel who enrolled and those who assigned participants to the interventions had access to the random allocation sequence. Who generated the random allocation sequence, who enrolled participants, and who assigned participants to the sequence of interventions	Blinding
Blinding	20a	Who was blinded after assignment to interventions (e.g., participants, care providers, outcome assessors, data analysts)	Blinding
	20b	If blinded, how blinding was achieved and description of the similarity of interventions	Caffeine ingestion protocol
Statistical methods	21a	Statistical methods used to compare groups for primary and secondary outcomes, including harms, which are appropriate for crossover design (that is, based on within participant comparison)	Statistical analysis
	21b	Definition of who is included in each analysis (e.g., all randomized participants), and in which group	Statistical analysis
	21c	How missing data were handled in the analysis	Not applicable
	21d	Methods for any additional analyses (e.g., subgroup and sensitivity analyses), distinguishing prespecified from post hoc	Not applicable
Results			
Participant flow, including flow diagram	22a	The numbers of participants who were randomly assigned, received intended treatment, and were analysed for the primary outcome, separately for each sequence and period	Participants
	22b	Number of participants excluded at each stage, with reasons, separately for each sequence and period	Participants
Recruitment	23a	Dates defining the periods of recruitment and follow-up for outcomes of benefits and harms	Participants/Study design
	23b	If relevant, why the trial ended or was stopped	Not applicable
Intervention and comparator delivery	24a	Intervention and comparator as they were actually administered (e.g., where appropriate, who delivered the intervention/comparator, how participants adhered, whether they were delivered as intended (fidelity))	Caffeine ingestion protocol / Statistical analysis
	24b	Concomitant care received during the trial for each group	Not applicable
Baseline data	25	A table showing baseline demographic and clinical characteristics by sequence and period	Participants
Numbers analysed, outcomes and estimation	26	For each primary and secondary outcome, based on within participant comparisons: ● Number of participants (denominator) included in each analysis and whether the analysis was by original assigned groups ● the number of participants with available data at the outcome time point ● result for each group, and the estimated effect size and its precision (such as 95% confidence interval). In addition, results for each intervention in each period are recommended ● for binary outcomes, presentation of both absolute and relative effect size	Statistical analysis / Results / Supplementary material
Harms	27	Describe all important harms or untended effects in a way that accounts for the design	Results / Supplementary material
Ancillary analyses	28	Any other analyses performed, including subgroup and sensitivity analyses, distinguishing pre-specified from post hoc	Not applicable
Discussion			
Interpretation	29	Interpretation consistent with results, balancing benefits and harms, and considering other relevant evidence	Discussion
Limitations	30	Trial limitations, addressing sources of potential bias, imprecision, generalizability, and, if relevant, multiplicity of analyses. Consider potential carry over effects	Limitations

SUPPLEMENTARY MATERIAL 2: Participants' outcome results.

MAIN ANALYSES

Table 1. Results of the statistical analyses of the knee angle at midstance.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.1244	0.06 $F_{(2,65)}$ = 2.1528	[0.00, 0.16]
Fatigue	.0010*	0.15 $F_{(1,65)}$ = 11.8172	[0.04, 0.29]
Treatment*Fatigue	.9334	2.12e-03 $F_{(2,65)}$ = 0.0690	[0.00, 0.01]

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0010*	7.33	[3.07, 11.6]	0.75
Pre			Post	
Median	IQR		Median	IQR
130.19º	128.31º-132.94º		131.70º	129.22º-134.37º

*Note. Abbreviations: PRE = Values before fatigue. POST = Values after fatigue. ηp2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

Table 2. Results of the statistical analyses of the tibial angle at midstance.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0835^	0.07 $F_{(2,65)}$ = 2.5809	[0.00, 0.18]
Fatigue	.0513^	0.06 $F_{(1,65)}$ = 3.9434	[0.00, 0.17]
Treatment*Fatigue	.6571	0.01 $F_{(2,65)}$ = 0.4227	[0.00, 0.07]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.4552	4.46	[-3.10, 12.03]		0.39
PLA-CAFF	.0856^	6.89	[-0.67, 14.46]		0.60
CON-CAFF	1.0000	2.43	[-5.14, 9.99]		0.21
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
28.24º	25.97º-30.68º	27.18º	25.90º-29.89º	27.70º	25.26º-29.36º

PAIR-WISE COMPARISON

Fatigue				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0513^	-5.00	[-10.00, 0.03]	-0.43
Pre			Post	
Median	IQR		Median	IQR
28.42º	26.05º-30.51º		27.24º	25.32º-29.94º

Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. ^ Denotes p = >.05 - <.10.

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Table 3. Results of the statistical analyses of the contact time of the right leg.
ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0016*	0.18 $F_{(2,65)}$ = 7.1485	[0.05, 0.31]
Fatigue	.1415	0.03 $F_{(1,65)}$ = 2.2150	[0.00, 0.13]
Treatment*Fatigue	.9538	1.46e-03 $F_{(2,65)}$ = 0.0474	[0.00, 0.00]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.0010*	8.93	[3.12, 14.73]		1.01
PLA-CAFF	.2299	4.25	[-1.56, 10.06]		0.48
CON-CAFF	.1556	-4.68	[-10.48, 1.13]		-0.53
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
0.287s	0.269s-0.304s	0.281s	0.266s-0.290s	0.284s	0.265s-0.304s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

Table 4. Results of the statistical analyses of the contact time of the left leg.
ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0212*	0.11 $F_{(2,65)}$ = 4.093	[0.01, 0.23]
Fatigue	.1231	0.04 $F_{(1,65)}$ = 2.441	[0.00, 0.14]
Treatment*Fatigue	.5135	0.02 $F_{(2,65)}$ = 0.6733	[0.00, 0.09]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.0341*	6.00	[0.34, 11.66]		0.70
PLA-CAFF	1.0000	0.64	[-5.02, 6.30]		0.08
CON-CAFF	.0694^	-5.36	[-11.02, 0.30]		-0.62
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
0.282s	0.263s-0.297s	0.276s	0.253s-0.287s	0.280s	0.256s-0.299s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 5. Results of the statistical analyses of the flight time of the right leg.
ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0723^	0.08 $F_{(2,65)}$ = 2.7359	[0.00, 0.19]
Fatigue	.0002*	0.19 $F_{(1,65)}$ = 15.0618	[0.07, 0.33]
Treatment*Fatigue	.7026	0.01 $F_{(2,65)}$ = 0.3549	[0.00, 0.06]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	1.0000	-1.75	[-6.60, 3.10]		-0.24
PLA-CAFF	.0708^	-4.57	[-9.42, 0.28]		-0.62
CON-CAFF	.4719	-2.82	[-7.67, 2.03]		-0.38
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
0.422s	0.390s-0.467s	0.425s	0.394s-0.469s	0.413s	0.393s-0.487s

PAIR-WISE COMPARISON

Fatigue				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0002*	-6.14	[-9.30, -2.98]	-0.85
Pre			Post	
Median	IQR		Median	IQR
0.426s	0.398s-0.477s		0.410s	0.383s-0.473s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 6. Results of the statistical analyses of the flight time of the left leg.

ART ANOVA

Effect	***p*-Value**	**η_p^2**	**90%CI η_p^2**
Treatment	.1017	0.07 $F_{(2,65)}$ = 2.3676	[0.00, 0.17]
Fatigue	.0002*	0.19 $F_{(1,65)}$ = 15.3215	[0.07, 0.33]
Treatment*Fatigue	.9512	1.54e-03 $F_{(2,65)}$ = 0.0500	[0.00, 0.00]

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	0.0002*	-6.43	[-9.71, -3.15]	-0.85
Pre			Post	
Median	IQR		Median	IQR
0.429s	0.402s-0.491s		0.415s	0.388s-0.489s

*Note. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

Table 7. Results of the statistical analyses of the step rate of the right leg.

ART ANOVA

Effect	***p*-Value**	**η_p^2**	**90%CI η_p^2**
Treatment	.0060*	0.15 $F_{(2,65)}$ = 5.5346	[0.03, 0.27]
Fatigue	.0070*	0.11 $F_{(1,65)}$ = 7.7697	[0.02, 0.24]
Treatment*Fatigue	.6796	0.01 $F_{(2,65)}$ = 0.3886	[0.00, 0.06]

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PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	1.0000	-2.04	[-7.33, 3.25]		-0.25
PLA-CAFF	.0759^	4.93	[-0.36, 10.22]		0.61
CON-CAFF	.0057*	6.96	[1.67, 12.25]		0.86
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
82.15 steps/min	80.04 steps/min-86.40 steps/min	82.10 steps/min	80.76 steps/min-87.56 steps/min	81.77 steps/min	78.65 steps/min-87.90 steps/min

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0070*	4.81	[1.36, 8.26]	0.61
Pre			Post	
Median	IQR		Median	IQR
82.01 steps/min	79.10 steps/min-86.87 steps/min		82.54 steps/min	80.18 steps/min-88.76 steps/min

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 8. Results of the statistical analyses of the step rate of the left leg.

ART ANOVA

Effect	***p*-Value**	**η_p^2**	**90%CI η_p^2**
Treatment	.0069*	0.14 $F_{(2,65)}$ = 5.3718	[0.03, 0.27]
Fatigue	.0057*	0.11 $F_{(1,65)}$ = 8.1630	[0.02, 0.24]
Treatment*Fatigue	.6477	0.01 $F_{(2,65)}$ = 0.4373	[0.00, 0.07]

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	1.0000	-1.89	[-7.23, 3.45]		-0.23
PLA-CAFF	.0738^	5.00	[-0.34, 10.34]		0.62
CON-CAFF	.0069*	6.89	[1.55, 12.23]		0.85
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
82.26 steps/min	80.07 steps/min-86.45 steps/min	82.08 steps/min	80.83 steps/min-87.51 steps/min	81.85 steps/min	78.65 steps/min-87.94 steps/min

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0057*	4.9	[1.48, 8.33]	0.62
Pre			Post	
Median	IQR		Median	IQR
82.09 steps/min	79.15 steps/min-87.06 steps/min		82.55 steps/min	80.21 steps/min-88.53 steps/min

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 9. Results of the statistical analyses of the stride length of the right leg.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0065*	0.14 $F_{(2,65)}$ = 5.4526	[0.03, 0.27]
Fatigue	.0055*	0.11 $F_{(1,65)}$ = 8.2627	[0.02, 0.24]
Treatment*Fatigue	.6777	0.01 $F_{(2,65)}$ = 0.3915	[0.00, 0.07]

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.9412	2.18	[-3.09, 7.45]		0.27
PLA-CAFF	.0911^	-4.75	[-10.02, 0.52]		-0.59
CON-CAFF	.0058*	-6.93	[-12.20, -1.66]		-0.86
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
2.13m	2.03m-2.19m	2.13m	2.00m-2.17m	2.14m	1.99m-2.23m

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0055*	-4.95	[-8.39, -1.51]	-0.63
Pre			Post	
Median	IQR		Median	IQR
2.13m	2.01m-2.21m		2.12m	1.97m-2.18m

Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 *= Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 10. Results of the statistical analyses of the stride length of the left leg.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0094*	0.13 $F_{(2,65)}$ = 5.0195	[0.02, 0.26]
Fatigue	.0071*	0.11 $F_{(1,65)}$ = 7.7257	[0.02, 0.23]
Treatment*Fatigue	.6507	0.01 $F_{(2,65)}$ = 0.4326	[0.00, 0.07]

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size (Estimate)**	**95%CI Simple effect size (lower CL, upper CL)**		**Cohen's D**
PLA-CON	1.0000	1.96	[-3.39, 7.32]		0.24
PLA-CAFF	.0987^	-4.75	[-10.11, 0.61]		-0.58
CON-CAFF	.0091*	-6.71	[-12.07, -1.36]		-0.82
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
2.13m	2.02m-2.19m	2.13m	2.00m-2.17m	2.14m	1.99m-2.23m

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0071*	-4.81	[-8.27, -1.35]	-0.61
Pre			Post	
Median	IQR		Median	IQR
2.13m	2.01m-2.21m		2.12m	1.98m-2.18m

Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 *= Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

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Table 11. Results of the statistical analyses of the running performance.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0003*	0.22 $F_{(2,65)}$ = 9.4208	[0.08, 0.36]
Fatigue	.0015*	0.14 $F_{(1,65)}$ = 10.9809	[0.04, 0.28]
Treatment*Fatigue	.0089*	0.14 $F_{(2,65)}$ = 5.0888	[0.02, 0.26]

PAIR-WISE COMPARISON

TREATMENT*FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
PLA,Post - PLA,Pre	.7089	7.75	[-3.93, 19.43]	0.76
PLA,Post - CON,Post	.8364	-7.46	[-19.14, 4.21]	-0.74
PLA,Post - CON,Pre	.8195	-7.50	[-19.18, 4.18]	-0.74
PLA,Post - CAFF,Post	1.0000	-4.29	[-15.96, 7.39]	-0.42
PLA,Post - CAFF,Pre	.0413*	11.93	[0.25, 23.61]	1.17
PLA,Pre - CON,Post	.0027*	-15.21	[-26.89, -3.54]	-1.50
PLA,Pre - CON,Pre	.0026*	-15.25	[-26.93, -3.57]	-1.50
PLA,Pre - CAFF,Post	.0380*	-12.04	[-23.71, -0.36]	-1.19
PLA,Pre - CAFF,Pre	1.0000	4.18	[-7.50, 15.86]	0.41
CON,Post - CON,Pre	1.0000	-0.04	[-11.71, 11.64]	-0.01
CON,Post - CAFF,Post	1.0000	3.18	[-8.50, 14.86]	0.31
CON,Post - CAFF,Pre	.0001*	19.39	[7.71, 31.07]	1.91
CON,Pre - CAFF,Post	1.0000	3.21	[-8.46, 14.89]	0.32
CON,Pre - CAFF,Pre	.0001*	19.43	[7.75, 31.11]	1.92
CAFF,Post - CAFF,Pre	.0011*	16.21	[4.54, 27.89]	1.60

PLA PRE		PLA POST	
Median	IQR	Median	IQR
258.00s	239.25s-267.25s	262.00s	248.00s-289.25s
CON PRE		CON POST	
Median	IQR	Median	IQR
277.00s	267.00s-289.75s	275.50s	260.25s-284.50s
CAFF PRE		CAFF POST	
Median	IQR	Median	IQR
245.50s	241.25s-266.00s	271.00s	252.75s-299.75s

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.0011*	-11.02	[-18.23, -3.80]		-1.00
PLA-CAFF	1.0000	0.04	[-7.18, 7.25]		0.01
CON-CAFF	.0011*	11.05	[3.84, 18.27]		1.01
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
260.00s	243.25s-282.50s	275.50s	263.75s-289.25s	259.00s	242.75s-287.25s

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0015*	7.95	[3.16, 12.70]	0.72
Pre			Post	
Median	IQR		Median	IQR
260.50s	242.25s-281.75s		273.50s	254.25s-290.00s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

BLINDING EFFECTIVENESS

Table 12. Blinding effectiveness, before and after the assessed exercises.

PRE SESSION		
	CAFF	**PLA**
CAFF Perception	4/14	1/14
PLA Perception	3/14	6/14
I don't know	7/14	7/14

POST SESSION		
	CAFF	**PLA**
CAFF Perception	4/14	6/14
PLA Perception	4/14	4/14
I don't know	6/14	4/14

Note. PLA = Placebo session. CAFF = Caffeine session. PLA PERCEPTION = Placebo perception. CAFF PERCEPTION = Caffeine perception.

SIDE EFFECTS

Table 13. Results of the side effects analyses.

Side effect	**Count in CAFF**	**Count in PLA**	**McNemar's Chi-Squared**	***p*-Value**
Insomnia	4/14	0/14	2.25	.1336
Increased urine production	3/14	1/14	0.25	.6171
Gastrointestinal problems	1/14	0/14	0	1.0000
Increased activeness	4/14	4/14	0	1.0000
Headache	1/14	1/14	0	1.0000
Irritability	0/14	0/14	NaN	NA
Muscular pain	3/14	2/14	0	1.0000
Tachycardia or palpitations	2/14	0/14	0.5	.4795

Note. PLA = Placebo session. CAFF = Caffeine session.

RELIABILITY

Table 14. Reliability of the analysed variables.

Variable	**$ICC_{(2,1)}$**	**95%CI**	**Interpretation**
Knee angle at the midstance (º)	0.97	[0.91,0.99]	Excellent
Tibial angle at the midstance (º)	0.98	[0.93,0.99]	Excellent
Contact time right leg (s)	0.94	[0.85,0.98]	Good to excellent
Contact time left leg (s)	0.95	[0.86,0.99]	Good to excellent
Flight time right leg (s)	0.92	[0.79,0.98]	Good to excellent
Flight time left leg (s)	0.91	[0.78,0.98]	Good to excellent

Note. ICC = Intraclass Correlation Coefficient. CI = Confidence Intervals. º = degrees. s = Seconds.



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ORIGINAL ARTICLE

Beyond the game: Social interaction, motivation, and well-being in 3x3 basketball

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ABSTRACT

This study examined the social, psychological, and recreational motives underlying participation in 3x3 basketball, a rapidly growing urban sport that combines physical activity with informal social interaction. A total of 305 athletes aged 12–60 years competing in officially organized 3x3 basketball tournaments in Greece completed validated instruments assessing recreational experiences and participation motives. The findings revealed that social interaction constituted the primary motive for participation, with strong emphasis on being with friends, team affiliation, and opportunities for forming new social connections. Participation was also closely associated with escape from daily routines and social pressures, contributing to psychological restoration, emotional balance, and perceived well-being. Achievement-related motives were mainly linked to social recognition and affirmation of personal competence, highlighting the importance of intrinsic motivation. High levels of enthusiasm, enjoyment, and creativity reflected the fast-paced, flexible, and expressive nature of the 3x3 format. Exercise-related motives emphasized physical fitness, positive feelings following activity, and health maintenance. Overall, the results highlight the multidimensional recreational value of 3x3 basketball as an accessible sport that promotes social connectedness, psychological well-being, and sustained engagement in physical activity, with important implications for community-based recreational sport programs and quality-of-life enhancement.

Keywords: Social interaction, Intrinsic motivation, Recreational sport, Psychological well-being, Quality of life.

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INTRODUCTION

In recent years, sports organizations have increasingly shifted their focus toward developing recreational programs in response to contemporary societal demands for health, well-being, and active lifestyles (Alexandris et al., 2016). Within this evolving context, sports clubs no longer operate exclusively as competitive institutions but increasingly function as environments that promote physical activity, social engagement, and positive lifestyle habits across the lifespan. The expansion of sports academies and camps for children and youth reflects this transformation, as such initiatives aim not only at physical development but also at socialization and the cultivation of positive attitudes toward exercise. At the same time, structured recreational programs targeting students and adults have gained prominence, emphasizing participation, enjoyment, and health promotion rather than performance outcomes (Alexandris & Balaska, 2015; Polatidou, 2015). Collectively, these developments highlight the growing role of sports clubs as facilitators of lifelong physical activity and quality of life, offering inclusive participation opportunities to individuals of diverse ages, interests, and fitness levels.

Participation in recreational activities, particularly those embedded in urban or natural environments such as parks, streets, and public spaces, has been shown to create meaningful opportunities for social interaction, personal growth, and sustained engagement in physical activity (Alexandris et al., 2017; Theodorakis et al., 2013). Such activities provide access to novel experiences that enhance perceived quality of life while reducing barriers associated with formal or highly competitive sport settings (Alexandris et al., 2017). Within this framework, 3x3 basketball has emerged as a contemporary and rapidly expanding form of physical activity that combines the enjoyment of play with the benefits of exercise and social interaction. As a variation of traditional basketball, 3x3 is played on a half-court with three players per team and one substitute, allowing for flexible organization in outdoor and urban environments such as public squares and parks. Its accessibility, minimal infrastructure requirements, and short game duration make it particularly suitable for recreational participation without the pressures typically associated with formal competitive basketball. In addition, the sport provides high-intensity physical activity, contributing to improvements in cardiovascular fitness, reaction speed, muscular strength, and overall physical condition.

Participation in sports and organized physical activity plays a critical role in children's and adolescents' physical, social, and psychosocial development. Central to understanding sustained engagement in sport is the concept of sport involvement, defined as the degree of psychological connection, interest, and emotional attachment an individual develops toward a specific activity. Sport involvement has been widely examined in the fields of sport and recreation, with research demonstrating its association with intrinsic motivation, enjoyment, satisfaction, and long-term participation (Alexandris et al., 2006, 2008, 2012; Beaton et al., 2011; Funk et al., 2007, 2016; Kyle et al., 2004; Ridinger et al., 2012). Higher levels of involvement foster emotional engagement and a stronger personal bond with the activity, reinforcing positive participation experiences (Park et al., 2007).

Recreational sport programs are typically designed to promote enjoyment and pleasure, support the development of general and sport-specific skills, enhance physical fitness and performance, and facilitate social interaction and relationship-building among participants, while also promoting sporting values and ethical behaviour (Malina et al., 2004). However, participation in recreational sport is not without barriers. Research by Alexandris and Carroll (1997) indicated that lower educational levels are associated with increased barriers to participation, particularly intrapersonal constraints such as limited prior sport experience, lack of information, and reduced awareness of available opportunities. Subsequent studies further demonstrated that psychological factors, personal characteristics, and time-related constraints

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negatively influence engagement in physical activity and constitute significant obstacles to participation in recreational sport programs (Alexandris et al., 2002, 2008).

Establishing habits related to regular physical activity, continued sport participation into adulthood, and lifelong exercise is therefore of considerable importance. Engagement in sport at an early age has been shown to produce long-term benefits for both physical health and psychosocial well-being, supporting holistic development across the lifespan (Malina, 2009). Empirical evidence from recreational sport research consistently indicates positive associations between participation in physical activity, perceived well-being, health status, and overall quality of life (Doyle et al., 2016; Leung & Lee, 2005; Ma & Kaplanidou, 2017, 2018; Wendel-Vos et al., 2004). Nevertheless, the underlying mechanisms through which leisure and recreational sport participation contribute to enhanced quality of life remain insufficiently understood. Iwasaki (2007) and Brajša-Žganec et al. (2011) emphasized the need for further investigation into the pathways linking leisure engagement with well-being outcomes. Existing evidence suggests that recreational activity participation promotes positive emotions, strengthens social connections, facilitates personal achievement, and supports psychological growth, all of which contribute to subjective well-being (Doyle et al., 2016; Downward & Rasciute, 2011; Seligman, 2011). Indeed, achieving well-being is widely recognized as a fundamental human goal (Forgeard et al., 2011).

Parallel to these developments, sporting events hosted in urban outdoor spaces have emerged as one of the most dynamic sectors of contemporary sports tourism. Such events utilize the urban environment as a platform for participation and experience, attracting athletes, spectators, and visitors while enhancing the destination's cultural and social identity. The literature highlights that sports events contribute to tourism development by integrating athletic activity with entertainment and community engagement, generating social, economic, and cultural benefits for host locations (Chalip, 2004, 2014; Chalip et al., 2017; Chalip & Costa, 2005). In this context, recreational and participatory sport events extend beyond competition, functioning as social experiences that promote community cohesion and active lifestyles.

Against this broader backdrop, the rapid global growth of 3x3 basketball has reshaped contemporary sport participation by blending the informal character of street basketball with a more organized and professional structure. Official recognition by FIBA and inclusion in the Olympic program in 2020 have further accelerated the sport's popularity across different age groups and cultural contexts, largely due to its accessibility, fast pace, and entertainment value (Yazici, 2023). Compared to traditional 5x5 basketball, the condensed format of 3x3 creates a highly intense and dynamic playing environment that demands speed, agility, creativity, and rapid decision-making. Importantly, this format appears to satisfy key intrinsic participation motives, including competence, autonomy, and social connectedness (Deci & Ryan, 2000). Despite its growing popularity and apparent relevance to recreational sport, limited empirical research has examined the social, psychological, and recreational motives that drive participation in 3x3 basketball. Therefore, the purpose of the present study is to investigate the social, psychological, and recreational motives underlying participation in 3x3 basketball, contributing to a deeper understanding of its role in promoting engagement, well-being, and quality of life within contemporary recreational sport contexts. There are three research hypotheses. Participation in 3x3 basketball is primarily motivated by social factors, as athletes report high levels of social interaction, friendship, group belonging, and the formation of new social relationships (H1). Participation in 3x3 basketball is positively associated with psychological benefits, including escape from daily routine and pressures, increased calmness, balance, enthusiasm, and emotional stimulation (H2). Participation in 3x3 basketball is positively related to physical exercise, creativity, recreational enjoyment, social recognition, and identity expression, making the sport a meaningful component of athletes' lifestyles (H3).

MATERIAL AND METHODS

Participants

The study sample included 305 athletes, comprising 65 women (22%) and 238 men (78%), who took part in 3x3 basketball tournaments held across Central, Northern, and Western Greece. Participants had a mean age of 20.78 years (SD = 8.76). On average, they reported remaining with the same team for 5.45 years (SD = 4.08) and having an overall basketball involvement of 10.60 years (SD = 6.54). Data collection took place during officially sanctioned 3x3 competitions. More specifically, the dataset was drawn from two types of events: (1) the 3x3GR National Tour, a nationwide 3x3 tournament series, and (2) 3x3GR events approved by the Hellenic Basketball Federation (HBF).

Measures

Service quality was assessed using the five-dimensional Sport Service Quality Scale developed by Alexandris et al. (2004), adapted to the context of the present study. In addition, the Recreation Experience Preference Scales and Domains (Driver, 1983) were employed to measure experiential motives, including social recognition, creativity, escape from daily routine, and social interaction (e.g., "*I play 3x3 to be with friends*"). These instruments were selected because they have demonstrated strong applicability and validity in both international and Greek research settings and are closely aligned with the objectives and research questions of the current study. A pilot study was first conducted with a satisfactory sample of 60 participants in order to test the questionnaires within the Greek population and ensure their suitability. Following the pilot phase, the main data collection took place, during which all research data required for analysis were gathered from participating athletes.

Procedures

Prior to data collection, ethical approval for the study was granted by the Ethics Committee of the Aristotle University of Thessaloniki, School of Physical Education and Sport Science (approval number 289/2025). Data were gathered during official 3x3 basketball tournaments held in Central, Northern, and Western Greece. Participants were informed about the purpose of the study and assured that their responses would remain confidential and anonymous. Participation was voluntary, and informed consent was obtained from all individuals before completing the questionnaires. The research instruments were administered in person at the tournament venues immediately following the athletes' participation in competition. This timing was selected to enhance the accuracy, immediacy, and relevance of participants' responses.

Analysis

Descriptive statistics were used to analyse the motivational factors related to participation in 3x3 basketball. Frequencies, percentages, relative frequencies, and cumulative frequencies were calculated for all variables in order to describe participants' responses across the examined dimensions, including social interaction, meeting new people, escape from personal and physical pressures, calmness, goal achievement, enthusiasm, creativity, exercise, and recreation. The distribution of responses allowed for the identification of dominant motivational patterns and experiential characteristics associated with 3x3 basketball participation.

RESULTS

Descriptive statistics were calculated for the demographic characteristics of the participants, including age, years of participation with the same team, years working with the same coach, and total years of involvement in basketball. The mean age of the participants was 20.78 years (SD = 8.76). On average, participants

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reported 5.45 years (SD = 4.08) of participation with their current team, 3.49 years (SD = 3.42) with their coach, and 10.60 years (SD = 6.54) of total involvement in basketball. Ages ranged from 12 to 60 years, while years of participation variables ranged from 0 to 45 years. A frequency analysis was then conducted for gender, educational level, occupational status, and playing position. Specifically, the sample consisted of 67 women and 238 men. The majority of participants were secondary school students (55.41%), followed by primary school students (19.02%), university students (15.74%), postgraduate degree holders (5.25%), and vocational institute graduates (4.59%). Regarding occupational status, 50.16% of participants identified as students, followed by university students (23.93%), private-sector employees (12.46%), unemployed individuals (5.25%), public-sector employees (4.92%), and entrepreneurs (3.28%). In terms of playing position, the largest group consisted of shooting guards (n = 85), followed by point guards (n = 79), power forwards (n = 52), forwards (n = 51), and centres (n = 37). This information is represented in Table 1.

Table 1. Descriptive characteristics of demographic variables.

	Age	Years of playing in the team	Years coach of the team	Years of involvement in basketball
Valid values.	305	304	304	304
Mean.	20.78	5.45	3.49	10.60
Standard deviation.	8.76	4.08	3.42	6.54
Minimum.	12	0	0	0
Maximum.	60	20	30	45

Social interaction

The concept of social interaction was captured through four main categories. The most frequently selected response was "*to be with friends*" (42.3%), indicating that friendship constitutes the core of social involvement for the majority of participants. This was followed by "*to be with team members*" (25.9%), highlighting the importance of collective experience and the sense of belonging to a broader group. Additionally, 19.3% of responses focused on "*enjoying the company of the people you came with*," emphasizing the pleasure derived from sharing the experience with familiar individuals. Finally, 12.5% selected "*to do things with your partners*," reflecting a more intimate and personal dimension of social interaction. These distributions are presented in Table 2.

Table 2. Frequency distributions for social interaction.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. Hang out with team members.	79	25.9	25.9	25.9
2. Be with friends.	129	42.3	42.3	68.2
3. Do stuff with your buddies.	38	12.5	12.5	80.7
4. Enjoy the company of the people who came with you.	59	19.3	19.3	100

New acquaintances

The concept of new acquaintances is analysed through six different formulations that cover various aspects of social expansion. The most frequent response (24.7%) was "*to talk with new and different people*," highlighting the desire for communication with individuals outside one's usual social circle. This is followed by "*to form new relationships*" at 21.1%, indicating that many perceive acquaintances as a potential basis for deeper connections. A total of 17.1% chose "*to create friendships with new people*," emphasizing the development of stable and positive social bonds. The option "*to get to know other people in the area*" accounted for 12.8%, linking acquaintances with the local community, while 12.5% answered "*to see new faces*," reflecting a more superficial yet potentially important first step. Finally, 11.8% stated simply "*to make*

new acquaintances," a more general and open-ended formulation. The above information is presented in Table 3.

Table 3. Frequency distributions for meeting new people.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. To talk to new and different people.	75	24.6	24.7	24.7
2. To meet other people in the area.	39	12.8	12.8	37.5
3. To form new relationships.	64	21	21.1	58.6
4. To make new acquaintances.	36	11.8	11.8	70.4
5. To form friendships with new people.	52	17	17.1	87.5
6. To see new faces.	38	12.5	12.5	100

Escape from personal and social pressures

The need to escape from personal and social pressures is reflected in six formulations that express different aspects of the desire to break away from routine. The most frequent response was "*to have a change from your daily routine*," at 27.9%, highlighting the need for relief and disengagement from habitual patterns. This is followed by "*to do something different from what you usually do*" at 19.7%, emphasizing the importance of diversifying experiences. A total of 16.7% chose "*to have a change in everyday life*," a formulation that confirms the value of renewal, while 14.8% focused on "*to add some variety to my daily routine*," stressing the small yet meaningful disruption of monotony. Another 11.1% responded "*to have a change of pace from everyday life*," expressing the need to alter the way and speed at which daily life unfolds. Finally, 9.8% selected "*to have something different*," revealing a deeper need for a temporary transcendence of the self and the roles imposed by everyday life. The above information is presented in Table 4.

Table 4. Frequency distributions for escaping from the daily routine.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. To have a change from your daily routine.	85	27.9	27.9	27.9
2. To have a change in your daily life.	51	16.7	16.7	44.6
3. To do something different from what you usually do.	60	19.7	19.7	64.3
4. To have a change of pace from everyday life.	34	11.1	11.1	75.4
5. To add some variety to my daily routine.	45	14.8	14.8	90.2
6. To have something different.	30	9.8	9.8	100

Escape from physical pressure calmness

The concept of calmness is analysed through eight different formulations, revealing the multiple dimensions through which participants perceive it. The most frequent response was "*to feel a sense of balance in the things around you*" (17.4%), indicating the need for inner and outer harmony. This is followed by "*to experience calmness*" at 16.4%, which directly expresses the desire for mental tranquillity.

Table 5. Frequency distributions for escaping from physical pressure.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. To experience tranquillity.	50	16.4	16.4	16.4
2. To experience solitude.	26	8.5	8.5	24.9
3. To experience peace and tranquillity.	29	9.5	9.5	34.4
4. To experience a soothing environment.	40	13.1	13.1	47.5
5. To experience an environment that calms and heals.	42	13.8	13.8	61.3
6. To feel a sense of balance in the things around me.	53	17.4	17.4	78.7
7. To enjoy the quiet and beauty.	45	14.8	14.8	93.4
8. To be where there is quiet.	20	6.6	6.6	100

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A total of 14.8% mentioned "*to enjoy silence and beauty*," linking calmness with aesthetic enjoyment and seclusion, while 13.8% chose "*to experience an environment that calms and heals*," emphasizing the soothing qualities of the setting. Another 13.1% stated "*to experience an environment that is soothing*," underlining the importance of atmosphere in achieving calmness. Furthermore, 9.5% referred to "*peace and calm*," adding a spiritual dimension, while 8.5% perceived calmness through solitude, highlighting the need for isolation. Finally, 96.6% selected "*to be in a place where silence prevails*," focusing simply and clearly on environmental quietness. The above information is presented in Table 5.

Goal achievement

Descriptive statistics were used to examine the goal achievement of 3x3 athletes. According to the data of the variable *social recognition*, responses were distributed across ten different options. The most frequent option was *"To show others that you can do it"*, with 53 responses (17.4%), indicating that the validation of abilities constitutes a key motive for a considerable number of participants. Very close behind was the option *"For others to see you doing things you are good at"*, which gathered 50 responses (16.4%), highlighting the importance of demonstrating skills within a social context. The option *"For others to value you because you do it"* received 36 responses (11.8%), while *"To do something that impresses others"* followed with 35 responses (11.5%). Next, the option *"To do something impressive"* recorded 33 responses (10.8%), and *"To make a good impression on others"* was reported with 28 responses (9.2%), emphasizing the significance of the impression one makes on their social environment. Among the least frequent options were the responses *"For others to see you doing it"* with 16 responses (5.2%), as well as *"To be recognized because you did it"* and *"To receive compliments for your abilities and skills"*, each with 14 responses (4.6%). The above information is presented in Table 6.

Table 6. Frequency distributions for social recognition.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. To be appreciated by others because you do it.	36	11.8	11.8	11.8
2. To show others that you can do it.	53	17.4	17.4	29.2
3. To be recognized and admired by others because you do it.	26	8.5	8.5	37.7
4. So that others see you doing things you are good at.	50	16.4	16.4	54.1
5. To do something that impresses others.	35	11.5	11.5	65.6
6. To make a good impression on others.	28	9.2	9.2	74.8
7. To do something impressive.	33	10.8	10.8	85.6
8. To be recognized for doing it.	14	4.6	4.6	90.2
9. To receive compliments for your abilities and skills.	14	4.6	4.6	94.8
10. To be seen by others doing it.	16	5.2	5.2	100

Enthusiasm

According to the participants' responses, enthusiasm is expressed through nine different forms. The most frequent option (21%) was *"to experience a lot of action"*, indicating that for many participants enthusiasm is associated with intense movement and activity. This is followed by *"to experience enthusiasm"* (19%), a direct and emotionally charged description of the experience itself, and *"to have a stimulating and exciting experience"* (15.7%), which emphasizes the intensity and dynamism of experiences.

The option *"to experience fast-paced situations"* (10.8%) attributes enthusiasm to conditions of speed and intensity, while the responses *"to experience thrills"* (9.5%) and *"to feel good"* (9.5%) each highlight that, for several participants, this emotion is linked to inner pleasure and emotional excitement. The option *"to live the exciting events that are happening"* (7.5%) places emphasis on external reality, whereas *"to feel energized"*

(3.9%) expresses enthusiasm as internal activation. Finally, *"to cause things to happen"* (3%) reflects a creative and proactive dimension of enthusiasm. The above information is presented in Table 7.

Table 7. Frequency distributions for enthusiasm.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. Feel excitement	29	9.5	9.5	9.5
2. Experience enthusiasm	58	19	19	28.5
3. Experience lots of action	64	21	21	49.5
4. Have a stimulating and exciting experience	48	15.7	15.7	65.2
5. Experience a fast pace	33	10.8	10.8	76.1
6. Feel good	29	9.5	9.5	85.6
7. Get energized	12	3.9	3.9	89.5
8. Experience exciting events	23	7.5	7.5	97
9. Cause things to happen	9	3	3	100

Creativity

Creativity, as expressed through the participants' responses, is structured into four main categories that encompass both personal expression and cognitive processing. The most frequent response was *"to be creative"* (29.8%), indicating a direct need for personal expression, imagination, and inventiveness. Very close to this was the option *"to create something new or different"* (29.2%), reflecting an intention toward originality and innovation through tangible actions.

A total of 22% selected *"to put some thoughts or ideas together"*, emphasizing the concept of synthesis and mental processing as integral aspects of creativity. Finally, 19% of participants stated that creativity means *"to gain a new perspective on life"*, thus attributing a more reflective dimension to the concept. The above information is presented in Table 8.

Table 8. Frequency distributions for creativity.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. Be creative.	91	29.8	29.8	29.8
2. Put some thoughts or ideas together.	67	22	22	51.8
3. Create something new or different.	89	29.2	29.2	81
4. Gain a new perspective on life.	58	19	19	100

Exercise

Exercise and physical fitness are important factors for the participants, as reflected in the six different responses recorded. The most frequent option was *"to exercise"* (28.5%), highlighting the general intention for physical activity as a primary goal. This was followed by *"to feel good after physical activity"* (20%), indicating that, for many, exercise is directly linked to enhancing psychophysical well-being.

Table 9. Frequency distributions for exercise.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. To exercise.	87	28.5	28.5	28.5
2. To stay in good physical condition.	55	18	18	46.6
3. To improve physical health.	42	13.8	13.8	60.3
4. To maintain physical condition.	38	12.5	12.5	72.8
5. To feel good after physical activity.	61	20	20	92.8
6. To tone my muscles.	22	7.2	7.2	100

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Eighteen percent (18%) chose *"to maintain good physical condition"*, while 12.5% stated *"for your physical fitness"*, with both responses emphasizing the importance of maintaining physical form. At the same time, 13.8% focused on *"improving physical health"*, underlining the preventive or therapeutic dimension of exercise. Finally, 7.2% mentioned *"muscle toning"*, focusing more on the aesthetic or bodily outcome of exercise. The above information is presented in Table 9.

Recreation

The data show that the majority of participants (55.7%) consider 3x3 basketball to be one of the most fun activities, indicating a high level of enjoyment and positive experience from this form of basketball. At the same time, a significant percentage (43.6%) reported that participating in 3x3 tournaments is one of the things that satisfies them, reinforcing the idea that events of this type have a positive impact on participants. These two frequencies highlight the close connection of 3x3 basketball with recreation and personal enjoyment.

It was also observed that the majority of participants (54.8%) enjoy discussing 3x3 basketball with their friends, demonstrating the social and communicative dimension of the sport. A smaller but notable percentage (27.9%) indicated that they are not particularly interested in 3x3, suggesting that the sport does not appeal equally to everyone. Finally, 17.4% stated that 3x3 basketball is very important to them, emphasizing its personal significance for part of the population.

The results show that the majority of participants (53.1%) feel that when they participate in 3x3 basketball, they can be themselves, highlighting the authentic and expressive nature of the sport for these young people. Additionally, 31.1% reported that through 3x3 they can show their value to others, emphasizing the importance of personal validation and recognition through participation. A smaller percentage (15.7%) believe that 3x3 says a lot about who they are, attributing identity and personal image characteristics to the sport.
Moreover, for a significant percentage of participants (67.5%), most of their friends are in some way connected to 3x3 basketball, highlighting the social dimension of the sport and its role as a means of networking and belonging to communities with shared interests. At the same time, 32.1% stated that many aspects of their life are organized around 3x3 basketball, indicating that for them the sport is a stable element of their daily routine. These two frequencies demonstrate that 3x3 basketball is not limited to athletic interest alone but also functions as a social and experiential context for many young people. The above information is presented in Table 10.

Table 10. Frequency distributions for recreation through participation in 3x3 basketball.

	Frequency	Percentage	Relative frequency	Cumulative frequency
1. 3x3 basketball is one of the most fun activities.	170	55.7	55.7	55.7
2. Participating in 3x3 tournaments is one of the things that makes me happy.	133	43.6	43.6	99.3
3. I like talking about 3x3 basketball with my friends.	167	54.8	54.8	54.8
4. I am not very interested in 3x3 basketball.	85	27.9	27.9	82.6
5. 3x3 basketball is very important to me.	53	17.4	17.4	100
6. 3x3 basketball says a lot about who you are.	48	15.7	15.7	15.7
7. When I participate in 3x3 basketball, I can show others what I am worth.	95	31.1	31.1	46.9
8. When I participate in 3x3, I am myself.	162	53.1	53.1	100
9. I think that many things in my life are organized around 3x3.	98	32.1	32.1	32.1
10. Most of my friends are connected to 3x3 in some way.	206	67.5	67.5	99.7

DISCUSSION

The findings of the present study highlight the complex and multidimensional nature of participation in 3x3 basketball, demonstrating that engagement is shaped by an interplay of social, psychological, emotional, and physical motives. Rather than being perceived merely as a competitive sport, 3x3 basketball emerges as an experiential context through which participants satisfy multiple personal and social needs. This perspective is consistent with contemporary research in recreational sport, which emphasizes the experiential and psychosocial dimensions of sport participation beyond performance outcomes (Alexandris et al., 2006; Funk et al., 2016). One of the most salient contributions of this study is the identification of social interaction as a central driver of participation. Friendships, team affiliation, and shared experiences were shown to play a pivotal role in motivating engagement, reinforcing previous findings that highlight the importance of social bonds and interpersonal relationships in recreational sport contexts (Kyle et al., 2004; Beaton et al., 2011). Moreover, the opportunity to interact with unfamiliar individuals and establish new social connections suggests that 3x3 basketball functions as a space for social development and informal networking, supporting the notion that sport participation contributes to social capital formation and community integration (Chalip et al., 2017).

Another important finding concerns the psychological role of 3x3 basketball as a mechanism for coping with everyday demands. Participants consistently associated their involvement with relief from routine and social pressures, indicating that participation functions as a form of psychological escape. This aligns with leisure research suggesting that recreational activities provide opportunities for stress reduction, mental detachment, and emotional recovery (Iwasaki, 2007; Brajša-Žganec et al., 2011). Notably, despite its fast-paced and competitive characteristics, 3x3 basketball was also linked to feelings of calmness and emotional balance. This coexistence of stimulation and restoration reflects the dual role of physically engaging leisure activities in promoting psychological well-being (Downward & Rasciute, 2011; Doyle et al., 2016).

Motivation related to goal attainment and social recognition further enriches the understanding of participation dynamics in 3x3 basketball. The opportunity to demonstrate skills and gain acknowledgment from others reflects the importance of competence affirmation within a social context. Importantly, recognition appears to be socially embedded rather than externally rewarded, reinforcing the role of intrinsic motivation in sustaining participation. This finding is consistent with Self-Determination Theory, which emphasizes competence, autonomy, and relatedness as fundamental psychological needs underlying motivated behaviour (Deci & Ryan, 2000). The dynamic structure of 3x3 basketball was also strongly associated with enthusiasm, excitement, and emotional activation, supporting previous research that links high involvement and enjoyment with sustained engagement in sport (Alexandris et al., 2012; Park et al., 2007).

Creativity emerged as another meaningful dimension of the 3x3 experience. Participants emphasized originality, improvisation, and the integration of ideas, highlighting the flexible and open nature of the format. This creative freedom may differentiate 3x3 basketball from more structured forms of the sport and enhance motivation and satisfaction, as creative engagement has been linked to positive effect and personal growth in leisure contexts (Iwasaki, 2007; Seligman, 2011).

Finally, exercise- and recreation-related motives confirm that physical activity and enjoyment remain fundamental elements of participation. The findings indicate that 3x3 basketball allows participants to express their identity, feel authentic, and integrate sport naturally into their social relationships and daily routines. Such outcomes align with evidence demonstrating strong associations between recreational sport participation, quality of life, and subjective well-being (Leung & Lee, 2005; Wendel-Vos et al., 2004; Forgeard

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et al., 2011). Overall, the present study contributes novel empirical evidence by positioning 3x3 basketball as a comprehensive recreational sport experience that integrates physical activity, social interaction, emotional engagement, and personal development, helping to explain its growing popularity among young people.

CONCLUSIONS

The results of the present study demonstrate that participation in 3x3 basketball is primarily driven by social and psychological motives, complemented by exercise-related benefits. Social interaction emerged as the dominant factor, with participants strongly motivated by friendship, team belonging, and opportunities to expand their social networks. In parallel, involvement in 3x3 basketball was associated with escape from daily routines and social pressures, contributing to emotional balance, calmness, and psychological restoration. Achievement-related motives were mainly expressed through social recognition and the affirmation of personal competence, indicating that participation satisfies intrinsic needs rather than externally imposed performance goals. The fast-paced and flexible structure of 3x3 basketball was closely linked to heightened enthusiasm, creativity, and enjoyment, supporting sustained engagement and personal expression. Additionally, participants consistently identified 3x3 basketball as a recreational activity that facilitates identity expression and integrates naturally into their social and everyday lives.

Taken together, these findings position 3x3 basketball as a multidimensional form of physical activity that simultaneously promotes social connectedness, psychological well-being, and regular exercise participation. The results underline the relevance of 3x3 basketball for youth sport development, recreational sport programming, and community-based physical activity initiatives aimed at enhancing quality of life and fostering long-term engagement in sport.

AUTHOR CONTRIBUTIONS

Dimitrios Stavropoulos contributed to the conceptualization and design of the study, data collection, coordination of data collection, and interpretation of the results. He also contributed to drafting and revising the manuscript. Georgia Stavropoulou served as the corresponding author and contributed to the study design, statistical analysis, interpretation of findings, and primary drafting and critical revision of the manuscript. Apostolia Ntovoli contributed to data collection, data organization, and preliminary analysis, and assisted in the interpretation of findings and manuscript revision. Christos Galazoulas contributed to the methodological framework, supervision of data analysis, and critical revision of the manuscript for important intellectual content. Evangelos Kontaxakis contributed to data collection, management of the research process during field implementation, and critical review of the manuscript. Afroditi Lola served by contributing to the overall research design, methodological guidance, theoretical framework, supervision of the research process, interpretation of results, and critical revision of the manuscript. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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AI STATEMENT

AI-assisted tools were used exclusively for language translation and linguistic editing to improve clarity and readability. All study design decisions, data analyses, results, and interpretations were conducted and produced by the authors.

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