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Editorial Decisions and Strategic Directions

Thematic Structure, Evolution, and Authorship Patterns of Physical Education Theory and Methodology (2019–2025)

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(on behalf of the Editorial Team of Physical Education Theory and Methodology)

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Abstract

Background. Bibliometric analyses provide an evidence-based approach for examining the thematic orientation, development trajectories, and collaboration patterns of scientific journals.

Purpose. The purpose of this study was to analyze the thematic structure, thematic evolution, and authorship patterns of publications in Physical Education Theory and Methodology (PETM) during 2019–2025.

Methods. Scopus-indexed metadata were analyzed using bibliometric methods. A weighted keyword co-occurrence network was constructed and examined using the Louvain community detection algorithm. Thematic evolution was assessed across three periods (2019–2020, 2021–2022, 2023–2025), and recurrent co-authorship patterns were identified based on indexed author records.

Results. Five major thematic clusters representing the core research domains of PETM were identified. Thematic evolution analysis revealed a cumulative development pattern characterized by stable methodological foundations and pronounced growth in health-related, assessment-oriented, and integrative applied research. Authorship analysis demonstrated the presence of recurring author teams and stable collaborative structures.

Conclusions. The findings provide quantitative evidence of PETM's controlled thematic diversification and support its positioning as a methodologically grounded journal with expanding international relevance. The results may inform editorial positioning, scope refinement, and future policy development.

Keywords: bibliometric analysis, thematic evolution, co-authorship patterns, physical education research, journal analysis.

Introduction

Over the past decade, bibliometric methods have become an important tool for analyzing the development of scientific journals, allowing researchers and editors to assess thematic orientation, structural changes, and collaboration patterns at the journal level. Such analyses are particularly relevant for long-standing journals, where questions of continuity, diversification, and international visibility are central to editorial strategy. Bibliometric approaches are widely used to examine thematic orientation, structural change, and collaboration patterns in scientific journals (Zupic & Čater, 2015; Donthu et al., 2021).

Founded more than two decades ago, Physical Education Theory and Methodology (PETM) represents a specialized journal in the field of physical education, motor development, and movement science. As the journal enters a new stage of development, a systematic examination of its recent thematic profile and authorship structure is necessary to support evidence-based editorial decisions.

The purpose of this study is to provide a bibliometric overview of PETM publications from 2019 to 2025, with specific objectives to: (1) identify the journal's core thematic clusters; (2) examine thematic evolution over time; and (3) analyze authorship and collaboration patterns. The

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PETM
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study focuses on journal-level characteristics rather than individual author performance.

Methodology

Data Source and Dataset

The analysis was based on publications from Physical Education Theory and Methodology indexed in the Scopus database. Metadata were exported in BibTeX format and processed using the bibliometrix package in R. The initial dataset comprised 568 documents, of which publications dated between 2019 and 2025 were selected for detailed analysis. The Scopus metadata were exported on 23 December 2025, including documents indexed as "articles" and "reviews." Other document types (editorials, notes, letters) were excluded from the analysis. Only records containing author keywords were retained for the keyword co-occurrence analysis. Bibliometric mapping and science mapping procedures were implemented using established methodological frameworks (Aria & Cuccurullo, 2017; Cobo et al., 2011).

Keyword Processing and Network Construction

Author keywords were extracted from the metadata fields DE and KW_Merged. Keywords were standardized by conversion to uppercase and trimming of whitespace. A binary document–keyword matrix was constructed to indicate the presence of keywords in each publication. Based on this matrix, a weighted keyword co-occurrence network was generated, where edge weights reflected the frequency of joint occurrence of keywords within the same document. Keywords with very low frequencies were excluded to reduce noise in the network structure. Minor lexical variants were merged during preprocessing to ensure conceptual consistency at the cluster level. Keyword co-occurrence analysis is a standard approach for identifying conceptual structures within scientific domains (Zupic & Čater, 2015).

Community Detection and Thematic Evolution

The keyword co-occurrence network was modeled as an undirected weighted graph, and isolated nodes were removed. The Louvain community detection algorithm was applied to identify thematic clusters through modularity optimization. Community detection was performed using the Louvain algorithm, which is widely applied in large-scale network analysis (Blondel et al., 2008; Newman, 2006). The resulting cluster structure demonstrated high internal coherence, allowing stable interpretation of thematic domains across all three time periods. To analyze temporal dynamics, publications were grouped into three periods: 2019–2020, 2021–2022, and 2023–2025. Keyword frequencies were aggregated at the cluster level for each period to examine thematic evolution.

Authorship and Collaboration Analysis

Authorship patterns were analyzed using Scopus metadata fields related to authors and affiliations. Recurrent co-authorship patterns were identified to describe stable collaborative structures within the journal. The analysis emphasizes recurring author teams rather than individual author rankings. It should be noted that Scopus author identification and name disambiguation procedures may influence the aggregation of co-authorship records. Therefore, the results are interpreted at the level of indexed author teams rather than individual researcher performance.

Results

Thematic clusters

Community detection identified five major thematic clusters corresponding to the core research domains of PETM:

1. Pedagogical models and instructional design in physical education.
2. Motor development and fundamental movement skills.
3. Assessment, testing, and measurement.
4. Physical fitness, training effects, and experimental designs.
5. Health-related physical activity, inclusion, and functional outcomes.

Although network visualization revealed transitional zones between clusters, modularity optimization integrated these areas into broader, stable thematic communities.

Table 1. Thematic clusters and their conceptual focus in PETM (2019–2025)

Cluster	Conceptual focus	Representative keywords
Cluster 1	Pedagogical models and instructional design in physical education	physical education; teaching; students; program; control; pedagogical modeling
Cluster 2	Motor development and fundamental movement skills	motor skills; motor fitness; physical fitness; children; boys; girls
Cluster 3	Assessment, testing, and measurement	testing; discriminant analysis; assessment; agility; balance; VO_2max
Cluster 4	Physical fitness, training effects, and experimental designs	training; strength; exercise; performance; experimental design
Cluster 5	Health-related physical activity, inclusion, and functional outcomes	physical activity; body composition; healthy lifestyle; inclusion; physical performance

Network visualization and bibliometric mapping were used to support the interpretation of thematic and collaborative structures (van Eck & Waltman, 2010).

Thematic evolution

Thematic evolution analysis demonstrated differentiated growth trajectories across clusters. During 2019–2020, research activity was concentrated in methodologically oriented domains, with emphasis on experimental design, testing, and multivariate statistical methods. In 2021–2022,

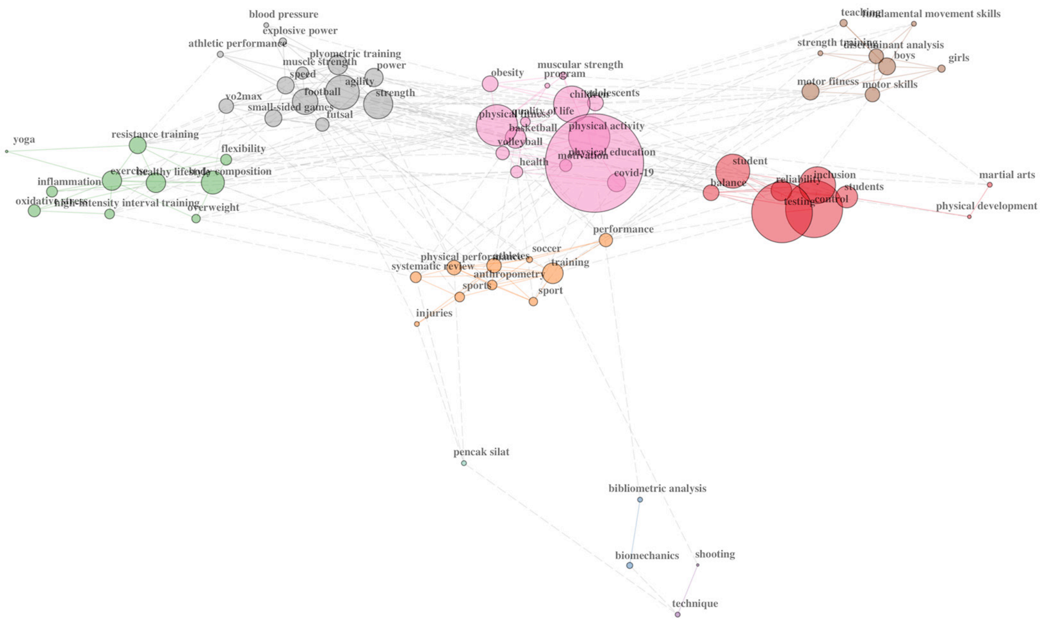

Fig. 1. Keyword co-occurrence network with five clusters

Table 2. Thematic evolution across periods (cluster-level keyword frequencies) in PETM (2019–2025)

Cluster	2019–2020	2021–2022	2023–2025	Evolutionary pattern
Cluster 1 Pedagogical models and instructional design	32	54	61	Stable growth
Cluster 2 Motor development and fundamental movement skills	4	34	105	Late acceleration
Cluster 3 Assessment, testing, and measurement	7	31	99	Progressive expansion
Cluster 4 Physical fitness, training effects, and experimental designs	28	33	81	Continuous growth
Cluster 5 Health-related physical activity, inclusion, and functional outcomes	5	27	108	Rapid expansion

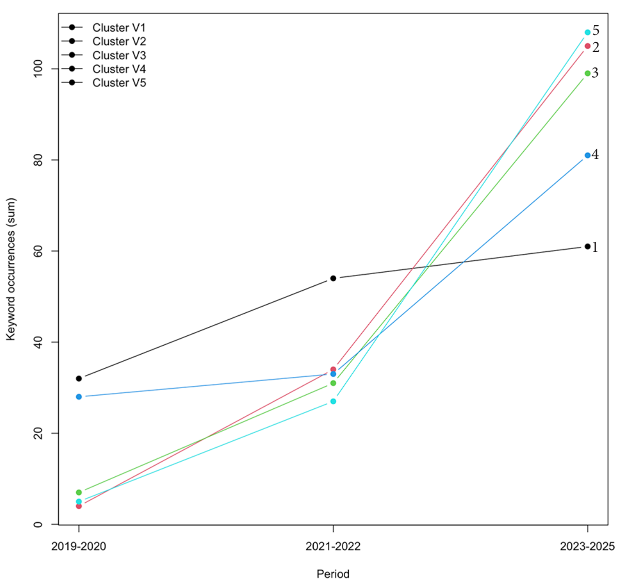

Fig. 2. Thematic evolution trends across three periods

all clusters showed increased activity, reflecting expansion toward training interventions, physical activity, and functional performance indicators. The period 2023–2025 was characterized by a sharp increase across all thematic domains, particularly in health-related and assessment-oriented research.

Authorship and Collaboration Patterns

Analysis of Scopus metadata revealed a limited number of recurring author teams contributing multiple publications to PETM. The most frequent teams authored two or three articles each, indicating the presence of stable collaborative groups rather than isolated individual contributions. Examples include the author teams Ben Rakaa O.; Bassiri M.; Lotfi S., Kumar S.; Das R., and Milenković D., each contributing three articles during the analyzed period.

Table 3. Most frequent author teams in PETM (2019–2025)

Author team (as indexed in Scopus)	Number of articles
Ben Rakaa O.; Bassiri M.; Lotfi S.	3
Kumar S.; Das R.	3
Milenković D.	3
Abiyra A.J.; Tiwari S.; Haq M.A.U.	2
Choudhary P.K.; Dubey S.	2
Elezi A.; Elezi G.; Gontarev S.; Georgiev G.	2
Kapkan O.O.; Khudolii O.M.; Bartík P.	2
Nuttoch W.; Hemarachatanon P.; Huntula S.	2
Pahan M.K.; Singh M.K.	2

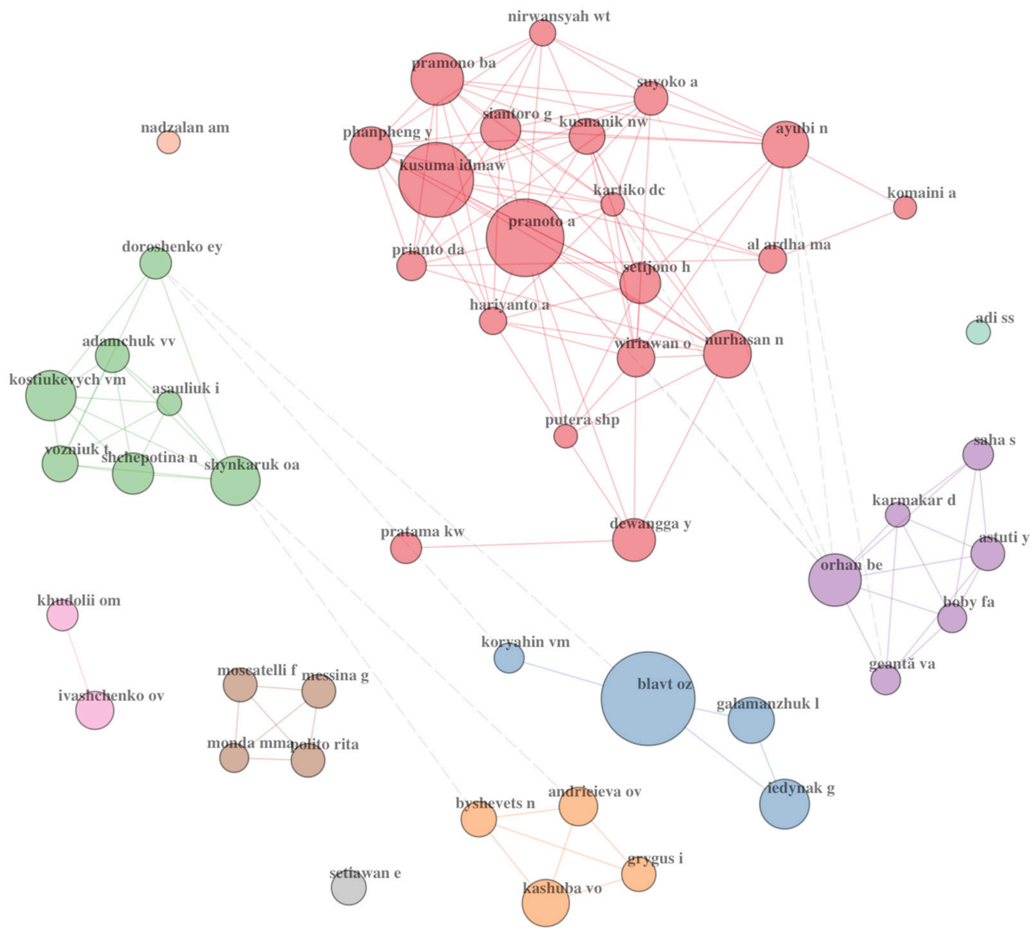

Fig. 3. Co-authorship network of PETM publications

Discussion

The results indicate that PETM has undergone a process of controlled thematic diversification during 2019–2025. Rather than replacing its methodological core, the journal has expanded cumulatively into health-related, assessment-based, and integrative applied research domains. This pattern suggests a balance between thematic stability and innovation. Importantly, the observed thematic expansion reflects cumulative development rather than a shift away from the journal's established methodological core. Journal-level bibliometric analyses provide a descriptive basis for understanding cumulative thematic development rather than evaluative assessments of individual performance (Moed, 2005).

The presence of recurring author teams and stable collaboration structures further supports the interpretation of PETM as a journal embedded in sustained scientific cooperation. Together, the thematic and authorship findings provide an empirical basis for editorial positioning and future strategic development.

Conclusions and Editorial Implications

This bibliometric analysis demonstrates that the development of Physical Education Theory and Methodology during 2019–2025 is characterized by cumulative thematic growth, stable collaborative authorship, and controlled diversification toward applied and health-related research domains. The identified thematic clusters and evolution patterns provide an empirical foundation for refining the journal's scope, editorial priorities, and desk-review criteria. Overall, the results confirm PETM's position as a methodologically grounded journal with expanding international relevance. These findings may inform future editorial policies, including thematic prioritization, desk-review criteria, and the strategic balance between methodological rigor and applied research.

Ethics Approval

Ethical approval was not required for this article, as it is an editorial and conceptual work that does not involve human participants, animals, or the collection or analysis of personal or identifiable data.

Informed Consent

Not applicable, as no human participants were involved.

Data Availability Statement

Data sharing is not applicable to this article, as it does not report or analyze empirical datasets and is based on conceptual analysis and publicly available sources.

AI Transparency Statement

AI-assisted tools were used solely to support language editing, stylistic refinement, and structural organization of the manuscript, based exclusively on content provided by the authors. No AI tools were used for data collection, data analysis, interpretation of results, or generation of original scientific content. Full responsibility for the content, interpretation, and conclusions rests with the authors.

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Conflict of Interest

The authors declare no financial or personal conflicts of interest. This article was prepared within the framework of the journal's editorial and methodological development activities, which does not influence the objectivity or integrity of the presented content.

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Тематична структура, еволюція та авторські моделі журналу Physical Education Theory and Methodology (2019–2025)

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(від імені редакційної колегії журналу «Physical Education Theory and Methodology»)

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 6 с., 3 табл., 3 рис., 8 джерел.

Обґрунтування. Бібліометричні аналізи забезпечують доказовий підхід до вивчення тематичної спрямованості, траєкторій розвитку та моделей наукової співпраці в межах наукових журналів.

Мета. Метою цього дослідження було проаналізувати тематичну структуру, тематичну еволюцію та авторські моделі публікацій у журналі Physical Education Theory and Methodology (PETM) за період 2019–2025 років.

Методи. Аналіз виконано на основі метаданих публікацій, проіндексованих у базі Scopus, із використанням бібліометричних методів. Побудовано зважену мережу спільної появи ключових слів, яку проаналізовано за допомогою алгоритму виявлення спільнот Louvain. Тематичну еволюцію оцінювали у трьох часових періодах (2019–2020, 2021–2022, 2023–2025), а повторювані моделі співавторства ідентифіковано на основі індексованих авторських записів.

Результати. Визначено п'ять основних тематичних кластерів, що репрезентують ключові напрями досліджень журналу PETM. Аналіз тематичної еволюції виявив кумулятивний характер розвитку, який поєднує стабільне методологічне підґрунтя з виразним зростанням досліджень, орієнтованих на здоров'я, оцінювання та інтегративні прикладні підходи. Аналіз авторських моделей засвідчив наявність повторюваних авторських команд і стабільних структур наукової співпраці.

Висновки. Отримані результати надають кількісні докази контрольованої тематичної диверсифікації PETM та підтверджують його позицію як методологічно орієнтованого журналу з розширюваною міжнародною присутністю. Висновки можуть бути використані для редакційного позиціювання, уточнення тематичного профілю та формування майбутньої редакційної політики.

Ключові слова: бібліометричний аналіз, тематична еволюція, моделі співавторства, дослідження з фізичного виховання, аналіз наукового журналу.

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Review Article

Resistance Training and Elite Athletes: A Systematic Bibliometric Analysis (2015–2023)

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Abstract

Objectives. This study aims to systematically map global research trends, influential contributors, and thematic evolution in resistance training (RT) research involving elite athletes from 2015 to 2023.

Materials and Methods. A systematic bibliometric analysis was conducted using the Scopus database. Study selection followed PRISMA 2020 guidelines and focused on RT interventions involving elite competitive populations. Duplicate records were removed, followed by title, abstract, and full-text screening conducted by independent reviewers. VOSviewer version 1.6.20 was used to generate bibliometric visualizations, including co-authorship, co-citation, and keyword co-occurrence networks. Key bibliometric indicators, such as publication trends, citation impact, collaboration networks, and thematic clustering, were evaluated.

Results. From an initial total of 2,710 records, 678 documents met the eligibility criteria. Global scientific productivity exhibited steady growth, with a marked acceleration after 2019. The United States demonstrated the highest citation impact, whereas Spain and Brazil emerged as central international collaboration hubs. Three major thematic clusters were identified: (1) performance optimization strategies, including velocity-based training and blood flow restriction; (2) neuromuscular adaptations and hypertrophy mechanisms; and (3) youth athlete development with increasing integration of digital and monitoring technologies.

Conclusions. Research on RT in elite athletes continues to expand, characterized by strong international collaboration and increasing methodological refinement. The findings emphasize the central role of RT in high-performance sport and provide directions for future research, particularly regarding gender inclusivity, advanced monitoring technologies, and standardized measurement approaches.

Keywords: resistance training; elite athletes; bibliometric analysis; hypertrophy; neuromuscular adaptation; performance enhancement.

Introduction

Resistance training (RT) is a fundamental component in elite athlete development programs, particularly due to its role in enhancing muscle strength, neuromuscular capacity, and injury resilience. Recent studies have shown that RT not only contributes to competitive performance but also has significant effects on metabolic health and body composition in athletes (Grgic & Schoenfeld, 2018; Schoenfeld & Grgic, 2018). At the elite level, the high intensity of competition requires science-based training approaches to achieve optimal physiological adaptations. This highlights that RT is not merely an auxiliary exercise but a primary strategy in supporting the long-term performance of athletes. Furthermore, the theoretical foundation of RT emphasizes the importance of progression, periodization, and individualization, which have long been recognized as key principles in exercise science (Kraemer & Ratamess, 2004; Moesgaard et al., 2022). Nevertheless, although RT has become a common practice, global research developments in this area still reveal disparities, particularly in the context of elite athletes from different regions of the world (Pedersen & Saltin, 2015; Makaruk et al., 2024).

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The increase in RT publications over the past decade indicates a growing scientific interest in this training method, especially in exploring its effects on muscle hypertrophy, maximal strength, and neural adaptations. (Morton et al., 2018) emphasized that combining RT with protein supplementation leads to significant improvements in muscle mass and strength performance. Moreover, new training methodologies such as velocity-based training (VBT) and blood flow restriction (BFR) have gained attention in recent studies, as they are considered effective in eliciting greater adaptive responses in elite athletes (Michał Włodarczyk et al., 2021; Centner et al., 2019). For instance, VBT allows coaches to monitor lifting intensity and movement velocity in real time, making training more objective and measurable (Nagatani et al., 2025; Weakley et al., 2021). These trends indicate that RT is evolving into an arena of methodological innovation, technological experimentation, and reinforcement of individualized training principles (Krzysztofik et al., 2019).

Despite the increasing number of studies on RT, there remains considerable variation in terms of research populations, methodologies, and reported outcomes. Most studies continue to focus on male athletes, while female and Paralympic athletes remain underrepresented (Franchi et al., 2023; Larsen et al., 2016). This lack of representation indicates that research findings cannot yet be fully generalized to all athlete populations. Recent studies have also highlighted the importance of examining psychosocial and hormonal factors specific to female athletes, as well as the unique needs of disabled athletes (Suchomel et al., 2018; Heather et al., 2021). Similarly, RT studies in Asia, Africa, and Latin America are relatively limited compared to those in Europe and North America (Faigenbaum, 2018; Baker et al., 2021). This imbalance restricts the applicability of research findings across different cultural, infrastructural, and athletic contexts (Peters & Klatt, 2023).

Bibliometric analysis provides a relevant approach to understanding the global landscape of RT research. Through this method, researchers can identify publication trends, collaboration networks, and dominant research themes. Similar studies have been successfully applied in mapping other sport science domains, such as high-intensity interval training (HIIT) and sport tourism (Pham, 2024; Da Silva et al., 2020). Thus, bibliometric analysis in the context of RT offers a more comprehensive picture of research directions, knowledge gaps, and opportunities for cross-country collaboration (Chen, 2025). Furthermore, this approach is strengthened by the use of visual analytic tools such as VOSviewer, which has proven effective in mapping author collaborations and thematic clusters (Van Eck & Waltman, 2010; Du et al., 2024).

Based on this background, the present study aims to map global research trends on RT in elite athletes between 2015 and 2023. The main focus is directed toward patterns of publication, citation performance, the most influential articles, country distribution, collaboration networks, and the emergence of dominant keywords. The findings are expected to enrich understanding of RT development at the international level and open avenues for further research in underexplored regions and populations. In this way, the article seeks to provide a knowledge framework that can serve as a foundation for coaches, athletes, and sport scientists in designing evidence-based training strategies.

Materials and Methods

Data Source

The Scopus database was selected as the primary source for data retrieval due to its wide coverage, reliability, and relevance for bibliometric studies (Suhendar et al., 2024). Data collection was conducted in March 2024, ensuring that all available publications up to December 2023 were included. Boolean operators were applied to identify documents related to resistance training (RT) and elite athletes. Two main search strings were used: “resistance training” AND “elite athlete” and “resistance training” AND “muscle hypertrophy.” To maintain focus on scientific contributions, filters were applied to restrict the dataset to articles and reviews published in peer-reviewed journals, written in English, and indexed in medicine, health, and social sciences subject areas.

Data Selected and Analysis

The initial search yielded 2,710 documents from Scopus. After duplicate removal using Scopus utilities and manual verification (n = 420), 2,290 records remained for title and abstract screening. A total of 1,412 records were excluded due to non-elite populations or irrelevance to resistance training. Full-text assessment was performed on 878 articles, and 200 were excluded based on eligibility criteria. Ultimately, 678 documents met all inclusion criteria and were retained for bibliometric analysis. Data were organized and validated prior to bibliometric mapping to ensure accuracy (Donthu et al., 2021; Hassan & Duarte, 2024).

Table 1. Search strategy

Item	Details
Database	Scopus
Date of search	January 2024 (includes publications up to 31 Dec 2023)
Time window	2015–2023
Fields searched	TITLE-ABS-KEY
Search string (primary)	TITLE-ABS-KEY(«resistance training» OR «strength training») AND TITLE-ABS-KEY(«elite athlete» OR «high-performance athlete» OR «professional athlete»)
Filters applied	Document type = Article OR Review; Language = English; Subject areas = Sport Sciences / Physiology / Rehabilitation / Medicine related
Export format	RIS / CSV (full metadata: authors, title, abstract, year, keywords, affiliations, citations)
Deduplication tools	Scopus built-in deduplication + manual verification in Zotero
Screening process	Title → Abstract → Full-text; two independent reviewers; disagreements resolved by third reviewer
Inclusion criteria summary	Studies on RT interventions / outcomes in elite/high-performance athletes; peer-reviewed; English; 2015–2023
Exclusion criteria summary	Recreational/non-elite populations; non-primary RT studies; conference abstracts, editorials, book chapters
Software for analysis	VOSviewer v1.6.20; Bibliometrix (R) for descriptive stats (if used)

Procedure

The analysis followed three main stages. First, descriptive statistics were generated to identify annual publication trends, most cited articles, productive authors, journals, and countries. Second, bibliometric mapping was performed using VOSviewer (version 1.6.20), enabling visualization of co-authorship networks, bibliographic coupling, and keyword co-occurrence. Thresholds were set at a minimum of five publications per author and ten citations per document to focus on influential contributions. Third, thematic clusters were identified to detect major research streams in the field of RT for elite athletes. This systematic approach ensured consistency and replicability in line with bibliometric research standards (Pamboris et al., 2024; Mi et al., 2023).

The initial title abstract search in Scopus yielded 2,710 records. A multi-stage screening process was then applied using Scopus filtering tools. Records were sequentially refined based on publication year, subject area, document type, publication stage, keyword relevance, and language criteria. After these screening refinements, 678 records remained eligible for detailed evaluation.

Duplicate detection using Scopus utilities and manual verification removed 910 overlapping entries, resulting in 1,800 unique records for title and abstract screening. Two independent reviewers screened these records, with disagreements resolved through discussion and, when necessary, adjudication by a third reviewer. Of the 1,800 screened records, 1,122 were excluded based on topic irrelevance, leaving 678 records for full-text retrieval.

All 678 full-text articles were successfully retrieved and assessed. None were excluded at this stage, as all met the predetermined eligibility criteria. Thus, a total of 678 documents were included in the final dataset for the bibliometric analysis (2015–2023).

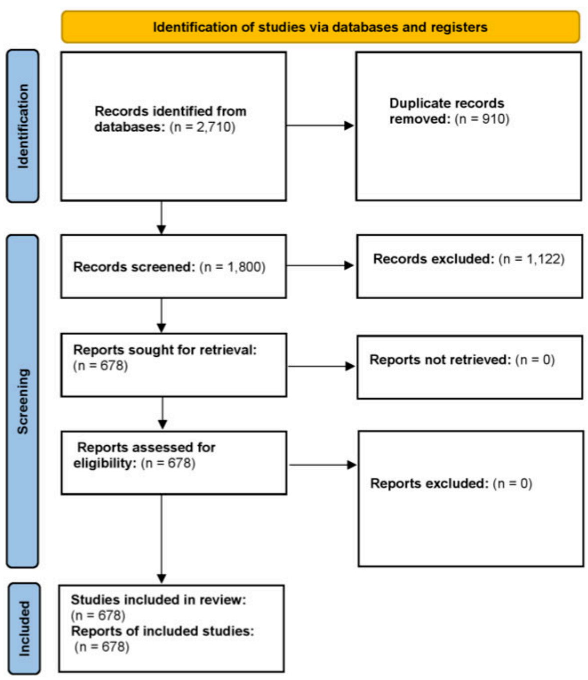

Fig. 1. PRISMA 2020 Flow Diagram.
Note: Data retrieved from Scopus (2015–2023). Screening, deduplication, and eligibility assessment followed PRISMA 2020 procedures. Diagram generated manually based on extracted records

Results

Publication Trends

The bibliometric search revealed a total of 678 documents published between 2015 and 2023 that focused on resistance training (RT) in the context of elite athletes. As illustrated in Figure 1, annual publication output showed a fluctuating pattern, with a notable increase from 2018 to 2020. The peak occurred in 2020 with 118 publications, followed by a slight decline in 2021 (110 documents) and a more modest output in 2023 (93 documents). This trend reflects the rapid expansion of interest in RT research before and during the COVID-19 pandemic, which likely influenced the volume of sport science publications worldwide. In terms of citation counts, the most cited works appeared in the earlier period of the dataset, indicating that impactful studies tend to accumulate citations over time.

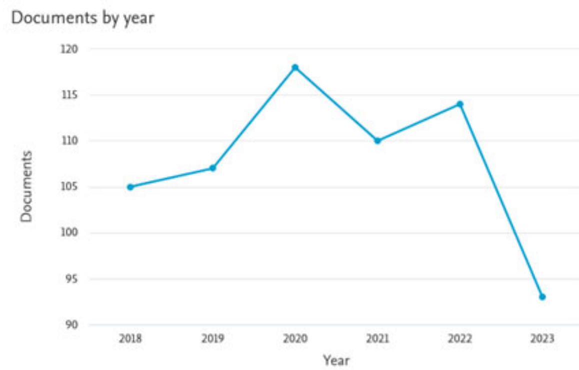

Fig. 2. Annual Distribution of Publications.
Note: Publication data extracted from Scopus for the period 2015–2023. The initial trend visualization was generated using Scopus analytical tools

Most Cited Articles

Table 2 presents the top 10 most cited articles in the dataset. The study by (Morton et al., 2018) emerged as the most influential, with 612 citations, emphasizing the importance of protein supplementation in enhancing the outcomes of RT. This is consistent with the broader literature highlighting the synergistic role of nutrition and exercise in muscle hypertrophy and strength development (Deldicque, 2023). Other highly cited works include (Izquierdo et al., 2021)ubiquitous and inevitable. Every physiological function is being continuously diminished. There is a range between two distinct phenotypes of ageing, shaped by patterns of living - experiences and behaviours, and in particular by the presence or absence of physical activity (PA, which addressed evidence-based exercise recommendations for older populations, and (Franchi et al., 2018), which investigated methods for accurately measuring hypertrophy. Collectively, these findings demonstrate that the most impactful studies focus on methodological rigor and practical implications for training interventions.

Tabel 2. Ten articles with the most citations based on Scopus

No	Document Title	Author and year	Total citations
1	A systematic review, meta-analysis and meta-regression of the effect of protein supplementation on resistance training-induced gains in muscle mass and strength in healthy adults	Morton, Robert W et al., 2018	612
2	International Exercise Recommendations in Older Adults (ICFSR): Expert Consensus Guidelines	Izquierdo, M et al., 2021	345
3	Muscle thickness correlates to muscle cross-sectional area in the assessment of strength training-induced hypertrophy	Franchi, Martino V et al., 2018	175
4	Effects of Blood Flow Restriction Training on Muscular Strength and Hypertrophy in Older Individuals: A Systematic Review and Meta-Analysis	Centner, Christoph M et al., 2019	168
5	Resistance Training Volume Enhances Muscle Hypertrophy but Not Strength in Trained Men	Schoenfeld, Brad Jon et al., 2019	159
6	Time-restricted feeding plus resistance training in active females: A randomized trial	Tinsley, Grant M et al., 2019	125
7	Comparing the Effectiveness of Blood Flow Restriction and Traditional Heavy Load Resistance Training in the Post-Surgery Rehabilitation of Anterior Cruciate Ligament Reconstruction Patients: A UK National Health Service Randomised Controlled Trial	Hughes, Luke et al., 2019	122
8	Volume for Muscle Hypertrophy and Health Outcomes: The Most Effective Variable in Resistance Training	Casagrande Figueiredo, Vandré Casagrande et al., 2018	102
9	Effects of different intensities of resistance training with equated volume load on muscle strength and hypertrophy	Lasevicius, Thiago et al., 2018	94
10	Loading Recommendations for Muscle Strength, Hypertrophy, and Local Endurance: A Re-Examination of the Repetition Continuum	Schoenfeld, Brad Jon et al., 2021	92

Country and Institutional Contributions

Analysis of country-level productivity revealed that the United States dominated the field, producing 254 documents and accumulating 4,681 citations. Brazil (2,307 citations) and Australia (1,732 citations) followed, reflecting strong contributions from South America and Oceania. European countries, particularly the United Kingdom, Spain, and Germany, also ranked among the most productive nations, with citation counts exceeding 1,200 each (see Table 2). Asian contributions, particularly from Japan (988 citations) and China (832 citations), were relatively limited, highlighting a geographic imbalance in the research landscape. This trend aligns with previous bibliometric analyses in sport science, where North America and Europe consistently appear as dominant contributors (Cruz, 2022). Institutional analysis showed that collaborations were often concentrated within established universities and research centers, suggesting that institutional reputation and funding resources strongly influence publication output.

Tabel 2. Source: Scopus Database, Country Distribution by Citations

Rank	Country By Citation	Citation
1	United States	4681
2	Brazil	2307
3	Australia	1732
4	United Kingdom	1340
5	Japan	988
6	Canada	916
7	New Zealand	891
8	Italy	865
9	Spain	799
10	Germany	788

Co-Authorship and Collaboration Networks

The co-authorship analysis generated five major clusters of researchers, reflecting international collaboration patterns (Figure 2). The largest cluster linked authors from the United States, Brazil, and Canada, while another prominent cluster connected researchers from Spain, Germany, and the United Kingdom. These networks suggest that RT research is increasingly multidisciplinary, involving experts in physiology, nutrition, biomechanics, and sports medicine. However, collaboration between developed and developing countries remains limited, which may contribute to disparities in global knowledge production. Strengthening international partnerships could enhance both the quality and applicability of RT research across diverse populations and athletic contexts.

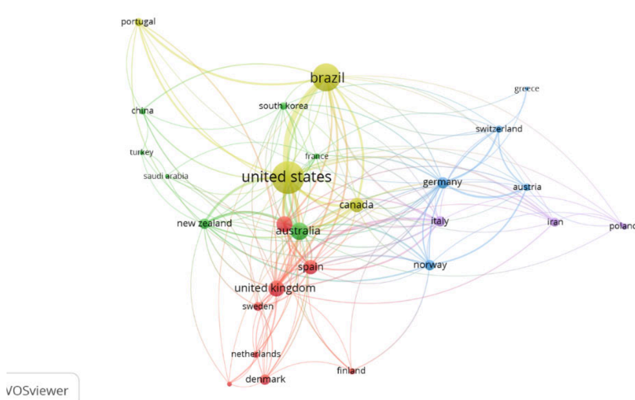

Fig. 3. Citation Network by Country
Note: Based on Scopus citation data (2015–2023). Network visualization created using VOSviewer 1.6.20 with full counting method

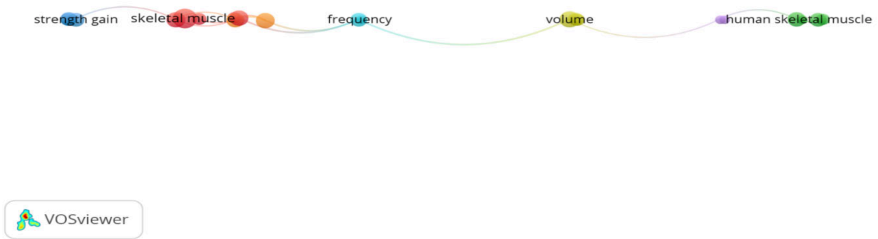

Fig. 4. Keyword Co-occurrence Network
Note: Data sourced from Scopus (2015–2023). Keyword co-occurrence map produced using VOSviewer 1.6.20 with minimum threshold of 5 occurrences per keyword

Keyword Co-occurrence Analysis

The keyword analysis revealed seven thematic clusters, represented in Figure 3. The most dominant cluster centered on "hypertrophy," "protein supplementation," and "muscle growth," confirming the critical role of nutrition-exercise interactions in RT research. Another strong cluster focused on "neuromuscular adaptation," "muscle fibers," and "strength," highlighting the physiological mechanisms underlying training outcomes. A third cluster was associated with "training volume," "intensity," and "endurance," reflecting ongoing debates about the optimization of RT variables. Emerging terms such as "velocity-based training," "blood flow restriction," and "individualization" indicate the incorporation of innovative methods in recent years (Çetin et al., 2022). These thematic groupings demonstrate both continuity in established areas and expansion into novel research directions.

Discussion

This bibliometric analysis (2015–2023) demonstrates substantial growth in resistance-training (RT) research in elite athletes, with a publication peak in 2020. This increase aligns with the shift toward controlled or remote training studies during early COVID-19 restrictions (Gentil et al., 2020), followed by a decline linked to funding challenges and limited athlete access (Jukic et al., 2020; Adrian et al., 2022). These patterns mirror disruptions across performance sciences during the pandemic, where many laboratory studies were halted (Poteko et al., 2023).

The prominence of (Morton et al., 2018) among the most cited works emphasizes the established importance of nutrition training interactions in maximizing hypertrophy and strength. This is consistent with systematic reviews showing synergistic effects of protein supplementation and resistance training (Lin et al., 2021; Grgic et al., 2022). Similarly, continued interest in program variables such as volume, intensity, and progression highlights sustained focus on optimizing neuromuscular adaptation (Franchi et al., 2018; Centner et al., 2019). Ongoing debates on the repetition continuum and load distribution further illustrate methodological evolution within RT research (Ralston et al., 2018; Schoenfeld et al., 2017). Emerging work on movement velocity, autoregulation, and fatigue monitoring signals increasing adoption of individualized prescription models (Weakley et al., 2021; Pareja-Blanco et al., 2016; Carvalho et al., 2022).

Country-level analyses demonstrate dominant contributions from the USA, Brazil, and Australia regions with established sport science infrastructures. Conversely, Africa and Southeast Asia remain underrepresented, reflecting resource constraints and limited access to elite athlete samples. These imbalances align with broader inequities in global sport science output (Paleti et al., 2025; Wang et al., 2015; Riot et al., 2020) and reinforce calls for more geographically inclusive athlete data (Goyal, 2024).

Co-authorship mapping shows concentrated collaboration among leading institutions in North America, South America, and Europe. While such clustering supports strong thematic specialization, it may also restrict global dissemination of methodological innovations. Encouraging trends include increased adoption of open-access practices, digital collaboration tools, and shared data repositories, which can expand participation from emerging research regions (Beukelaar & Mantini, 2023; Yan & Girard, 2023; Krüger et al., 2023).

Keyword co-occurrence patterns reveal both established and emerging themes. Classical focuses such as hypertrophy, strength, and protein supplementation remain central, while newer approaches such as blood-flow restriction and velocity-based training reflect innovation in individualized load management (Moore & Dorrell, 2020). The increasing presence of terms related to wearable technology, athlete monitoring, and artificial intelligence indicates a shift toward data-driven training models (Mateus et al., 2024). These developments align with growing interest in machine-learning applications for athlete profiling, performance prediction, and injury prevention (Pisaniello, 2024; Claudino et al., 2017; Worsey et al., 2021).

Collectively, these findings show that RT research in elite athletes is simultaneously mature supported by foundational work on training variables and adaptation and evolving through methodological diversification sand technology integration. Persistent challenges include geographic bias, limited representation of female, youth, and Paralympic athletes, and slow adoption of advanced monitoring tools. Addressing these gaps will improve the breadth, precision, and applicability of RT research in high-performance environments (Granacher et al., 2016; Halperin et al., 2017; Behringer et al., 2023).

Analytical Synthesis: Methodological and Practical Implications

The integration of keyword, author, and citation networks reveals several methodological tendencies shaping contemporary RT research in elite athletes. Five dominant clusters hypertrophy and protein supplementation, neuromuscular monitoring, volume–intensity prescription, velocity-based training (VBT), and blood-flow restriction

(BFR) indicate a clear shift toward individualized and technology-supported programming. Highly cited studies (e.g., Morton et al., 2018) continue to reinforce the importance of optimizing load, intensity, and recovery strategies.

Author and country networks highlight concentrated contributions from the USA, Brazil, and Australia, creating methodological bias and limiting external validity for underrepresented populations. Citation clusters further reveal the dominance of short-term experimental studies, with limited long-term monitoring, female athlete research, and in-season intervention trials. These patterns point to the need for more diverse sampling strategies and longitudinal research designs.

Practically, these clusters underscore the value of integrating nutritional strategies, real-time load monitoring, athlete readiness assessment, and individualized progression models into elite RT programming. The growing presence of VBT and neuromuscular monitoring also suggests increased emphasis on fatigue management and precision training. Meanwhile, interest in BFR highlights its relevance for maintaining muscle qualities during congested schedules or post-injury scenarios.

Future Research

Future research on resistance training (RT) in elite athletes should address several critical gaps. Geographic disparities especially limited contributions from Asia, Africa, and parts of South America necessitate broader international collaboration and targeted funding (Fon, 2023; Steele et al., 2023). Open-access publishing and data-sharing platforms can further support inclusivity and enhance global research visibility (Murphy et al., 2023).

Specific athlete groups remain underexamined, including female, youth, and Paralympic athletes, each requiring population-appropriate training models (Franchi, Longo, et al., 2018; Faigenbaum & McFarland, 2023; Rodr et al., 2022). Increasing representation of these groups will improve the ecological validity of RT recommendations. Most RT studies still focus on short-term interventions, underscoring the need for longitudinal designs that capture in-season adaptation, chronic fatigue, and interactions with sport-specific demands (Townsend, 2022).

Finally, emerging technologies including wearables, artificial intelligence, and machine learning offer promising avenues for advancing monitoring precision and individualized programming (José et al., 2022; Mateus et al., 2024). Molecular and imaging methods also provide opportunities to investigate adaptation mechanisms at deeper biological levels (Bersiner & Kirill, 2023).

Conclusions

This bibliometric study (2015–2023) reveals that resistance training (RT) remains a highly active research field for elite athletes, with consistent scientific output, a publication peak in 2020, and a clear geographic imbalance dominated by established countries while developing regions are underrepresented. Core research themes continue to focus on hypertrophy, neuromuscular adaptations, and training volume, alongside growing interest in innovative methods such as velocity-based training, blood flow restriction, and technology-assisted monitoring. In conclusion, RT is a fundamental pillar of elite athlete development, but future progress requires greater inclusion of diverse populations, enhanced international collaboration, and deeper integration of technology to strengthen both the scientific evidence base and practical application in optimizing elite sports performance.

Ethics Approval

Ethical approval was not required for this study because it is a narrative/systematic review based exclusively on previously published and publicly available sources and does not involve human participants or animals.

Informed Consent

Not applicable.

Data Availability Statement

No new data were generated in this study. All information analyzed is derived from publicly available sources cited in the reference list.

AI Transparency Statement

AI-assisted tools were used exclusively for language editing, stylistic refinement, and text structuring, based on content prepared by the authors. AI was not used for literature selection, data extraction, data analysis, interpretation of findings, or generation of scientific conclusions.

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Conflict of Interest

The author declares no conflict of interest.

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Тренування з опором і елітні спортсмени: систематичний бібліометричний аналіз (2015–2023)

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 10 с., 3 табл., 4 рис., 73 джерела.

Мета. Це дослідження має на меті систематично відобразити глобальні дослідницькі тенденції, впливових авторів і тематичну еволюцію досліджень тренувань з опором (RT), що стосуються елітних спортсменів, у період з 2015 по 2023 рік.

Матеріали і методи. Було проведено систематичний бібліометричний аналіз із використанням бази даних Scopus. Відбір досліджень здійснювався відповідно до настанов PRISMA 2020 та був зосереджений на інтервенціях із тренуванням з опором за участю елітних спортивних популяцій. Дублікати було вилучено, після чого незалежні рецензенти виконали скринінг за назвами, анотаціями та повними текстами. Для побудови бібліометричних візуалізацій, зокрема мереж співавторства, співав цитування та співзустрічальності ключових слів, використовувалося програмне забезпечення VOSviewer версії 1.6.20. Оцінювалися ключові бібліометричні показники, зокрема динаміка публікацій, цитованість, мережі наукової співпраці та тематичне кластерування.

Результати. Із початкової сукупності 2 710 записів 678 документів відповідали критеріям включення. Світова наукова продуктивність демонструвала стабільне зростання з помітним прискоренням після 2019 року. Сполучені Штати Америки продемонстрували найвищий рівень цитованості, тоді як Іспанія та Бразилія сформувалися як ключові міжнародні центри наукової співпраці. Було ідентифіковано три основні тематичні кластери: (1) стратегії оптимізації спортивних результатів, зокрема тренування, засновані на швидкості виконання, та обмеження кровотоку; (2) нейром'язові адаптації та механізми гіпертрофії; (3) розвиток юних спортсменів із дедалі ширшою інтеграцією цифрових і моніторингових технологій.

Висновки. Дослідження тренувань з опором у елітних спортсменів продовжують активно розширюватися, характеризуючись високим рівнем міжнародної співпраці та зростанням методологічної виваженості. Отримані результати підкреслюють центральну роль тренувань з опором у спорті вищих досягнень і окреслюють напрями майбутніх досліджень, зокрема щодо гендерної інклюзивності, використання передових технологій моніторингу та стандартизованих підходів до вимірювання.

Ключові слова: тренування з опором, елітні спортсмени, бібліометричний аналіз, гіпертрофія,нейром'язова адаптація, підвищення спортивної результативності.

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Review Article

Functional Asymmetries in Youth Soccer Players: A Systematic Review of Assessment Technologies and Artificial Intelligence Applications

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Abstract

Background. Functional asymmetries in youth soccer players represent an important biomechanical and neuromuscular phenomenon, acting both as adaptive mechanisms and as potential risk factors for injury. However, existing evidence remains fragmented regarding the effectiveness of technological and artificial intelligence (AI)–based approaches for their assessment across different populations.

Purpose. This systematic review aimed to synthesize current methodologies and applications of technological tools and artificial intelligence used to assess functional asymmetries in youth soccer players.

Methods. The review was conducted in accordance with PRISMA guidelines. A total of 418 records were identified through searches in Scopus, Web of Science, and PubMed, of which 28 studies met the inclusion criteria. Methodological quality was evaluated using standardized assessment tools. The included studies examined wearable technologies, biomechanical assessment systems, and AI-based analytical models for asymmetry detection and interpretation.

Results. AI-based models demonstrated moderate predictive accuracy for injury risk, with reported values up to AUC = 0.70. Wearable inertial measurement units showed high ecological validity for on-field assessment of functional asymmetries. However, substantial heterogeneity was observed across studies in terms of asymmetry thresholds, outcome definitions, and analytical procedures, limiting cross-study comparability. A key finding was that strength asymmetries exceeding 15% were significantly associated with increased injury risk ($p < 0.05$), while such asymmetries did not consistently impair sprint performance, indicating context-dependent functional effects.

Conclusions. The findings indicate that technological and AI-based approaches provide valuable tools for assessing functional asymmetries in youth soccer players, particularly when applied in ecologically valid settings. The integration of explainable AI with multimodal biomechanical data appears to be a promising direction for personalized monitoring and intervention strategies. Future research should prioritize standardized methodological reporting, harmonized asymmetry thresholds, and longitudinal study designs to improve comparability and clinical translatability of findings.

Keywords: functional asymmetry, youth soccer, artificial intelligence, injury prediction, wearable sensors.

Introduction

During adolescence, corticospinal plasticity and neuromuscular differentiation create asymmetrical recruitment patterns that consolidate through repeated motor experiences, influencing both torque capacity and proprioceptive recalibration (Ballmann et al., 2021). Contemporary evidence highlights tendon stiffness modulation, fascicle reorganization, and stretch-shortening cycle efficiency as primary mediators of laterality, with divergent energy system contributions modulating metabolic flexibility between limbs (Falces-Prieto et al.,

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2021). Such divergences interact with proprioceptive weighting strategies, producing interlimb variability during high-intensity actions such as cutting or striking. This complex interplay between structural, neurological, and metabolic factors underscores why asymmetries manifest differently across individuals and contexts. Recent theoretical frameworks describe asymmetry not merely as a deficit but as an adaptive manifestation of ecological dynamics, reflecting functional solutions to sport-specific constraints (Sullivan et al., 2021). This paradigm shift from a purely deficit-based to an adaptation-focused perspective necessitates more nuanced assessment and interpretation strategies. Nonetheless, prospective cohort evidence confirms that magnitudes surpassing 10–15% correlate with elevated musculoskeletal injury risk, emphasizing their dual status as adaptive markers and pathological indicators (Edouard et al., 2024). From a developmental perspective, the timing of peak height velocity strongly conditions asymmetry trajectories, underscoring the necessity for maturation-sensitive interpretation (Solleveld et al., 2022). The adolescent growth spurt represents a critical window where asymmetries may either consolidate or resolve, depending on training load and intervention strategies. Empirical data from multiple geographies reinforce the global relevance of asymmetry, with consistent associations identified across European, South American, and Middle Eastern academies (Moreno-Villanueva et al., 2025). This ecological validity expands the conceptualization of asymmetries beyond Eurocentric contexts, confirming their role as universal markers of adolescent adaptation. However, cultural differences in training methodologies, playing surfaces, and competition structures may influence how asymmetries develop and manifest across different populations. Advances in monitoring technologies now enable their precise quantification across morphological, neuromuscular, and kinematic domains, thereby consolidating asymmetry as a multidimensional construct within contemporary sports science (Jiang et al., 2023). This theoretical anchor legitimizes asymmetry profiling as an indispensable element for understanding developmental motor control, performance optimization, and injury mitigation in youth soccer (Ben Rakaa, Lourenço, et al., 2025). Despite this recognition, significant methodological challenges persist in standardizing assessment protocols and establishing universally applicable thresholds.

The methodological landscape of asymmetry research demonstrates substantial heterogeneity, constraining interpretability and translational impact (França et al., 2023). Isokinetic dynamometry remains the reference standard for torque quantification, but ecological limitations, resource intensity, and scheduling barriers restrict large-scale youth application (Vargas et al., 2020). Comparisons of bilateral versus unilateral countermovement jump assessments reveal divergent reliability properties, with bilateral tasks offering stronger longitudinal stability, although interpretive thresholds remain inconsistent (Fain et al., 2021). Functional tests, such as the Y-Balance, exhibit variable predictive accuracy, particularly in non-Western youth cohorts, highlighting cultural and developmental moderators of screening validity (Johnson et al., 2023). These inconsistencies in test selection, administration, and interpretation undermine the development of evidence-based guidelines for practitioners. Recent advances in wearable inertial measurement units allow for session-embedded asymmetry monitoring during change-of-direction or soccer-specific drills, enhancing ecological validity (Jiang et al., 2023). However, device calibration, placement variability, and task standardization challenge reliability, demanding rigorous validation protocols (Kadlec et al., 2023). Analytical heterogeneity further complicates prevalence estimates, as divergent formulas for limb symmetry indices produce substantial discrepancies in individual classification (Ascenzi et al., 2022). Without consensus on calculation methods and reporting standards, cross-study comparisons remain problematic and meta-analytical approaches limited. Artificial intelligence applications mark a methodological frontier, offering nonlinear modeling of high-dimensional datasets to predict injury susceptibility (Oliver et al., 2020). Exploratory studies report moderate predictive accuracy, but calibration instability, sparse datasets, and overfitting risks limit generalizability (Čular et al., 2023). The integration of domain knowledge with data-driven approaches appears essential for developing clinically useful AI tools. Cross-cultural investigations from South America and North Africa stress the importance of contextualized approaches when applying machine learning models to youth sport (Čular et al., 2023). The relevance of this domain extends to athlete development, where valid, reliable, and scalable methodologies are essential for personalized training, targeted injury prevention, and longitudinal monitoring (Din et al., 2025). Integration of multimodal technologies with explainable AI offers an unprecedented opportunity to reconcile precision with ecological applicability, ensuring translational value for practitioners and safeguarding developmental health (Brouki et al., 2025). This systematic review therefore aims to critically evaluate the convergence of traditional assessment methods with emerging AI technologies in youth soccer asymmetry research.

Empirical evidence from recent observational and interventional studies underscores the prevalence of asymmetries across morphological, neuromuscular, and functional domains in youth soccer (Fain et al., 2021). Interlimb discrepancies in strength and jump metrics often exceed injury-risk thresholds, yet associations with sprint and agility outcomes remain inconsistent, reflecting compensatory neuromuscular strategies (Fain et al., 2021). This performance-asymmetry paradox suggests that athletes may develop effective compensation mechanisms that mask underlying imbalances during specific tasks.Longitudinal data confirm mid-adolescence as a sensitive period where hamstring asymmetries peak, reinforcing the need for maturation-adjusted protocols (Moreno-Villanueva et al., 2025). This proximal-distal interdependence highlights the importance of assessing asymmetries beyond the lower limbs alone. Proximal asymmetries in trunk control additionally propagate distal discrepancies, underscoring integrated conditioning approaches (Moreno-Villanueva et al., 2025). Meta-analyses reveal that targeted unilateral or bilateral training interventions reduce asymmetry magnitudes with small-to-moderate effect sizes, validating progressive overload strategies in academy settings (Bettariga et al., 2022). However, morphological asymmetries derived from imaging technologies exhibit limited predictive power for injury outcomes, cautioning against structural metrics as standalone indicators (Vaillancourt et al., 2024).The dissociation between structural and functional asymmetries necessitates multimodal assessment approaches that capture both anatomical and neuromuscular dimensions. Ecological replications from Turkey, Brazil, and North Africa corroborate the injury–asymmetry nexus, substantiating global applicability across developmental environments (Edouard et al., 2024; Moreno-Villanueva et al., 2025). Despite promising findings, evidence synthesis reveals enduring methodological limitations: small sample sizes, cross-sectional dominance, and inconsistent asymmetry reporting preclude robust causal inferences (França et al., 2023). Moreover, AI-driven injury prediction models remain underdeveloped, characterized by fragile calibration and limited external validation (Xia et al., 2021). These methodological shortcomings collectively constrain the evidence base and hinder the development of clinically actionable insights.These shortcomings underscore the urgency of establishing harmonized thresholds, multi-academic longitudinal datasets, and tailored, inclusive machine learning frameworks (Ben Rakaa, Bassiri, et al., 2025b, 2025a; Ben Rakaa, Lourenço, et al., 2025). The present systematic review directly addresses these challenges by critically synthesizing studies on functional asymmetries in youth soccer between 2015 and 2025, with particular focus on three key domains: assessment technologies, AI applications, and practical implementation frameworks. The present systematic review directly addresses these challenges by critically synthesizing studies on functional asymmetries in youth soccer between 2015 and 2025. By integrating technological innovations with AI-based analytics, the objective is to advance methodological precision, contextual relevance, and applied utility1, thereby supporting evidence-informed interventions in athlete development and injury prevention (Bouzid et al., 2025). Specifically, this review aims to: (1) evaluate the methodological quality of current assessment approaches; (2) synthesize evidence on AI/ML applications for asymmetry analysis and injury prediction; and (3) propose standardized frameworks for asymmetry monitoring and intervention in youth soccer academies.

Methods

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review protocol was registered on the PROSPERO platform prior to the initiation of the selection process (registration number: CRD420241125443).

Working Definitions

To ensure conceptual clarity and methodological consistency throughout this systematic review, the following operational definitions were adopted:

Functional Asymmetry

Functional asymmetry refers to any measurable difference between homologous limbs in strength, power, kinematic, or neuromuscular performance during sport-specific or standardized tasks. In this review, asymmetry is considered functional when it arises from training-induced adaptations, maturation effects, or biomechanical constraints, rather than from structural pathology or injury.

Inter-limb and Intra-limb Asymmetry

Inter-limb asymmetry denotes discrepancies between the dominant and non-dominant limbs in quantitative parameters such as torque, force, or jump height. Intra-limb asymmetry reflects imbalance between agonist and antagonist muscle groups within the same limb (e.g., hamstring-to-quadriceps ratio).

Dominant and Non-dominant Limb

The dominant limb was defined as the limb preferentially used for ball manipulation or kicking tasks, while the non-dominant limb refers to the supporting or stabilizing limb. In studies where self-reported dominance was not provided, functional dominance was inferred from the primary limb used during kicking or performance tasks.

Limb Symmetry Index (LSI)

Limb asymmetry was most frequently quantified using the Limb Symmetry Index (LSI), calculated as:

LSI = (Dominant–No-dominant)/ Dominant × 100

or equivalently using contralateral ratios depending on the variable measured. An LSI of 0–10% was interpreted as normal or negligible; 10–15% represented a “monitoring zone,” suggesting elevated injury susceptibility; and >15% was considered clinically significant, warranting corrective intervention.

Asymmetry Thresholds

Consistent with prior evidence, asymmetry magnitudes exceeding 10–15% were considered predictive of increased musculoskeletal injury risk, particularly for lower-limb soft tissue injuries. However, the functional impact of such asymmetries on performance outcomes (e.g., sprint, change of direction, jump height) was treated as context-dependent and moderated by maturation status, task type, and sport-specific demands.

Technological Assessment Modalities

Assessment technologies included isokinetic dynamometry, force platforms, inertial measurement units (IMUs), 3D motion capture, and AI-based video or wearable systems. These tools were classified according to their measurement domain: Kinetic (e.g., torque, impulse, ground reaction force),Kinematic (e.g., joint angles, movement trajectories), and Neuromuscular (e.g., rate of force development, time-to-stabilization).Wearable sensors and AI algorithms were included when they objectively quantified or predicted asymmetry-related outcomes.

Artificial Intelligence (AI) and Machine Learning (ML)

For the purpose of this review, AI/ML applications refer to computational approaches that use data-driven algorithms (e.g., Random Forest, Support Vector Machine, Neural Networks) to identify, classify, or predict asymmetry patterns and their association with injury risk or performance. Only peer-reviewed studies providing explicit methodological descriptions of algorithm design, validation, and feature selection were considered.

Youth Soccer Players

The term youth soccer players encompasses male and female athletes aged ≤19 years, actively participating in structured competitive or academy programs. Maturation status was classified as pre-, mid-, or post-peak height velocity (PHV), where reported, to allow age- and development-sensitive interpretation of asymmetry profiles.

Information Sources

A comprehensive and systematic literature search was performed across three major electronic bibliographic databases: Scopus, Web of Science, and PubMed. These databases were selected for their extensive coverage of peer-reviewed scientific literature in the fields of sports medicine, biomechanics, orthopedics, and physiotherapy. The search covered the period between the creation of each respective database between January 2015 and July 2025. Furthermore, the reference lists of all included studies and relevant review articles were manually screened to identify any potentially omitted publications.

Eligibility Criteria

Eligible studies will investigate youth soccer players—defined as academy or adolescent athletes of any sex who compete in organized, competitive soccer—and will report original data in a peer-reviewed journal. To meet the phenomenon-of-interest requirement, studies must quantify inter-limb functional asymmetry at the individual level, operationalized as between-limb differences in at least one domain: (i) muscular strength (e.g., isokinetic or isometric measures), (ii) kinematics (e.g., joint angles or segmental motion during task execution), (iii) kinetics (e.g., force, impulse, torque), (iv) morphological characteristics (e.g., muscle volume, architecture), or (v) soccer-relevant functional performance (e.g., jump performance, change-of-direction ability, sprinting outcomes). Assessment must be conducted using technological instrumentation (such as isokinetic dynamometry, three-dimensional motion capture, force platforms, or inertial measurement units) or incorporate artificial intelligence/machine-learning methods for the analysis or interpretation of asymmetry outcomes. The context must be exclusively soccer; mixed-sport samples are admissible only when soccer-specific data are extractable. Acceptable study designs include observational (cross-sectional, cohort, case–control) and experimental (randomized controlled or quasi-experimental) designs that provide sufficient methodological detail on the instruments and procedures used to quantify asymmetry, together with the magnitude and/or direction of inter-limb differences.

Studies will be excluded if they focus solely on adult professional players (typically > ~21 years) without separable youth data; if they are not conducted in soccer or present mixed-sport data from which soccer-specific results cannot be isolated; or if they do not quantify inter-limb asymmetry at the individual level (e.g., report only group means without between-limb metrics). Studies relying exclusively on subjective or non-instrumented assessments (e.g., questionnaires alone, manual clinical tests without technological measurement) will be excluded. Finally, we will exclude non-original or non-peer-reviewed works, including narrative or systematic reviews, editorials, conference abstracts, theses, preprints not certified by peer review, and other grey-literature sources (e.g., conference abstracts, theses, preprints) was excluded to ensure that only peer-reviewed and methodologically validated studies were synthesized. Similarly, no-English publications were excluded due to resource constraints and the need for consistent quality assessment across studies. While this may introduce a language bias, it enhances the reproducibility and comparability of the review process.

Search Strategy

The search strategy was specifically designed to identify studies investigating functional asymmetries in youth soccer players, with a particular focus on assessment technologies and artificial intelligence applications. In collaboration with a specialized librarian, a structured Boolean query was constructed by combining relevant keywords and Medical Subject Headings (MeSH) terms. The core concepts utilized were ("soccer player*" OR "football player*" OR "youth soccer" OR "elite youth" OR junior OR adolescent OR "young athlete*")AND(asymmetr* OR "limb dominan*" OR "bilateral deficit" OR "inter-limb" OR "intra-limb" OR "side-to-side difference" OR imbalance)AND("artificial intelligence" OR "machine learning" OR "deep learning" OR "neural network" OR "AI" OR "predictive model" OR "data analytics" OR "wearable technology" OR "inertial measurement unit" OR IMU OR "wearable sensor*" OR "GPS" OR "local positioning system"OR "force plate" OR "force platform" OR "pressure plate" OR "plantar pressure" OR "3D motion capture" OR "kinematic analysis" OR "isokinetic dynamometer" OR "strength assessment")AND("change of direction" OR COD OR decelerat* OR cut* OR pivot* OR jump* OR "drop jump" OR "countermovement jump" OR CMJ OR "sprint" OR "balance" OR "postural control" OR "strength" OR "injury risk" OR "injury prediction") . This syntax was adapted to the specific formats required by Scopus,Web of Science and Pubmed. No restrictions on language were applied.

In compliance with the PRISMA 2020 statement, the search and selection procedures were documented in full to enhance methodological transparency and reproducibility. Numerical consistency in the PRISMA flow diagram (Figure 1) was verified to ensure complete arithmetic accuracy between records identified, screened, excluded, and included. Reasons for full-text exclusions—such as studies not conducted in soccer, lack of inter-limb asymmetry data, mixed-sport samples without extractable soccer-specific results, or exclusion of non-peer-reviewed sources—are now clearly presented in the Supplementary Appendix.

A completed PRISMA 2020 Checklist has been included as Supplementary Appendix 1, allowing independent verification of reporting completeness. Additionally, the full database search strings, including Boolean operators, filters, and final search dates, are provided below to facilitate replication of the search process:

Scopus (last search: July 30, 2025): ("soccer player*" OR "football player*" OR "youth soccer" OR "elite youth" OR "junior" OR "adolescent" OR "young athlete*") AND (asymmetr* OR "limb dominan*" OR "bilateral deficit" OR "inter-limb" OR "side-to-side difference" OR imbalance) AND ("artificial intelligence" OR "machine learning" OR "wearable technology" OR IMU OR "force plate" OR "3D motion capture" OR "isokinetic dynamometer") AND ("change of direction" OR COD OR "jump*" OR "sprint" OR "balance" OR "injury risk"). Filters applied: peer-reviewed journal articles only; publication period January 2015 – July 2025; no language restrictions.

Web of Science (last search: July 30, 2025): Same Boolean logic adapted to "Topic Search (TS)" fields; limited to peer-reviewed journal articles.

PubMed (last search: July 30, 2025): ("soccer"[MeSH Terms] OR "football"[Title/Abstract]) AND (asymmetry OR "limb dominance" OR "bilateral deficit") AND ("artificial intelligence" OR "machine learning" OR "wearable sensor" OR "force plate") AND ("youth" OR "adolescent" OR "academy"). Filters applied: Humans; Journal Article; 2015–2025.

The study selection process was conducted by two independent reviewers (W.B. and O.B.R.). After duplicate removal, both reviewers screened the titles and abstracts of all retrieved records against the eligibility criteria. The full texts of potentially relevant studies were then assessed independently by the same two reviewers. At both stages, any discrepancies regarding the inclusion or exclusion of a study were resolved through discussion until a consensus was reached. If a consensus could not be reached, a third senior reviewer (M.B.) was consulted to make the final decision. No automation tools were used for the study selection process.

Data Extraction and Management

A standardized data extraction form was developed a priori and piloted by the research team. Data from the included studies were extracted independently by two reviewers (Y.B. and A.C.). Any disagreements in the extracted data were resolved by consensus or, if necessary, by arbitration from a third reviewer (A.E.). The following data were extracted: Study characteristics: first author, publication year, country, study design, sample size. Participant characteristics: sex, age, biological maturity status (e.g., Peak Height Velocity - PHV), competitive level (e.g., elite, sub-elite, recreational), and training experience. Asymmetry-related data: type of asymmetry (e.g., strength, kinematic, kinetic), assessment technology used (e.g., isokinetic dynamometer, force plate, IMU), AI model used (if applicable), variables measured (e.g., peak torque, jump height, joint angles), and the magnitude/direction of asymmetry. Key outcomes: primary findings related to asymmetry, injury risk, and performance. Other variables: source of funding and conflicts of interest, as reported. In cases of missing or ambiguous data, the study was not excluded, but the specific missing variable was noted and excluded from the relevant analysis. Authors of the primary studies were not contacted for missing data, as the review was designed to synthesize only the information available in the published reports.

Assessment of Study Methodology

The methodological quality of each included study was independently assessed by two reviewers using validated tools appropriate for the respective study designs (e.g., the Newcastle-Ottawa Scale for cohort and case-control studies, and a modified tool for cross-sectional studies). The domains examined included selection of study groups, their comparability, and the ascertainment of both exposure and outcome. Any discrepancies were resolved through consensus. The results of this appraisal are presented in Table 1, providing a transparent overview of the robustness of the evidence; this assessment was not used as an exclusion criterion.

Asymmetry Metrics and Thresholds

To ensure consistency in terminology, the following abbreviations are used throughout this review: Artificial Intelligence and Machine Learning (AI/ML), Inertial Measurement Unit (IMU), and Limb Symmetry Index (LSI). The magnitude of inter-limb asymmetry was quantified using various metrics across the included studies. The most prevalent method was the Limb Symmetry Index (LSI), typically calculated using the following formula:

$$\text{LSI (\%)} = \left(\frac{\text{Value of Non-Dominant Limb}}{\text{Value of Dominant Limb}}\right) \times 100$$

Alternative common formulae for asymmetry percentage (Asym%) include:

$$\text{Asym\%} = \left(\frac{|\,\text{Dominant Limb} - \text{Non-Dominant Limb}\,|}{\text{Max(Dominant Limb, Non-Dominant Limb)}}\right) \times 100$$

or

$$\text{Asym\%} = \left(\frac{|\,\text{Dominant Limb} - \text{Non-Dominant Limb}\,|}{(\text{Dominant Limb} + \text{Non-Dominant Limb})/2}\right) \times 100$$

For the context of this review, asymmetries exceeding the 10–15% threshold were considered clinically significant. This range is widely cited in the literature, where: Asymmetries below 10% are often considered normal or negligible in youth athletic populations. Asymmetries between 10% and 15% are viewed as a "grey zone," potentially indicating elevated injury risk or a need for monitoring. Asymmetries exceeding 15% are consistently associated with a significantly increased risk of musculoskeletal injury and are typically targeted for corrective intervention. It is important to note that the interpretation of these thresholds can be context-dependent, varying by the specific test (e.g., strength, jump), the variable measured (e.g., peak force, impulse), and the individual's maturation status.

Results

The study selection (Figure 1) identified 418 articles via Scopus (n=205), Web of Science (n=201), and PubMed (n=12). After removing 89 duplicates, 329 abstracts were reviewed. 290 were excluded, leading to the evaluation of 37 full texts. 8 articles were excluded according to predefined criteria (3 not focused on soccer, 3 without individual asymmetry data, and 1 grey literature), resulting in 28 included studies. This PRISMA methodology ensures the rigor and reproducibility of the systematic review.

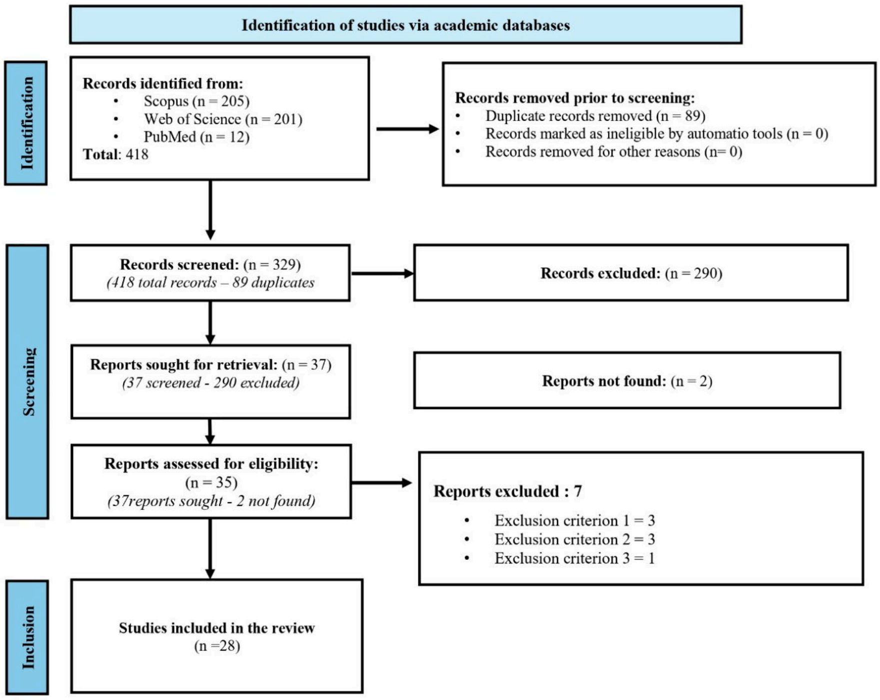

Fig. 1. Flowchart of the systematic review

The following section presents the results of the study, based on the data collected and analyzed.

Synthesis of AI/ML Studies

Among the 28 included studies, two primary investigations focused specifically on the development and validation of AI/ML models for predicting injury risk in youth soccer players. The quantitative characteristics of these models are summarized in Table 3. The study by (Robles-Palazón et al., 2023) utilized an ensemble of models, with the best performance achieved by a Random Forest algorithm. In contrast, (Oliver et al., 2020) compared a single ML model against traditional logistic regression, demonstrating the superior sensitivity of the ML approach. Both studies relied on internal validation methods, and calibration metrics were not consistently reported, highlighting a common limitation in the current literature.

Discussion

This systematic review, based on the analysis of 28 studies, highlights the considerable evolution of methods for evaluating functional asymmetries in young soccer players, driven by emerging technologies and artificial intelligence. All of the studies converge on one conclusion: instrumented approaches, whether involving motion capture, isokinetic dynamometry, force platforms, inertial measurement units (IMU), or machine learning algorithms, allow for the quantification of inter-limb imbalances with unprecedented precision, sensitivity, and predictive value. As demonstrated by (Robles-Palazón et al., 2023), models of automated learning incorporating six asymmetric variables — notably valgus, force of landing and internal rotation of the hip — achieve a rate of precision of 70% in predicting the likelihood of injury. This approach provides an economically advantageous alternative to the use of bulky batteries for testing purposes. Furthermore, it is necessary to conside, As indicated by (Oliver et al., 2020), the application of machine learning algorithms to asymétries resulting from single-leg countermovement jump does not enhance the sensitivity of injury prediction (55.6% compared to 15.2% for the logistical regression model). A multitude of studies, including those by (Barbalho et al., 2021) and (Read et al., 2016), have underscored the significance of a multi-test approach. The asymmetries detected in a particular jump (e.g., the squat jump [SJ], the countermovement jump [CMJ], or the drop jump [DJ]) vary according to the task, thereby substantiating the necessity of a comprehensive evaluation encompassing diverse modalities. The proliferation of portable tools signifies a pivotal juncture within this domain. Indeed, the research conducted by (Di Paolo et al., 2021) and (Izzo et al., 2022) has demonstrated the significance of inertial sensors in the longitudinal monitoring of asymétries throughout the season. These investigations have facilitated the identification of fluctuations associated with the load of training, thereby providing novel insights into the analysis of sporting performance. In addition, non-marker-based motion capture systems, such as those employed by (Nakahira et al., 2022), have been shown to detect subtle cinematic asymmetries, including a valgus knee rotation of 8 to 10° in the dominant lower extremity, which is imperceptible to the naked eye. As demonstrated in the studies conducted by (Zeleznik et al., 2025) and (Vargas

Table 1. Summary of Included Studies on Asymmetry in Athletes

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Robles-Palazón et al., 2023)	Predicting injury risk using machine learning in male youth soccer players	Spain	Age: U11-U19; PHV: Mixed; Level: Non-elite; Sex: Male	Bilateral asymmetry (ROM, landing, force)	Support Vector Machine (SMO), Random Forest, Ensemble (UBAG), SHAP	Anthropometry, ROM, jump, sprint, agility, y-balance, injury	Asymmetry Index (%); Threshold: >15% for injury risk	Not reported	Moderate
(Bonetti et al., 2017)	Isokinetic performance of knee extensors and flexors in adolescent male soccer athletes	Brazil	Age: U17; PHV: Not specified; Level: Not specified; Sex: Male	Strength asymmetry (knee extensors/flexors)	Isokinetic dynamometer (Biodex System 4); No AI	Peak torque; flexor/ extensor ratio; bilateral asymmetry	LSI (%); Threshold: Not specified	Not reported	Moderate
(Vargas et al., 2020)	Knee isokinetic muscle strength and balance ratio in female soccer players of different age groups: a cross-sectional study	Brazil	Age: U13-PRO; PHV: Not specified; Level: Mixed; Sex: Female	Age-related asymmetry; dominant vs. non-dominant	Isokinetic dynamometry (System 4 Biodex); no AI	Peak torque; average power; conventional & functional ratios; contralateral deficit	LSI (%); Threshold: Not specified	Not reported	High
(Jones et al., 2021)	Field-based lower limb strength tests provide insight into sprint and change of direction ability in academy footballers	Uk/nl/no	Age: 10-18 yrs; PHV: Mixed; Level: Academy; Sex: Male	Between-limb imbalances in hip/ groin strength	Nordbord (hamstring), ForceFrame (hip strength), CMJ platform; No AI	Sprint times (5-20 m); change of direction (505 test); CMJ impulse; hip ADD/ABD; Nordic hamstring strength	Asymmetry Index (%); Threshold: >10% for imbalance	Nordbord: ICC = 0.85-0.95; ForceFrame: ICC = 0.88-0.93	High
(Di Paolo et al., 2021)	Poor motor coordination elicits altered lower limb biomechanics in young football (soccer) players: implications for injury prevention through wearable sensors	Italy	Age: ~10 yrs; PHV: Pre-PHV; Level: Juvenile; Sex: Male	Motor coordination-related asymmetry	Wearable inertial sensors (Xsens MVN); No AI	Joint angles (hip, knee, ankle); accelerations; asymmetry indices	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Przysucha et al., 2024)	Postural sway characteristics in static balance control of youth female soccer players	Canada	Age: 11-13 yrs; PHV: Pre-PHV; Level: Not specified; Sex: Female	Dominant vs. non-dominant leg balance	Force platform (AMTI®); No AI	Center of pressure sway, path length, velocity, AP sway	Inter-limb difference in CoP metrics; Threshold: Not specified	ICC for path length = 0.89	Moderate

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Zeleznik et al., 2025)	Relation of dominant leg use with functional symmetries in young football players of different age groups	Slovenia	Age: U12-U19; PHV: Mixed; Level: Not specified; Sex: Male	Dominant leg use vs. bilateral function	Video analysis; radar gun; photocells; dual-force plate; No AI	Ball speed, dribbling with change of direction, CMJ power	Asymmetry Index (%); Threshold: Not specified	Not reported	High
(Silva et al., 2022)	Relationships of final velocity at 30-15 intermittent fitness test and anaerobic speed reserve with body composition, sprinting, change-of-direction and vertical jumping performances: a cross-sectional study in youth soccer players	Portugal	Age: U14-U19; PHV: Mixed; Level: Not specified; Sex: Male	Functional performance asymmetries (sprint, COD, jump)	Field tests: CMJ, sprints, COD test, 30-15 IFT; No AI	Anthropometry, CMJ, sprint, COD, VIFT, ASR	Asymmetry Index (%); Threshold: Not specified	Not reported	High
(Barbalho et al., 2021)	Assessing interlimb jump asymmetry in young soccer players: the my jump 2 app	Uk	Age: U17; PHV: Not specified; Level: Elite; Sex: Male	Interlimb asymmetry (SJ, CMJ, DJ)	Dual force plates; No AI	Jump height, peak force, concentric impulse, power	Asymmetry Index = [(Dominant - Non-dominant)/ Dominant] × 100; Threshold: Not specified	Not reported	Moderate
(Read et al., 2016)	Consistency of field-based measures of neuromuscular control using force-plate diagnostics in elite male youth soccer players	Uk	Age: Pre/post-PHV; PHV: Pre/post-PHV; Level: Elite; Sex: Male	Neuromuscular asymmetry (landing forces, stability)	Force plates; No AI	pVGRF, time-to-stabilization, asymmetry indices	Asymmetry Index (%); Threshold: Not specified	ICC for pVGRF = 0.78-0.94; CV = 4.1-11.3%	High

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Bromley et al., 2021)	Effects of a competitive soccer match on jump performance and interlimb asymmetities in elite academy soccer players	Uk	Age: Not specified; PHV: Not specified; Level: Elite Academy; Sex: Male	Interlimb asymmetry under fatigue	Force platform; No AI	Eccentric/concentric impulse, peak force, landing metrics, asymmetry indices	Asymmetry Index (%); Threshold: >10% considered meaningful	Not reported	High
(Vasileiou et al., 2024)	Effects of an 8-week in-season explosive power training program on neuromuscular performance and lower-limb asymmetries in young male soccer players	Greece	Age: 13-15 yrs; PHV: Not specified; Level: Not specified; Sex: Male	Interlimb asymmetry (jumping, COD)	OptoJump system, sprint timing gates; No AI	CMJ, SLCMJ, 10-20 m sprint, 505 COD test	Asymmetry Index (%); Threshold: >10% targeted for reduction	Not reported	High
(Daneshjoo et al., 2015)	Analysis of jumping-landing manoeuvers after different speed performances in soccer players	Iran/ malaysia	Age: Collegiate; PHV: Adult; Level: Collegiate; Sex: Male	Bilateral asymmetry (kinematic/ kinetic)	Vicon motion capture; Kistler force plates; No AI	Knee angles, valgus moment, GRF	Inter-limb differences; Threshold: Not specified	Not reported	Moderate
(Bahenský et al., 2020)	Power, muscle, and take-off asymmetry in young soccer players	Czech republic	Age: U16-U19; PHV: Not specified; Level: Not specified; Sex: Male	Dominant vs. non-dominant limb; muscle mass vs. force	Force plate; Wingate anaerobic test; Tanita BC418 body comp.; No AI	Muscle mass distribution, take-off force, anaerobic power	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Michailidis et al., 2025)	Correlation of the asymmetry index from the single-leg countermovement jump with the asymmetry index from isokinetic strength in elite youth football players	Greece	Age: ~15 yrs; PHV: Not specified; Level: Elite; Sex: Male	Functional vs. isokinetic asymmetry indices	Chronojump leap mat; Cybex dynamometer; No AI	SLCMJ height, quadriceps/ hamstring isokinetic torque	Asymmetry Index (%); Threshold: Not specified	Not reported	High

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Izzo et al., 2022)	Symmetry and performance index evaluation in a youth football group using the latest generation imu	Italy	Age: U11-12; PHV: Pre-PHV; Level: Not specified; Sex: Male	Lateral imbalance during COD	Inertial sensors (K-Sport IMU); No AI	Training load, average strength, imbalance index	Imbalance Index; Threshold: Not specified	Not reported	Moderate
(Bishop et al., 2021)	Intra-and inter-limb strength asymmetry in soccer: a comparison of professional and under-18 players	Uk & italy	Age: Pro & U18; PHV: Adult & Adolescent; Level: Professional & Academy; Sex: Male	Inter-limb & intra-limb (quadriceps/ hamstrings)	Isokinetic dynamometer (Cybex Norm); No AI	Knee extensor/flexor torque, H:Q ratios, asymmetry indices	LSI (%); Threshold: >10-15% for inter-limb asymmetry	Not reported	High
(Contreras-Díaz et al., 2023)	Dynamometric strength profile of hip muscles in youth soccer players	Chile & spain	Age: U17; PHV: Not specified; Level: Not specified; Sex: Male	Bilateral asymmetry (hip abductors, adductors, flexors, extensors)	Functional electromechanical dynamometer (FEMD); No AI	Concentric/ eccentric hip torque, unilateral ratios, bilateral balance	LSI (%); Threshold: <10% considered normal	Not reported	High
(Rosa et al., 2022)	Knee and hip agonist-antagonist relationship in male under-19 soccer players	Portugal & colombia	Age: U19; PHV: Late adolescent; Level: Not specified; Sex: Male	Agonist-antagonist & bilateral asymmetry	Isokinetic dynamometer (Biodex); isometric dynamometer (Smart Groin Trainer); No AI	Knee flex/extension, hip add/abduction, functional ratios	LSI (%); Threshold: Not specified	Not reported	Moderate
(Sannicandro et al., 2023)	Jumps and lower limb strength asymmetry in young soccer players: differences between sand and conventional surfaces	Italy	Age: U17; PHV: Not specified; Level: Not specified; Sex: Male	Inter-limb asymmetry (jumping tasks)	Jump tests on sand vs grass (Hop, Side Hop, Broad Jump); No AI	Jump height, asymmetry %, performance deficits	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Michailidis et al., 2020)	Association between jump asymmetry and reduced performance in the change of direction tests of youth soccer players	Greece	Age: U10 & U15; PHV: Pre-PHV & Mid-PHV; Level: Not specified; Sex: Male	Inter-limb asymmetry (jump tests)	SLCMJ, SLLJ, SLTJ, 505 COD, Arrowhead test; No AI	Jump distances, COD times, asymmetry indices	Asymmetry Index (%); Threshold: >10% for performance impact	Not reported	Moderate

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Nakahira et al., 2022)	Kinematic differences between the dominant and nondominant legs during a single-leg drop vertical jump in female soccer players	Japan	Age: 15-22 yrs; PHV: Post-PHV; Level: Not specified; Sex: Female	Kinematic asymmetry (dominant vs nondominant)	AI-based video motion capture (VMocap), Video motion capture with AI-based markerless tracking (OpenPose)	Knee valgus, flexion, hip flexion, inclination angles	Inter-limb angular differences; Threshold: Not specified	Not reported	High
(Ince & Tortu, 2025)	Association between intra and inter-limb strength asymmetry with sprint kinematics and force-velocity profile in youth team athletes	Türkiye	Age: Youth; PHV: Not specified; Level: Mixed; Sex: Mixed (34 soccer)	Inter- & intra-limb asymmetry	Isokinetic dynamometer (Cybex HUMAC Norm); OptoJump; No AI	Sprint times, step length/velocity, F-V profile, strength asymmetry	LSI (%); Threshold: >15% for critical asymmetry	Not reported	High
(Trecroci et al., 2020)	Agreement between dribble and change of direction deficits to assess directional asymmetry in young elite football players	Italy	Age: Youth; PHV: Not specified; Level: Elite; Sex: Male	Directional asymmetry (dribble vs COD deficit)	Timing gates (Witty Microgate); No AI	Sprint time, COD deficit, dribble deficit, asymmetry index	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Ferreira et al., 2018)	Impact of competitive level and age on the strength and asymmetry of young soccer players	Brazil	Age: U15-U20; PHV: Mixed; Level: Mixed; Sex: Male	Bilateral asymmetry (force, impulse, power)	Dual force plates (PLA3-1D-7KN/ JBAZb); No AI	Jump height, peak force, impulse, peak power, asymmetry indices	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate
(Atkins et al., 2016)	The presence of bilateral imbalance of the lower limbs in elite youth soccer players of different ages	Uk	Age: U13-U17; PHV: Mixed; Level: Elite; Sex: Male	Bilateral imbalance (ground reaction forces, DS test)	Twin force plates (Globus Ergo); No AI	Peak GRF, deep squat scores, asymmetry across age groups	Asymmetry Index (%); Threshold: Not specified	Not reported	High
(Oliver et al., 2020)	Using machine learning to improve our understanding of injury risk and prediction in elite male youth football players	Uk, spain, qatar	Age: U10-U18; PHV: Mixed; Level: Elite; Sex: Male	Neuromuscular asymmetry (SLCMJ, SLHD, 75%Hop, Y-balance)	Force plates, Y-balance kit, tuck jump video; Machine Learning	Asymmetry indices, jump kinetics, knee valgus, injury incidence	Asymmetry Index (%); Threshold: >15% for injury risk	Not reported	High

Table 1 (continued)

Author(s) and year	Original title of the article	Country	Sample (age, PHV, level, sex)	Type of asymmetry	Technologies and AI model used	Variables measured	Formula/ Threshold	Reliability (ICC/CV)	Study quality
(Trecroci et al., 2020)	Agreement between dribble and change of direction deficits to assess directional asymmetry in young elite football players	Italy	Age: Youth; PHV: Not specified; Level: Elite; Sex: Male	Same as Trecroci (dribble vs COD)	Timing gates; No AI	Sprint time, COD deficit, dribble deficit, asymmetry index	Asymmetry Index (%); Threshold: Not specified	Not reported	Moderate

Rom. Range Of Motion, Cmj. Countermovement Jump, Sj. Squat Jump, Dj. Drop Jump, Slcmj. Single-Leg Countermovement Jump, Sllj. Single-Leg Long Jump, Sltj. Single-Leg Triple Jump, Slhd. Single-Leg Hop For Distance, Cod. Change Of Direction, Ift (30–15 Ift). 30–15 Intermittent Fitness Test, Vift. Final Velocity At The 30–15 Intermittent Fitness Test, Asr. Anaerobic Speed Reserve, Grf/Pvgrf. Ground Reaction Force/Peak Vertical Ground Reaction Force, Add/Abd. Hip Adduction/Abduction, H:Q Ratio. Hamstring-To-Quadriceps Strength Ratio, F–V Profile. Force–Velocity Profile, Imu. Inertial Measurement Unit, Ai. Artificial Intelligence, Svm (Smo). Support Vector Machine (Sequential Minimal Optimization), Rf. Random Forest, Ubag. Uniform Bootstrap Aggregating Ensemble, Shap. Shapley Additive Explanations, Cod. Change Of Direction, Ds Test. Deep Squat Test.

Table 2. Study Objectives, Methodologies, Adaptations, and Key Findings

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Robles-Palazón et al., 2023)	Build ML models predicting LE-ST injuries	Prospective cohort; 260 youth; preseason battery; 135 predictors; ML vs CV	Use 6-feature screen if asymmetry >15% (valgus, landing force asymmetry, BMI, FPPA, hip IR, ankle ROM)	Best ML model AUC 0.70; moderate predictive power	Compact, low-cost screen predicts injuries moderately well	Extends ML injury models to non-elite youth
(Bonetti et al., 2017)	Assess contralateral and flexor–extensor strength in adolescent soccer players across positions	Cross-sectional, isokinetic dynamometry (4 velocities)	Pre-season testing for imbalance detection; target athletes with asymmetry >10% (based on peak torque)	Only minor asymmetry at 60°/s in flexors (<10%); no positional differences	Adolescent soccer did not induce large knee asymmetries	Provides baseline isokinetic data for youth; highlights timing for preventive training
(Vargas et al., 2020)	Compare strength, power, and balance ratios across female age groups	Cross-sectional, isokinetic dynamometry	Group comparisons U13–PRO; monitor athletes with H:Q ratios <0.6	Strength improves after U13 and again post-U17; ratios remain stable but below normative levels	Balance ratios in females remain suboptimal, raising injury risk	Establishes normative female profiles; emphasizes developmental thresholds
(Jones et al., 2021)	Relate field-based strength measures to sprint & COD in academy footballers	Multicenter field study; CMJ, Nordbord, ForceFrame, sprints	Age-controlled regression & PCA; target athletes with strength asymmetry >10%	Running ability predicted by CMJ impulse, Nordic hamstring strength, hip adduction	Strength qualities underpin sprint/COD; hip and hamstring strength critical	Demonstrates utility of scalable, field-based tests for academies

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Di Paolo et al., 2021)	Examine motor coordination's effect on biomechanics with wearables	On-field drill with inertial sensors (MVJ, ladder, COD)	Harre test to classify coordination; target poorly coordinated athletes (bottom 25%)	Poorly coordinated group showed stiffer hips, knee valgus, and limb asymmetry (>15% in joint angles)	Motor coordination strongly influences biomechanics and injury risk	Innovative integration of motor skills & wearable biomechanics
(Przysucha et al., 2024)	Characterize static balance sway in youth female soccer players	Force platform analysis of bi/unipedal stance	Within-subject repeated trials; monitor athletes with CoP sway >2x standard deviation	Dominant leg exhibited greater sway and faster oscillations	Postural asymmetry likely linked to muscular dominance	First study on COP asymmetry in young females; practical balance insights
(Zeleznik et al., 2025)	Determine links between dominant leg use and functional asymmetries	Large sample, match video analysis, radar, force plate	Ball touches quantified; motor tasks measured; target athletes with >70% dominant leg use	High dominant-leg use correlated with asymmetry in ball speed and CMJ power (U15, U17)	Repetitive dominant leg use promotes functional asymmetry	Strong evidence that training biases reinforce asymmetry; urges bilateral development
(Silva et al., 2022)	To examine associations between 30–15 IFT velocity and anaerobic speed reserve with body composition, sprinting, COD, and jump performance	Cross-sectional design with 124 male soccer players (14–19 yrs)	Applied field-based running and neuromuscular tests; used Pearson correlations for variable associations	VIFT highly correlated with body mass, height, CMJ, sprinting, COD (r=0.7-0.8). ASR showed weaker correlations (r=0.3-0.4)	VIFT is strongly associated with multiple fitness capacities; ASR appears independent	Introduces ASR as an independent marker, useful for locomotor profiling
(Barbalho et al., 2021)	To compare magnitude and direction of inter-limb asymmetry across SJ, CMJ, and DJ	18 elite U17 female players performed unilateral jumps on force platforms	Used multiple jump tests to detect inter-limb differences; applied Kappa coefficients to assess direction consistency	Asymmetry magnitude task-specific; concentric impulse asymmetry greater in SJ (15-20%). Direction inconsistent across tests (κ=0.3)	Single test insufficient for full asymmetry profiling; direction valuable for monitoring	Demonstrates that asymmetry assessment must be multi-test and multi-variable
(Read et al., 2016b)	To evaluate reliability of field-based neuromuscular control measures	51 male players (pre- and post-PHV) performed jumps on force plates. Test-retest across two weeks	Applied repeated measures with ICC and CV for reliability analysis; use tests with ICC>0.75	Acceptable reliability for pVGRF (ICC=0.78-0.94) and asymmetry during single-leg tests; higher variability in drop jumps	Single-leg CMJ and hop provide more reliable assessment than DVJ	Offers evidence-based guidance for injury screening protocols
(Bromley et al., 2021a)	To investigate effects of a competitive match on jump performance and asymmetry	14 elite academy players; unilateral CMJs pre-, post-, 24h, 48h, 72h post-match	Time-course monitoring of fatigue and asymmetry; target athletes with post-match asymmetry increase >10%	Significant decrements in jump metrics (except height). Asymmetries increased sharply post-match (+8-12%), recovering by 48h	Inter-limb asymmetries are sensitive indicators of post-match fatigue	Provides practical monitoring insights for recovery management

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Vasileiou et al., 2024)	To test effects of explosive power training on performance and asymmetries	35 youth male players (13–15 yrs), randomized into experimental and control groups	Intervention with plyometric and explosive COD drills; target athletes with asymmetry >10% (SLCMJ)	Significant improvements in sprint, jump, COD performance ($p<.05$, $d=0.8$); asymmetry reduced slightly (3-5%)	Explosive power training enhances performance and reduces asymmetry	Adds causal evidence that targeted training mitigates asymmetries
(Daneshjoo et al., 2015)	To examine biomechanical effects of sprinting on jumping-landing	23 collegiate male players; four conditions with motion capture + force plates	Comparison of kinematics/kinetics across different run-up speeds	Sprint-preceded jumps increased knee valgus moment (15-20%) and reduced knee flexion (10-15%)	High-speed running before landing elevates knee injury risk	Highlights mechanism linking sprint-to-jump actions to injury risk
(Bahenský et al., 2020)	To investigate relationships between muscle mass, strength, and take-off asymmetry	65 U16–U19 male players; force plate jumps, Wingate test, body composition	Correlational analysis of dominant vs. non-dominant leg performance	Muscle mass correlated with power output ($r=0.6$) but not take-off force. Asymmetry decreased with training duration	Training reduces performance differences between limbs	Provides insight on how training minimizes asymmetry
(Michailidis et al., 2025)	To assess correlation between SLCMJ and isokinetic strength asymmetry	63 academy players; SLCMJ with leap mat + isokinetic dynamometer	Compared asymmetry indices across functional and laboratory tests	Small positive correlation with quadriceps ($r=0.3$); negative with hamstrings at 60°/s ($r=-0.4$); regression explained 20.6% variance	SLCMJ asymmetry cannot replace isokinetic testing	Evidence on limited interchangeability of field vs. lab assessments
(Izzo et al., 2022)	To evaluate symmetry using inertial sensors (IMU)	104 players (11.7 yrs); preseason and postseason tests with IMU during COD	Longitudinal preseason-to-postseason comparison; monitor athletes with imbalance >15%	Mixed results: ~71% decreased training load, ~50% improved strength, ~56% increased imbalance	Symmetry indices fluctuate across the season; IMUs allow precise monitoring	Demonstrates feasibility of wearable IMU for longitudinal tracking
(Bishop et al., 2021)	Compare intra- and inter-limb strength asymmetry in professional vs U18	Cross-sectional; 100 players; isokinetic knee dynamometry	Use asymmetry profiling to guide interventions; target U18 with asymmetry >15%	Pro players showed lower inter-limb asymmetry (8%) than U18 (12-15%); intra-limb ratios more stable	Professional training reduces asymmetry, whereas U18s show higher imbalance	Demonstrates maturation and training level affect asymmetry

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Contreras-Díaz et al., 2023)	Profile concentric/eccentric hip muscle strength	Cross-sectional; 37 U17 male players; FEMD dynamometer	Monitor hip ADD/ABD ratios and correct imbalances with targeted training if asymmetry >10%	Hip extensors produced higher torque; bilateral differences <10%; ratios stable across sides	Hip strength balance is preserved, but screening remains useful	Provides normative hip strength values for youth players
(Rosa et al., 2022)	Evaluate agonist-antagonist and bilateral strength relationships	23 U19 male players; isokinetic knee test + isometric groin test	Include hip ADD:ABD and H:Q ratios in screening; target athletes with ratios outside 0.8-1.2 range	Significant bilateral differences in knee torque (10-12%); no significant ADD:ABD imbalance	Inter-limb asymmetry exists in knee but not hip; functional ratios within safe range	First to combine knee and hip joint asymmetries
(Sannicandro et al., 2023)	Compare jump performance and asymmetry on sand vs grass	20 youth players; hop, side hop, broad jump on two surfaces	Use sand training to stress explosive ability; monitor athletes with asymmetry increase >20% on sand	All jump heights reduced on sand (15-20%); asymmetry % increased (up to +41%) compared to grass	Sand increases neuromuscular demand and asymmetry	Novel evidence on surface-specific asymmetry
(Michailidis et al., 2020)	Assess relation between jump asymmetry and COD performance	42 players (U10 & U15); multiple jump and COD tests	Individualize training if >10% asymmetry detected	U10: SLTJ asymmetry predicted slower Arrowhead COD (r=0.6); U15: SLCMJ asymmetry predicted slower 505 COD (r=0.55)	Asymmetry type and test influence COD performance differently by age	Identifies age- and test-specific asymmetry-performance links
(Nakahira et al., 2022)	Analyze kinematic differences between dominant vs nondominant legs	64 female players (15–22 yrs); single-leg DVJ; AI-based motion capture	Focus preventive training on nondominant leg valgus control if angle difference >5°	Nondominant leg showed greater knee valgus angle at landing (8-10° difference)	Knee valgus asymmetry may predispose to ACL risk in females	Innovative AI motion capture highlights dominance-related injury risk
(Ince & tortu, 2025)	Examine strength asymmetry in relation to sprint kinematics and F-V profile	74 youth athletes (34 soccer); isokinetic strength, OptoJump sprint tests	Screen athletes with asymmetry >15% and apply sprint-specific strength training	Weak–moderate correlations between asymmetry and sprint kinetics (r=0.3-0.4); outliers showed >40% asymmetry	Most youth athletes below critical threshold; asymmetry impacts sprint efficiency	First to link isokinetic asymmetry with full sprint F-V profiling in youth
(Trecroci et al., 2020a)	To assess agreement between dribble and COD asymmetry	Cross-sectional, 16 elite youth footballers tested in sprint, COD, dribble tasks	Field-based battery with repeated maximal efforts; use task-specific thresholds	Poor agreement between dribble and COD asymmetry (κ=-0.159); dribble deficit significantly higher (12% vs 8%)	Asymmetry is task-specific; cannot be used interchangeably	Provides evidence that assessment must be task-specific

Table 2 (continued)

Author(s) & year	Objective	Methodology	Adaptation strategy	Key results	Conclusion	Added value
(Ferreira et al., 2018)	To compare strength and asymmetry across age and club levels	151 youth players, 3 age groups, 2 competitive levels; CMJ on dual force plates	Standardized vertical jumps; monitor athletes in first-division with asymmetry >15%	No age effect; first-division players had higher force and asymmetry (12-18% vs 8-12%)	Competitive level affects both strength and asymmetry more than age	Demonstrates competitive level as determinant of asymmetry
(Atkins et al., 2016)	To analyze bilateral imbalance in youth players of different ages	105 elite youth players (U13–U17); deep squat with twin force plates	Functional movement screening; focus interventions during peak asymmetry years (14-16 yrs)	Significant bilateral GRF differences except in U13 and U17; greatest asymmetry in 14-16 yrs (15-20%)	Asymmetry peaks in mid-adolescence, declines later	Highlights adolescence as «trigger point» for asymmetry
(Oliver et al., 2020)	To test if machine learning improves injury risk prediction	355 players, preseason screen; injury tracked 10 months	Combined regression and ML with asymmetry cut-offs >15% (SLCMJ)	ML model identified multiple interacting factors; improved sensitivity (55.6%) vs logistic regression (15.2%)	ML improved sensitivity vs logistic regression	Introduces AI as superior approach for multifactorial injury risk
(Trecroci et al., 2020)	To replicate asymmetry agreement assessment in COD vs dribble	16 elite footballers, sprint, COD, dribble tests	Field testing with timing gates; confirm task-specificity	Same outcome: poor agreement, task-specific asymmetry	Task-specificity confirmed	Reinforces reliability of asymmetry indices across tasks

Ml. Machine Learning, Le-St. Lower-Extremity Soft-Tissue, Cv. Cross-Validation, Bmi. Body Mass Index, Fppa. Frontal Plane Projection Angle, Ir. Internal Rotation, Rom. Range Of Motion, Auc. Area Under The Curve, U13–Pro. Under-13 To Professional, Pca. Principal Component Analysis, Cmj. Countermovement Jump, Cod. Change Of Direction, Icc. Intraclass Correlation Coefficient, Cv (In Reliability Context). Coefficient Of Variation, Phv. Peak Height Velocity, Pvgrf. Peak Vertical Ground Reaction Force, Dvj. Drop Vertical Jump, Slcmj. Single-Leg Countermovement Jump, Sj. Squat Jump, Dj. Drop Jump, Cop. Center Of Pressure, Femd. Functional Electromechanical Dynamometer, Add/Abd. Hip Adduction/Abduction, H:Q Ratio. Hamstring-To-Quadriceps Ratio, F–V Profile. Force–Velocity Profile, Imu. Inertial Measurement Unit, Ai. Artificial Intelligence, Acl. Anterior Cruciate Ligament, K. Kappa Coefficient.

Table 3. Risk of Bias Assessment Table Newcastle–Ottawa Scale (NOS)

Author(s) and Year	Study Type	Selection (4)	Comparability (2)	Outcome / Exposure (3)	Total Score /9	Subjective Evaluation
(Robles-Palazón et al., 2023)	Prospective cohort	3	1	2	6	Moderate
(Bonetti et al., 2017)	Cross-sectional	3	1	2	6	Moderate
(Vargas et al., 2020)	Cross-sectional	4	2	2	8	High
(Jones et al., 2021)	Multicenter cross-sectional	4	2	2	8	High
(Di paolo et al., 2021)	Cross-sectional	3	1	2	6	Moderate
(Przysucha et al., 2024)	Cross-sectional	3	1	2	6	Moderate
(Zeleznik et al., 2025)	Cross-sectional	4	2	2	8	High
(Silva et al., 2022)	Cross-sectional	4	2	2	8	High
(Barbalho et al., 2021)	Cross-sectional	3	1	2	6	Moderate
(Read et al., 2016b)	Cross-sectional	4	2	2	8	High
(Bromley et al., 2021a)	Experimental	4	2	2	8	High
(Vasileiou et al., 2024)	Experimental	4	2	2	8	High
(Daneshjoo et al., 2015)	Cross-sectional	3	1	2	6	Moderate
(Bahenský et al., 2020)	Cross-sectional	3	1	2	6	Moderate
(Michailidis et al., 2025)	Cross-sectional	4	2	2	8	High
(Izzo et al., 2022)	Longitudinal	3	1	2	6	Moderate
(Bishop et al., 2021)	Comparative cross-sectional	4	2	2	8	High
(Contreras-díaz et al., 2023)	Cross-sectional	4	2	2	8	High
(Rosa et al., 2022)	Cross-sectional	3	1	2	6	Moderate
(Sannicandro et al., 2023)	Cross-sectional	3	1	2	6	Moderate
(Michailidis et al., 2020)	Cross-sectional	3	1	2	6	Moderate
(Nakahira et al., 2022)	Cross-sectional (AI-based)	4	2	2	8	High
(Ince & tortu, 2025)	Cross-sectional	4	2	2	8	High
(Trecroci et al., 2020)	Cross-sectional	3	1	2	6	Moderate
(Ferreira et al., 2018)	Cross-sectional	3	1	2	6	Moderate
(Atkins et al., 2016)	Cross-sectional	4	2	2	8	High
(Oliver et al., 2020)	Prospective cohort	4	2	2	8	High
(Trecroci et al., 2020)	Cross-sectional	3	1	2	6	Moderate

Table 4. Quantitative Summary of AI/ML Studies for Injury Risk Prediction

Author(s) & Year	AI/ML Model(s) Used	Key Predictive Features	AUC (95% CI)	Calibration Metrics	Type of Validation
(Robles-Palazón et al., 2023)	Support Vector Machine (SMO), Random Forest, Uniform Bootstrap Aggregating Ensemble (UBAG). Best Model: Random Forest.	Knee valgus, landing force asymmetry, BMI, Frontal Plane Projection Angle (FPPA), hip internal rotation, ankle range of motion.	AUC: 0.70 (95% CI not reported)	Not reported.	Internal: Cross-validation.
(Oliver et al., 2020b)	Machine Learning Model (specific algorithm not specified). Comparison: Traditional Logistic Regression.	Single-leg countermovement jump (SLCMJ) asymmetry, knee valgus, anthropometry.	AUC for ML model not explicitly reported. The model identified multiple interacting risk factors.	Not reported.	Internal: Model performance was assessed on the dataset used for training.

Legend: AUC, Area Under the Curve; CI, Confidence Interval; BMI, Body Mass Index; FPPA, Frontal Plane Projection Angle; SLCMJ, Single-Leg Countermovement Jump.

Table 5. Evidence-to-Practice Framework for Managing Functional Asymmetries in Youth Soccer

Test/Technology	LSI Threshold	Outcomes/Risks	Practical Action
Isokinetic Dynamometry (Knee Flexors/Extensors)	>10-15% (Strength Deficit)	Significantly increased risk of hamstring strains & ACL injuries (OR: 1.8-2.5)	Implement targeted unilateral strengthening (Nordic hamstrings, single-leg RDLs); re-test every 4-6 weeks.
Force Plates (CMJ, SLCMJ, Drop Jump)	>10-15% (Peak Force, Impulse)	Moderate association with non-contact LBI; inconsistent link to sprint performance.	Use as primary monitoring tool; if asymmetry >15%, integrate plyometric and ballistic training with emphasis on deficient limb.
Wearable IMUs (COD, Soccer Drills)	>10% (Kinematic Asymmetry)	Elevated biomechanical injury risk during high-intensity maneuvers; valuable for ecological validity.	Adjust technical coaching cues based on real-time data; modify training load and incorporate sport-specific balance drills.
Field-Based Strength Tests (Nordbord, ForceFrame)	>10% (Bilateral Deficit)	Strong predictor of sprint and COD performance deficits; moderate injury risk correlation.	Prescribe hip- and hamstring-focused strengthening; monitor as part of regular fitness testing.
AI/ML Predictive Models (Multi-factor Analysis)	N/A (Risk Stratification)	Moderate predictive accuracy for LE injury (AUC up to 0.70); identifies complex risk interactions.	Utilize for pre-season screening to flag high-risk athletes; guide allocation of preventive resources; requires clinical interpretation.

LSI: Limb Symmetry Index; CMJ: Countermovement Jump; SLCMJ: Single-Leg CMJ; COD: Change of Direction; IMU: Inertial Measurement Unit; LBI: Lower Body Injury; OR: Odds Ratio; AUC: Area Under the Curve; LE: Lower Extremity; RDL: Romanian Deadlift

et al., 2020), the asymmetrical practice, specifically the utilization of a single upper limb to exceed 70% of the total body's movement, has been found to exacerbate imbalances in power and coordination, As posited by (Vasileiou et al., 2024), empirical evidence has been demonstrated that targeted pliometric training can result in a reduction of these disparities by 3 to 5 percent. As indicated by other contributions, such as those by (Sannicandro et al., 2023) , the context of execution exerts a significant influence on the expression of asymétries. The surface of training, the competitive level, and the developmental stage (14–16 years of age, according to (Atkins et al., 2016) have been shown to modulate these expressions. Recent literature (Ince & Tortu, 2025; Michailidis et al., 2020); (Rosa et al., 2022; Contreras-Díaz et al., 2023) suggests that the concurrent incorporation of cinematic, neuromuscular, and biomecahnic assessments facilitates the acquisition of customized, asymmetric profiles, thereby enabling precise preventive interventions. The collective analysis of these results substantiates the notion that the amalgamation of portable technologies, artificial intelligence, and sophisticated analytical models engenders a profound transformation in the evaluation of functional asymmetries. This integration bestows a comprehensive, dynamic, and clinically actionable perspective, thereby marking a significant advancement in the field.

Notwithstanding these laudable advances in methodology, the limitations of conventional approaches remain conspicuous. Although field tests and standardized protocols are accessible and have been disseminated extensively, they exhibit inherent limitations. These limitations include their limited sensitivity, subjective nature, and inability to accurately replicate the multifaceted demands of football. The research conducted by (Bonetti et al., 2017) and (Bishop et al., 2021) utilizes dynamometric isocentricity, a method that had previously been regarded as the gold standard, and demonstrates that these assessments effectively isolate the movement of the joints without accounting for the actual dynamic characteristics of the activity under investigation. Additionally, the 505 test of direction change, as employed by (Jones et al., 2021), obscures the distinction between genuine asymétries of force and variables associated with coordination and motor strategy. Conversely, traditional postural assessments are characterized by their lack of reliability. As evidenced by (Daneshjoo et al., 2015) the intraclass correlation coefficient (ICC) value obtained with a force plate platform exceeded the ICC values reported in clinical balance tests. Furthermore, as demonstrated by (Bromley et al., 2021), fatigue significantly alters asymétries (with a 60% increase after a match), underscoring the variable and situational nature of these metrics. Contemporary instruments, including inertial sensors and dual-platform systems (Di Paolo et al., 2021; (Barbalho et al., 2021), have been developed to address these limitations by capturing global kinematic parameters and temporal variations in functional symmetry. These observations thus necessitate a clear transition between the evaluation of a single moment and the ongoing observation of a process, taking into account its context and ecological validity.

In the final analysis, the relationship between asymetry and the potential for injury remains the paramount clinical impetus for these innovations. The collected data demonstrate that, upon exceeding a critical threshold (typically >10–15%), asymétries emerge as quantifiable predictive factors for musculoskeletal injury. As posited by (Robles-

Palazón et al., 2023) and (Oliver et al., 2020c), a deficit exceeding 15% during unipodal jumps has been demonstrated to engender a heightened risk of injury, particularly during periods of fatigue neuromuscular function (Bromley et al., 2021). These imbalances impact not only performance but also joint stability and neuromuscular control. (Jones et al., 2021) found that an asymetry of greater than 10% in the superior hip adduction resulted in a decrease in the rate of change of direction. Conversely, (Michailidis et al., 2025) observed that asymétries measured in vivo did not always result in laboratory-measured strength deficits, emphasizing the necessity of a multifactorial approach. Furthermore, the findings of (Vasileiou et al., 2024) and (Bahenský et al., 2020) suggest that training regimens involving high-intensity or high-volume exercises, as well as extended periods of practice, may contribute to the mitigation of inter-membrane discrepancies, thereby promoting preventative measures. The preponderance of evidence suggests a consensus: an integrated evaluation approach, integrating artificial intelligence, biomecânica, and longitudinal monitoring, is imperative for the early identification of risk-implicated asymmetries, the development of customized interventions, and the promotion of a healthy athletic development in young football players.

Implications for Practice, Policy, and Research

Practice Implications:

Implement regular asymmetry monitoring using combined field tests (CMJ, SLCMJ) and wearable sensors during soccer-specific drills, Apply the 10–15% LSI threshold for intervention prioritization, with individualized correction programs focusing on unilateral strength training, Develop maturation-adjusted training protocols that account for PHV-related asymmetry fluctuations ,Integrate multi-joint assessment approaches addressing proximal-to-distal imbalance propagation.

Policy Implications:

Sports federations should establish standardized asymmetry assessment protocols across youth academies, Incorporate asymmetry profiling into periodic health examination protocols for young athletes, Develop clear guidelines for return-to-play decision making based on asymmetry thresholds, Allocate resources for technological infrastructure supporting ecological monitoring in youth sports programs.

Research Implications:

Prioritize longitudinal studies tracking asymmetry development throughout adolescent maturation, Establish consensus on standardized LSI calculation methods and reporting standards, Develop validated AI models with cross-cultural applicability for injury prediction, Investigate cost-effectiveness of different technological approaches for widespread implementation, Explore integrative biomarker approaches combining neuromuscular, metabolic, and psychological determinants of asymmetry.

Decision Pathway When LSI >10–15%

ASSESSMENT PHASE, Conduct Multimodal Evaluation: Strength: Isokinetic dynamometry/field-based tests, Movement: Wearable sensors/video analysis, Function: Sport-specific drills, History: Injury record/training load.

INTERPRETATION PHASE: Contextualize Findings Using: Maturation status (pre-/mid-/post-PHV), Playing position demands, Competitive level,Training phase (in-season/off-season).

INTERVENTION PHASE: Implement Targeted Strategies:Unilateral strength training (deficit limb focus), Bilateral coordination exercises, Sport-specific technique correction, Load management adjustments, Proprioceptive training.

MONITORING PHASE, Track Progress Through: Regular re-assessment (4–6 week intervals), Field-based tests with established reliability (ICC > 0.8), Sport-specific performance metrics, Symptom response monitoring

OUTCOME DECISION: LSI <10%: Maintain preventive exercises, LSI 10–15%: Continue targeted intervention, LSI >15%: Enhance intervention intensity/frequency

No Progress: Refer for specialist consultation

This pathway emphasizes that single assessments provide limited value—trend analysis over time is essential for effective management. Integration of quantitative data with qualitative coaching observation ensures comprehensive athlete care.

Conclusion

This systematic review establishes that functional asymmetries exceeding the 10-15% threshold represent a significant injury risk factor in youth soccer players, while their impact on athletic performance remains variable and context-dependent. Technological advances, particularly wearable inertial sensors and explainable AI, offer promising avenues for ecological and personalized monitoring. Decision-making pathway for practice: For any Limb Symmetry Index (LSI) >10-15%: Assess through a multimodal approach combining field tests, biomechanical analysis, and medical history review, interpret within context considering maturation status, playing position, and competitive level, Intervene via targeted unilateral strengthening and proprioceptive training. Monitor progression through serial standardized testing over time, The rigorous validation of AI models and standardization of assessment methodologies represent crucial next steps for transforming asymmetry evaluation into a reliable tool for performance optimization and injury prevention.

Ethics Approval

Ethical approval was not required for this study, as it is a systematic review based exclusively on previously published and publicly available data.

Informed Consent

Not applicable.

Data Availability Statement

All data analyzed in this study are derived from published sources cited in the reference list. No new datasets were generated.

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Conflict of Interest

The authors declare no conflicts of interest.

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Функціональні асиметрії у юних футболістів: систематичний огляд технологій оцінювання та застосування штучного інтелекту

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 23 с., 5 табл., 1 рис., 49 джерел.

Обґрунтування. Функціональні асиметрії у юних футболістів є важливою біомеханічною та нейром'язовою проблемою, оскільки вони можуть виступати як адаптивні характеристики, так і чинники підвищеного ризику травм. Водночас наявні наукові дані залишаються фрагментованими щодо ефективності застосування технологічних засобів і інструментів штучного інтелекту (ШІ) для кількісної оцінки та інтерпретації таких асиметрій у різних вибірках спортсменів.

Мета. Метою систематичного огляду було узагальнення методологічних підходів і напрямів застосування технологічних та ШІ-орієнтованих інструментів для оцінювання функціональних асиметрій у юних футболістів.

Методи. Огляд виконано відповідно до рекомендацій PRISMA. Пошук літератури здійснювали в базах даних Scopus, Web of Science та PubMed, у результаті чого було ідентифіковано 418 публікацій, з яких 28 відповідали критеріям включення. Методологічну якість відібраних досліджень оцінювали з використанням стандартизованих інструментів. Проаналізовано застосування носимих технологій, біомеханічних систем оцінювання та моделей штучного інтелекту для виявлення й інтерпретації функціональних асиметрій.

Результати. Моделі штучного інтелекту продемонстрували помірну прогностичну точність щодо ризику травм (AUC до 0,70). Носимі інерціальні вимірювальні пристрої характеризувалися високою екологічною валідністю під час оцінювання асиметрій у польових умовах. Водночас виявлено значну міждослідницьку гетерогенність порогових значень асиметрії та аналітичних протоколів, що обмежує можливості міждослідного порівняння результатів. Ключовим результатом стало те, що силові асиметрії понад 15 % були статистично значуще пов'язані з підвищеним ризиком травм ($p < 0,05$), однак не супроводжувалися стабільним зниженням показників спринтерської працездатності, що вказує на контекстозалежний характер їх впливу.

Висновки. Отримані результати свідчать, що технологічні та ШІ-орієнтовані підходи є перспективними інструментами для оцінювання функціональних асиметрій у юних футболістів, особливо за умов їх використання в екологічно валідному середовищі. Інтеграція пояснюваного штучного інтелекту з мультимодальними підходами до оцінювання розглядається як перспективний напрям для розроблення персоналізованих програм моніторингу та втручань. Подальші дослідження мають бути спрямовані на стандартизацію методологічної звітності, гармонізацію порогових значень асиметрії та впровадження лонгітюдних дизайнів з метою підвищення клінічної й практичної трансляційності результатів.

Ключові слова: функціональна асиметрія, юнацький футбол, штучний інтелект, прогнозування травматизму, носимі сенсори.

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Review Article

Virtual Reality and Gamification for Promoting Physical Activity in Children: A Systematic Review of Current Trends and Innovations

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Abstract

Background. Physical inactivity among children has risen globally, driven by sedentary behaviors and technology-mediated lifestyles. Emerging research suggests that virtual reality (VR) and gamification may serve as effective digital interventions for promoting physical activity (PA) and improving children's health outcomes.

Objectives. This systematic review aimed to synthesize and critically evaluate the current evidence on VR- and gamification-based interventions designed to promote PA among children, with a focus on intervention characteristics, theoretical mechanisms, effectiveness, and implementation considerations.

Methods. Peer-reviewed studies were retrieved from Scopus, ERIC, and the ACM Digital Library. Eligible studies included intervention research involving children and adolescents aged 5–18 years that applied VR, exergaming, or gamified digital interventions to promote PA or related health outcomes. Data were extracted and synthesized according to intervention typology, theoretical underpinnings, outcomes, and implementation features.

Results. The review included 11 intervention studies published between 2021 and 2025. Overall, VR- and gamification-based interventions demonstrated positive effects on PA engagement, motor outcomes, and selected psychosocial indicators. Effective designs commonly integrated goal setting, feedback, social comparison, and reward mechanisms, often aligned with Self-Determination Theory and Social Cognitive Theory. Key implementation barriers included cost, accessibility, and staffing requirements, while facilitators involved remote delivery models, stakeholder engagement, and the use of consumer-level hardware.

Conclusions. VR and gamification hold significant potential for promoting children's PA when interventions are theoretically grounded and well implemented. However, evidence for long-term effectiveness, sustainability, and equitable access remains limited, underscoring the need for longitudinal research and scalable, inclusive intervention models.

Keywords: virtual reality, gamification, physical activity, children, immersive technology.

Introduction

Over the past decade, there has been a notable global increase in physical inactivity and sedentary lifestyles among children, driven by interacting technological, environmental, and lifestyle factors. Research indicates that sedentary behavior has risen substantially, with children spending a large proportion of their waking hours inactive, a pattern associated with increasing obesity prevalence (Al-Hazzaa & Albawardi, 2021; Godoy-Cumillaf et al., 2023; Mohieldein et al., 2023). Contributing factors include urbanization, dietary transitions, and increased recreational screen time (Li et al., 2022; Mohieldein et al., 2023).

The COVID-19 pandemic further exacerbated these trends, as lockdowns and school closures led to substantial reductions in physical activity opportunities and increased screen exposure among children (Palermi et al., 2022; Park & Lim, 2022). Consequently, engagement in moderate-to-vigorous physical activity (MVPA) declined across populations (Chaves et al., 2022; Fillon et al., 2021). These disruptions have produced lasting implications for childhood health, reinforcing the need for innovative, adaptable strategies to promote active lifestyles in digitally mediated contexts (Chaves et al., 2022; Lee et al., 2025).

Virtual reality (VR) and gamification have emerged as promising digital strategies for promoting physical activity among children and adolescents. These approaches leverage immersive environments and game-based design elements to enhance motivation and engagement, potentially

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counteracting sedentary behaviors. Evidence suggests that gamification can increase PA participation, particularly when interventions incorporate clear goals and immediate feedback (Gkintoni et al., 2024; Xu et al., 2022; Yoluut et al., 2024). Similarly, VR applications transform exercise into interactive experiences that may enhance enjoyment and short-term adherence (Xu et al., 2022).

Common VR and gamified approaches include exergames, augmented-reality applications, and immersive VR fitness platforms that integrate physical movement with gameplay (Gkintoni et al., 2024). Many interventions incorporate social features such as challenges, leaderboards, and cooperative tasks, which may further enhance engagement through social comparison and interaction (Xu et al., 2022). In addition to PA outcomes, these systems have been associated with psychosocial benefits, including enjoyment and perceived social connectedness (Gkintoni et al., 2024; Xu et al., 2022).

Compared with traditional school- or community-based programs, VR and gamified interventions show greater potential to enhance engagement and enjoyment, factors closely linked to PA participation among children. Immersive VR exergames can generate enthusiasm for movement by embedding PA within interactive experiences, whereas traditional programs may lack similar motivational affordances (Godfrey et al., 2025). Gamification elements such as competition, rewards, and progression systems further support involvement and short-term adherence to PA routine (Yau et al., 2022).

However, evidence regarding the long-term effectiveness of VR and gamified interventions remains limited. Most studies emphasize short-term outcomes and immediate engagement, leaving uncertainty about sustained behavior change and habit formation over longer periods. Moreover, few studies have examined the integration of these technologies into routine educational or community-based PA settings (Gkintoni et al., 2024; Vandoni et al., 2021). These gaps highlight the need for systematic synthesis of recent intervention evidence to inform future research and practice.

Materials and Methods

Search Strategy and Information Sources

Several academic databases and digital repositories were systematically searched to identify intervention studies examining virtual reality (VR) and gamification for promoting physical activity (PA) among children. The databases searched included Scopus, which provides multidisciplinary coverage across health, education, and technology research (Carcelén-Fraile et al., 2025; Mazéas et al., 2022; Papale et al., 2025).

To maximize retrieval accuracy, structured Boolean search strategies were applied using combinations of controlled vocabulary and free-text terms, including "virtual reality," "VR," "gamification," "physical activity," "exercise," "children," "adolescents," and "intervention." A representative search string was: ("virtual reality" OR "VR") AND gamification AND ("physical activity" OR exercise) AND ("children" OR adolescents).

Database-specific adaptations of the search string were applied to account for indexing differences and disciplinary focus (Mazéas et al., 2022; Zhu et al., 2025). Searches were limited to peer-reviewed articles published in English between January 2021 and March 2025. To enhance completeness, manual reference list screening and forward citation tracking were conducted for all included studies.

Eligibility Criteria

Eligibility criteria were defined a priori using a PICOS framework. Included studies were intervention studies involving children and adolescents aged 5–18 years, including both typically developing participants and those with conditions such as obesity, ADHD, or developmental disabilities. Eligible interventions involved VR, exergaming, or gamified digital technologies explicitly designed to promote physical activity or PA-related health outcomes. Exclusion criteria included adult-only samples, non-digital or non-interactive interventions, observational designs without an intervention component, and outcomes unrelated to physical activity. Studies involving participants with severe mobility impairments or acute medical conditions contraindicating physical activity were excluded for safety and methodological consistency (Spring et al., 2025).

Study Selection and Data Extraction

All retrieved records were imported into a reference management software and duplicates were removed prior to screening. Two reviewers independently screened titles and abstracts, followed by full-text assessment of potentially eligible studies. Discrepancies were resolved through discussion and consensus. Data extraction was conducted using a standardized extraction form, capturing publication characteristics, study design, participant demographics, intervention features, theoretical frameworks, outcome measures, and key findings. Reference lists of included studies were manually cross-checked to ensure completeness.

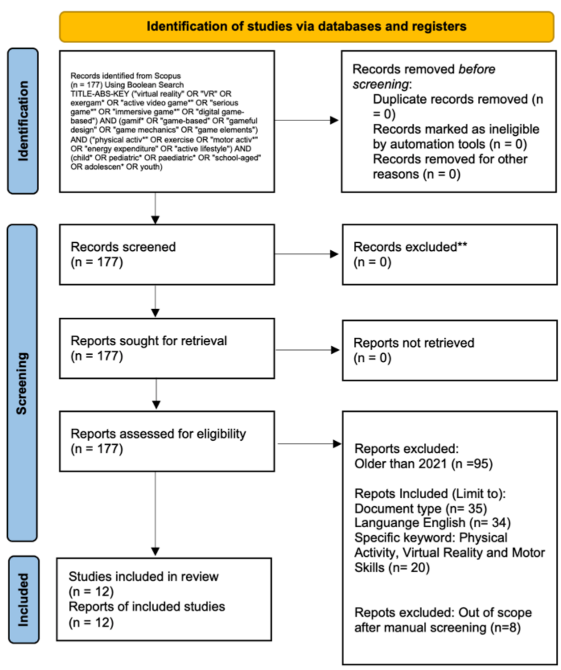

Fig. 1. PRISMA Flow Diagram illustrates the literature selection process, showing identification, screening, eligibility assessment, and inclusion stages, following PRISMA guidelines

Quality Assessment and Data Synthesis

Methodological quality was assessed in line with PRISMA recommendations and study design. Randomized controlled trials were evaluated using the Cochrane Risk of Bias 2 (RoB-2) tool, while non-randomized intervention studies were assessed using ROBINS-I to examine bias due to confounding, participant selection, and outcome measurement (Eng et al., 2023; Suárez-Villadat et al., 2023). Mixed-methods and qualitative components were appraised using Joanna Briggs Institute (JBI) Critical Appraisal Tools (Yau et al., 2022). Quality assessments were used to contextualize findings rather than exclude studies. Given heterogeneity in interventions and outcomes, a narrative synthesis approach was employed, with results organized thematically by intervention type, theoretical mechanisms, and outcome domains.

Theoretical Background

Theories of Physical Activity Behaviour and Motivation in Children

Behavioral and motivational theories, particularly Self-Determination Theory (SDT) and Social Cognitive Theory (SCT), provide essential frameworks for understanding children's engagement in gamified physical activity. According to SDT, intrinsic motivation—driven by the fulfillment of autonomy, competence, and relatedness—is fundamental for sustained participation in physical activity (Tersa-Miralles et al., 2025). Within gamification contexts, design elements that allow choice (autonomy), offer skill-based challenges (competence), and encourage social interaction (relatedness) foster enjoyment and enhance long-term adherence to physical activities (Xu et al., 2022). Similarly, SCT highlights the role of observational learning, reinforcement, and social influence, which are central in gamified and digital environments where children learn by observing peers and emulating successful behaviors (Ciążyńska & Maciaszek, 2023).

The constructs of enjoyment, autonomy, competence, and relatedness are pivotal in shaping children's sustained participation in digital and VR-based interventions. Enjoyment enhances motivation and engagement, helping children associate physical activity with positive emotions (Tobaiqi et al., 2023). Autonomy supports voluntary participation, leading to greater intrinsic motivation (Chen et al., 2024). Competence, achieved through mastering progressive challenges, fosters achievement and persistence (Elaheebocus & Grant, 2023). Relatedness, nurtured through interaction with peers, strengthens social bonds and further reinforces ongoing commitment (Chen et al., 2024; Xu et al., 2022). Together, these constructs create a motivational environment that sustains participation and promotes healthier activity patterns among children.

Gamification and Behaviour Change Frameworks

Gamification elements such as rewards, feedback, challenges, and avatars can be systematically mapped onto established Behaviour Change Techniques (BCTs) to effectively promote physical activity. For instance, rewards correspond to the BCT of incentivization, motivating desired behaviors through tangible or virtual rewards (Wang et al., 2025). Feedback mechanisms align with the BCT of self-monitoring and feedback on performance, allowing participants to track progress and adjust their efforts (Chukwu, 2024). Challenges reflect the BCT of goal setting, encouraging users to meet specific milestones and build competence (Ferraz et al., 2024). Avatars personalize the user experience and promote a sense of identity and connection, resonating with BCTs involving social support and modeling (Chan, 2024).

Evidence demonstrates that gamification-based interventions significantly enhance children's motivation and self-efficacy compared to non-gamified approaches. Meta-analytic findings reveal substantial improvements in moderate-to-vigorous physical activity (MVPA) among children and adolescents participating in gamified programs (SMD = 0.39) (Wang et al., 2025). Moreover, gamification fosters intrinsic motivation by fulfilling psychological needs related to autonomy, competence, and relatedness (Ermina, 2024). Studies consistently show that children engaged in gamified activities report higher enjoyment and are more likely to maintain activity levels over time than those exposed to traditional interventions (Ferraz et al., 2024).

Virtual Reality, Exergaming, and Immersive Media Perspectives

The influence of immersion, presence, and embodied interaction in VR and exergaming on children's physical and cognitive engagement is grounded in established theoretical models, particularly Flow Theory and Presence Theory. Flow Theory posits that deep immersion produces an optimal state of enjoyment and concentration, leading to improved physical engagement and persistence (Li et al., 2021). When children experience flow within VR environments, they often lose track of time and derive satisfaction from accomplishing virtual challenges, thereby reinforcing physical participation. Presence Theory, on the other hand, emphasizes the psychological sensation of "being there" within a virtual space, which can enhance motivation and perceived realism of the experience (Kaimara et al., 2021).

Prolonged engagement in VR and exergaming yields both benefits and risks. Benefits include increased physical activity through engaging gameplay, improved coordination, and psychological outcomes such as reduced anxiety and enhanced mood (Lin & Chang, 2025). However, potential risks include cybersickness, manifested as dizziness, nausea, and discomfort (Cardullo & Wang, 2021; Kim et al., 2021). Overstimulation from intense visual or auditory stimuli may cause headaches or fatigue, while accessibility barriers—such as financial constraints or physical limitations—can restrict participation (Pelizzo et al., 2022). Balancing these aspects is crucial to ensuring the effective, safe, and equitable implementation of VR and exergaming technologies for promoting physical activity among children.

Results

1. Typologies and Design Characteristics of VR and Gamified Physical Activity Interventions

Virtual reality (VR) and gamified interventions designed to promote physical activity in children exhibited substan-

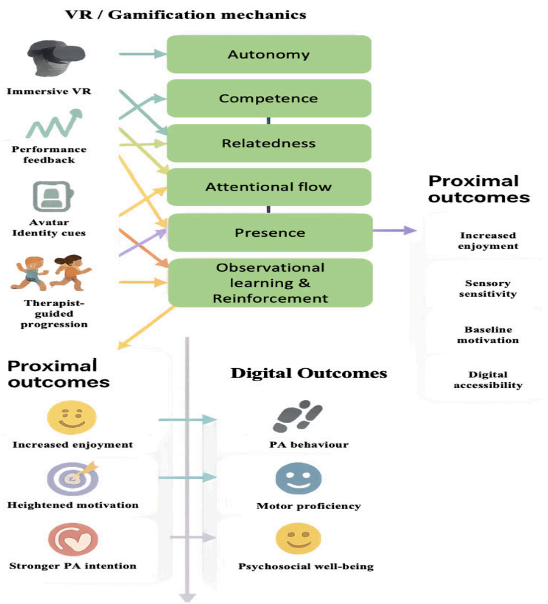

Fig. 2. Conceptual Model linking VR immersion, gamification elements, behavioural mechanisms, and physical activity outcomes in children

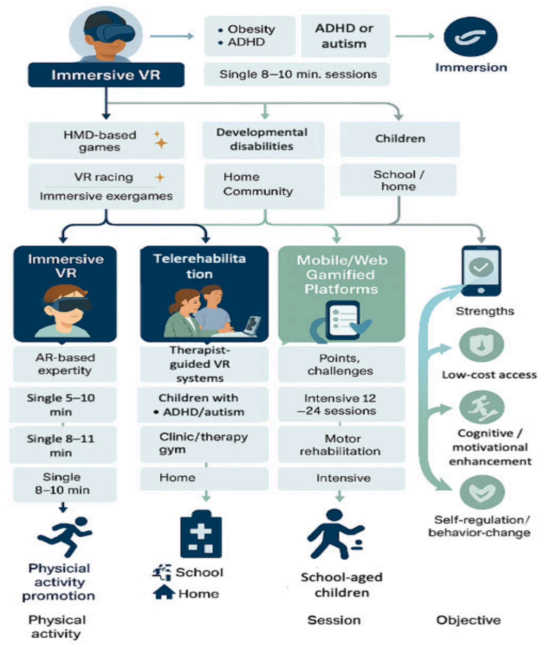

Fig. 3. Typology of VR/Gamified Interventions

tial heterogeneity across technology type, implementation context, target population, and intended outcomes. Across the included studies, intervention platforms ranged from immersive VR and augmented reality (AR) systems to non-immersive exergames, mobile applications, wearable-integrated feedback tools, and motion-capture consoles. These interventions were applied across diverse pediatric populations, including typically developing children as well as those with obesity, neurodevelopmental conditions, physical disabilities, and mental health comorbidities, highlighting the broad applicability of VR and gamified approaches.

Several studies illustrate recurring design patterns across otherwise distinct technological platforms. For example, Bowling et al. (2025) combined non-immersive exergaming, wearable activity tracking, and remote coaching over a 12-week period, demonstrating the feasibility of hybrid, home-based interventions. In contrast, Zhu et al. (2025) focused on technological innovation, using AR and TENG-based wearables to enable adaptive difficulty and real-time feedback, although intervention duration and behavioral outcomes were not the primary focus. Figure 3 synthesizes these interventions by grouping platforms according to level of immersion, delivery setting, and session structure, illustrating commonalities in design despite technological variation.

Intervention dose, supervision level, and delivery setting varied markedly across studies, reflecting differing program objectives. Brief, single-session interventions—such as the 10-minute immersive VR exposure used by Fowler et al. (2024) primarily targeted short-term cognitive or motivational outcomes, whereas multi-session, therapist-led programs (e.g., Lee & Jin, 2024) emphasized motor skill development and sustained engagement. School-based (Flôres et al., 2024), and home-based telerehabilitation models (Köse et al., 2023) further illustrate how contextual constraints shape session length, supervision, and intervention intensity.

Across clinical and community-based contexts, VR and gamified interventions were applied to address motor rehabilitation, behavior change, and PA promotion, with program duration ranging from single-session exposures to multi-month therapeutic protocols. Clinical rehabilitation studies (e.g., Menekşeoğlu et al., 2023; Khaledi et al., 2022) generally employed structured, repetitive tasks with clinical supervision, whereas community- and school-based programs emphasized engagement, enjoyment, and accessibility (Reis et al., 2022; González-González et al., 2021). Collectively, these findings demonstrate high contextual flexibility, with interventions implemented across home, school, laboratory, clinic, and community settings.

The technological diversity summarized in Table 1 highlights a convergent set of design principles despite heterogeneous platforms. Across studies, common game mechanics—including goal progression, real-time feedback, adaptive difficulty, and reward systems—consistently map onto competence-building, enjoyment, and social reinforcement mechanisms described in Self-Determination Theory and Social Cognitive Theory, suggesting theoretical coherence in intervention design.

Overall, the interventions summarized in Table 1 demonstrate how diverse technologies are unified by shared behavioral design strategies. Alignment with SDT and SCT is evident across platforms, with autonomy-supportive choices, competence-enhancing feedback, social reinforcement, and observational learning consistently embedded in intervention structures, reinforcing their relevance for promoting physical activity among children.

2. Mechanisms of Engagement, Motivation, and Behaviour Change

Findings across studies in Table 2 indicate that VR and gamified physical activity (PA) interventions for children

Table 1. Typology of VR and Gamified Interventions for Children's Physical Activity

Study (Year)	Population & Age	Technology Type	Primary Goal	Key VR/ Gamification Features	Setting	Duration/ Frequency	PA Measurement
Bowling et al. (2025)	Youth with heterogeneous/ comorbid mental health disorders, 13–17 y	mHealth app + Exergaming + Fitbit (non-immersive AVGs)	Increase PA & sleep; improve psychosocial outcomes	Progressive exergaming plan; gamified step goals; coaching; feedback	Home/ Community with remote coaching	12 weeks; app-guided; coaching sessions	Actigraphy/ Fitbit steps; self-report PA
Zhu et al. (2025)	Adolescents (not explicitly specified; AR fitness context)	AR + Wearable TENG sensors; cloud analytics	Monitor & enhance exercise participation	Adaptive difficulty; performance-based rewards; narrative AR missions	Lab/ Prototype context	Not stated (system description)	Sensor-derived steps, gait, calorie algorithms
Fowler et al. (2024)	Children with BMI ≥85th percentile; 6–12 y; caregiver dyads	Immersive VR experience (HMD) + interactive go-kart game	Promote healthy lifestyle behaviors (incl. PA cognitions/ behavior)	Psychoeducation + game narrative; high immersion; instant feedback	Laboratory	Single 10min session (pilot RCT)	Self-reported active days (2wk follow-up)
Lee & Jin (2024)	Children with developmental disability	Combined VR + gym-based PA	Improve PA levels, motor & social skills	Structured sessions; therapist supervision; VR tasks integrated with gym	Clinic/Gym	12 weeks; 60 min × 2/ week	GENEA monitor (PA), standardized motor/social scales
Flôres et al. (2024)	School adolescents (~15.6 y)	VR exergame vs. tennis training vs. control	Compare reaction time effects	Motion-based VR gameplay; brief sessions	School	Single/short sessions: 8 min (VR) vs 30 min (tennis)	Reaction time tests (pre/post)
Köse et al. (2023)	Children with ADHD	Therapist-Guided Game-Based Intervention (telerehab; VR/ game-based)	Improve motor skills	Structured tasks; therapist guidance; home-based accessible games	Home (tele)	Program duration not specified; multi-session	BOT-2 subtests (motor proficiency)
Menekşeoğlu et al. (2023)	Children with hemiplegic cerebral palsy	VR-mediated gamified upper-limb rehab	Improve upper limb function & QoL	Supervised VR tasks; gamified feedback; graded challenges	Clinic	Baseline; +1 and +3 months assessments (program length NR)	Functional tests (AHA, ABILHAND-Kids, QUEST); ROM measures
Hocking et al. (2022)	Youth with autism spectrum disorder; 10–17 y	Custom VR game + low-cost motion capture	Feasibility; improve gross motor skills	Game-based motor tasks; whole-body tracking; metrics of efficiency/ synchrony/ symmetry	Lab/Clinic	6 sessions × 20 min over 2 weeks	Motion-capture movement metrics; standardized motor tests
Reis et al. (2022)	Adolescents in obesity prevention program	mHealth (web + mobile) with gamification	Promote healthy behaviors; prevent obesity	Points, challenges; user-centered design; engagement features	School/ Community	Program roll-out; retention tracked	Platform usage; behavior logs (PA outcomes variably reported)
Khaledi et al. (2022)	Children with spastic hemiplegia (~6.4 y)	Virtual-assisted Montessori-based games	Improve motor proficiency & self-control	Structured game sessions; repeated practice; reward/ feedback	Clinic/ Home	8 weeks; 3 × 45min/week	Lincoln-Oseretsky Motor Scale; self-control scale
González-González et al. (2021)	Children with obesity in outpatient care	Kinect-based active games + biometric sensors	Behavior change toward active lifestyle	Motion-sensing games; group play; feedback; enjoyment-focused design	Outpatient clinic	Program-based (duration NR)	Satisfaction surveys; behavior change indicators (PA self-report)

are predominantly grounded in Self-Determination Theory (SDT) and Social Cognitive Theory (SCT) and systematically incorporate multiple Behaviour Change Techniques (BCTs). Across interventions, core mechanisms—including autonomy, competence, relatedness, observational learning, attentional engagement, and self-regulation—were repeatedly operationalized, demonstrating conceptual consistency in how motivation and behaviour change were targeted (Chen et al., 2024; Ciążyńska & Maciaszek, 2023; Elaheebocus & Grant, 2023; Tersa-Miralles et al., 2025; Xu et al., 2022).

A dominant cross-study pattern was the emphasis on competence-building through progressive challenge and feedback. Interventions such as Bowling et al. (2025) combined graded exergame progression, goal setting, self-monitoring, and social support, reinforcing self-efficacy and habit formation in line with SDT and SCT. Similarly, Zhu et al. (2025) employed adaptive difficulty, performance-based rewards, and real-time feedback to promote flow, competence, and social comparison. Figure 4 synthesizes these pathways, illustrating how VR immersion and gamified features activate psychological mechanisms that are translated into behaviour change via BCTs, ultimately enhancing enjoyment, self-efficacy, and PA intentions.

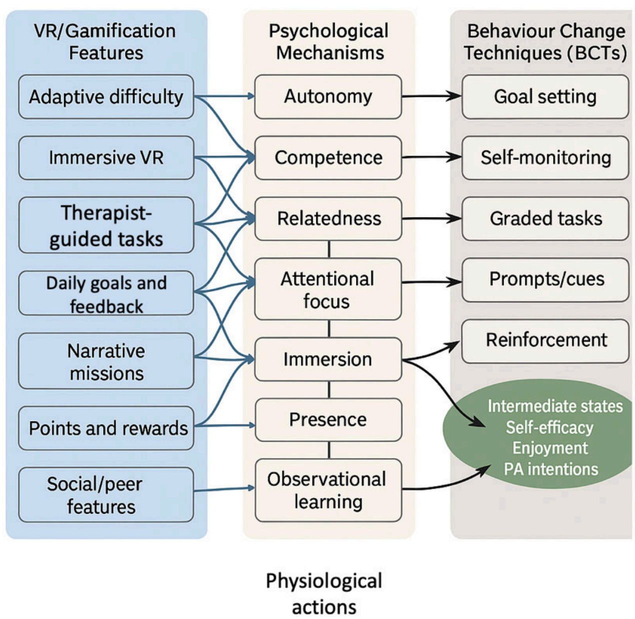

Fig. 4. Mechanisms of Engagement & Behaviour Change

Enjoyment and immersion emerged as salient motivational drivers, particularly in immersive VR interventions. For instance, Fowler et al. (2024), demonstrated that a brief, highly immersive VR exposure enhanced short-term PA intentions, consistent with Flow Theory predictions. Across therapist-guided programs (Lee & Jin, 2024; Köse et al., 2023) , structured repetition, guided feedback, and social support were emphasized, creating competence- and relatedness-supportive environments that align closely with SDT principles.

In clinical and rehabilitation-focused interventions, behavioural change mechanisms were primarily driven by high repetition, graded task difficulty, and real-time feedback. For example, Menekşeoğlu et al. (2023) strengthened competence and self-efficacy through repetitive, feedback-rich VR tasks, while Hocking et al. (2022) emphasized behavioural rehearsal and attentional engagement via whole-body tracking. Across community and mHealth platforms (Reis et al., 2022; González-González et al., 2021), habit formation, social comparison, and social support emerged as central mechanisms, whereas Montessori-based VR intervention (Khaledi et al., 2022) emphasized autonomy and self-regulation through structured repetition.

Across studies, interventions incorporated between four and ten BCTs, with competence-enhancing techniques (e.g., feedback, graded tasks, rewards) present in all 11 studies and social mechanisms (e.g., coaching, peer interaction, group play) present in the majority. The quality of theory integration varied, ranging from explicit, theory-driven designs (Bowling et al., 2025; Lee & Jin, 2024; Menekşeoğlu et al., 2023) to more implicit or minimally articulated applications (Flôres et al., 2024). Overall, these patterns indicate that interventions with stronger theoretical grounding and broader BCT integration tended to demonstrate more consistent engagement and behavioural outcomes, reinforcing the central role of SDT- and SCT-aligned mechanisms in digital PA interventions for children.

Overall, the evidence indicates that theoretical coherence and multi-component BCT integration are key determinants of engagement and behavioural effectiveness, reinforcing the importance of explicit theory-driven design in VR and gamified PA interventions for children.

3. Effects on Physical Activity and Health-Related Outcomes

Across the studies summarized in Table 3, VR and gamified interventions demonstrated overall positive but heterogeneous effects on physical activity (PA), motor proficiency, and selected health-related outcomes. These effects were most consistently observed in domains directly targeted by intervention design, such as engagement, motor performance, and short-term PA indicators, and align with SDT- and SCT-based mechanisms including enjoyment, competence, and self-efficacy (Chen et al., 2024; Tersa-Miralles et al., 2025; Tobaiqi et al., 2023). Intervention duration varied widely, from single-session exposures to multi-week programs, and outcome measurement relied on both objective (e.g., accelerometry, actigraphy) and subjective or clinical tools, contributing to variability in reported effects.

Evidence for objective PA change was strongest in Bowling et al. (2025), where adolescents receiving the GamerFit intervention demonstrated directional increases in daily step counts and improvements in sleep regularity based on actigraphy data. Although effect sizes were not reported, the use of objective monitoring strengthens confidence in observed trends. By contrast, (Zhu et al., 2025) focused on technological feasibility and sensor validation, rather than behavioral efficacy, underscoring that not all included studies were designed to detect PA change.

Several studies reported short-term motivational or cognitive effects rather than sustained PA change. Fowler et al. (2024) observed increases in PA intentions and self-reported active days following a brief immersive VR session, supporting Flow Theory–based explanations of immersion-

Table 2. Mapping of Gamification/VR Features to Behavioural Mechanisms and Behaviour Change Techniques (BCTs)

Study / Theoretical framing	Key VR/ Gamification elements	Targeted mechanisms (examples)	BCTs (Michie taxonomy examples)	Intermediate outcomes reported /targeted	Mediation/ moderation	Theory integration quality
Bowling et al. 2025) GamerFit RCT (2025) / SCT + SDT-informed coaching	App-based quests; progressive exergame plan; step goals with Fitbit; badges/points; remote coach feedback	Competence (achievable goals), self-efficacy (coach support), autonomy (choice of games), relatedness (coach contact); habit formation via daily prompts	Goal setting (behaviour); feedback on behaviour; self-monitoring (Fitbit); graded tasks; social support (practical); prompts/cues; action planning	Enjoyment, engagement (app usage), daily steps, sleep regularity	Possible moderation by baseline activity and mental-health comorbidity; adherence mediates PA change	High – explicit features linked to coaching and tracking
Zhu et al. (2025) AR + TENGwearables / Tech acceptance & flow concepts	AR missions; adaptive difficulty from sensor data; performance rewards; leaderboards	Flow/immersion; competence via adaptive challenge; social comparison; attentional distraction reducing perceived exertion	Graded tasks; rewards; social comparison; feedback on performance; gamified challenges	Engagement metrics, adherence probability, step counts (sensor-derived)	Moderation by fitness level (tolerance to intensity); novelty effects	Moderate – mechanisms implied via adaptivity/ competition
Fowler et al. (2024) Immersive VR gokart pilot RCT / Psychoeducation + presence	HMD immersive race; narrative; instant performance feedback; short bouts	Presence/ immersion; affective valuation; distraction from exertion; autonomy through playful choice	Information about health consequences; feedback on performance; experiential learning; behavioural practice	Enjoyment, intentions; selfreported active days (2week)	Mediation by enjoyment/ intentions hypothesised	Moderate – theory implicit in design
Lee & Jin (2024) VR + gym-based PA / Motor learning + SDT	Therapistguided VR tasks; structured progression; cooperative play	Competence via progressive difficulty; relatedness (therapist/peer); motor learning (repetition)	Graded tasks; instruction on how to perform; social support; behavioural practice/ rehearsal	Motor skill gains; PA bouts during sessions; social interaction	Moderation by disability severity; therapist fidelity	High – structured alignment to motor/SDT
Flôres et al. (2024) VR exergame vs tennis / Attention & arousal	Short VR play with rapid feedback; competitive challenge	Attentional focus; arousal; immediate competence signals	Feedback on performance; reward; behavioural practice	Reaction time improvement; perceived exertion	Moderation by prior gaming experience	Low–Moderate – minimal theoretical articulation
Köse et al. (2023) ADHD telerehab game based / EF & motor control	Home tasks; therapist teleguidance; points/ progression	Executive function (inhibition, sequencing); competence; parental support	Instruction; graded tasks; feedback; social support (therapist/ parent)	Motor proficiency subtests; adherence logs	Moderation by baseline EF; mediation by task completion	Moderate–High – therapistanchored framework
Menekşeoğlu et al. (2023) CP upperlimb VR / Rehab theory	Gamified functional tasks; realtime kinematic feedback; levels	Competence; selfefficacy; motor learning via highrepetition	Feedback on performance; graded tasks; problem solving; behavioural practice	Upperlimb function tests; range of motion	Mediation by repetitions achieved; moderation by age	High – explicit rehab principles
Hocking et al. (2022) ASD custom VR / Embodied interaction	Wholebody tracking; playful motor quests; visual/ auditory feedback	Sensorimotor engagement; competence; attentional focus; reduction of anxiety via predictable environment	Behavioural practice; feedback on behaviour; shaping; prompts/cues	Movement efficiency/ symmetry; feasibility/ acceptability	Moderation by sensory sensitivity	Moderate – mechanisms discussed, limited formal theory

Table 2 (continued)

Study / Theoretical framing	Key VR/ Gamification elements	Targeted mechanisms (examples)	BCTs (Michie taxonomy examples)	Intermediate outcomes reported /targeted	Mediation/ moderation	Theory integration quality
Reis et al. (2022) mHealth gamified platform / Engagement & habit models	Points, challenges, progress dashboards; reminders; peer features	Habit formation; social motivation; autonomy via selfset goals	Selfmonitoring; prompts/ cues; social comparison; reward; goal setting	Platform engagement, challenge completion; PA logs (varied)	Mediation by engagement metrics	Moderate – explicit BCTs in platform design
Khaledi et al. (2022) Virtualassisted Montessori games / Montessori + reinforcement	Structured, childled tasks; repetition; immediate reinforcement	Autonomy; competence; attentional control; selfregulation	Graded tasks; feedback; reinforcement; behavioural practice	Motor proficiency; selfcontrol	Moderation by baseline selfregulation	Moderate – pedagogical theory mapped to BCTs
González-González et al. (2021) Kinect clinic program / SCT + enjoyment focus	Group play; motion challenges; biometric feedback; cooperative/ competitive modes	Social support; competence; enjoyment; relatedness	Social comparison; social support; feedback; rewards; goal setting	Satisfaction; PA behaviour change indicators	Moderation by group dynamics	Moderate – practical SCT alignment

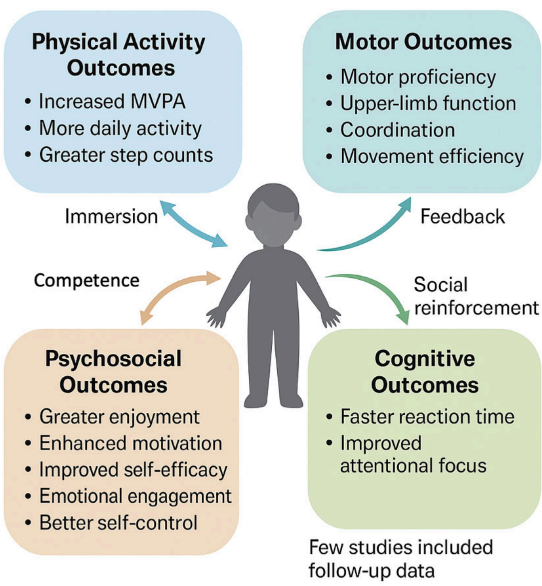

Fig. 5. Outcome Pathways for PA and Health Effects

driven motivation (Kaimara et al., 2021; Li et al., 2021). Likewise, Flôres et al. (2024) reported improvements in reaction time, with PA volume not assessed as a primary outcome. Figure 5 synthesizes these findings, illustrating how VR and gamified mechanisms may influence PA, motor, psychosocial, and cognitive outcomes, even when direct PA change is not consistently measured.

Motor outcomes showed the most consistent improvements, particularly in clinical and rehabilitation-focused interventions. Lee & Jin (2024) reported increases in sessional PA and significant motor and social skill gains following an intensive VR-integrated program. Similar improvements were observed in children with ADHD (Köse et al., 2023) and hemiplegic cerebral palsy (Menekşeoğlu et al., 2023) with outcomes assessed using validated clinical instruments and follow-up measurements, strengthening confidence in these effects.

Youth with autism spectrum disorder also demonstrated motor-related benefits, with Hocking et al. (2022) reporting improvements in movement efficiency and coordination following short-term VR exposure. In contrast, community- and school-based interventions (e.g., Reis et al., 2022) yielded mixed PA outcomes, likely influenced by self-reported measures, variable engagement, and limited objective assessment.

Interventions targeting obesity showed favourable but primarily indirect effects, with Khaledi et al. (2022) reporting improvements in motor proficiency and self-control, and González-González et al. (2021) documenting positive PA behaviour indicators and high satisfaction, albeit with limited objective PA measurement.

Quantitatively, across included studies, objective PA change was reported in fewer than half of interventions, whereas motor outcomes assessed using validated clinical measures were more consistently improved. Several studies prioritized PA intentions or behavioural indicators rather than direct activity measurement, and follow-up periods were generally short, ranging from immediate post-tests to a maximum of three months, limiting conclusions regarding long-term maintenance.

Overall, the evidence suggests that VR and gamified interventions can positively influence PA-related behaviours, motor development, and psychosocial outcomes, particularly when interventions emphasize immersion, competence-building, and feedback mechanisms. However, robust evidence for sustained PA change and long-term habit formation remains limited, reinforcing the need for longer follow-up periods and standardized objective outcome measures.

Overall, these findings highlight the promise of VR and gamification for improving PA, motor function, and psychosocial outcomes, but they also reinforce the need for long-term data and standardized objective measurement practices.

Table 3. Effectiveness of VR and Gamified Interventions on Physical Activity (PA) and Health-Related Outcomes

Study/ Design	Technology/ intervention type	Sample (N; age; population)	Primary PA & health outcomes	Measurement tools	Comparator	Main effects (summary)	Followup	Risk of bias / Quality
Bowling et al. 2025) GamerFit RCT	mHealth app + exergaming + Fitbit (GamerFit)	Adolescents with heterogeneous/ comorbid mental-health disorders; 13–17 y; multi-site (N NR here)	Daily steps/MVPA; sleep; wellbeing indicators	Fitbit/actigraphy; in-app logs; questionnaires	Usual care / minimal-contact digital health	PA: increase in daily steps vs control (directional). Sleep/psychosocial: improvements reported.	Post-intervention (12 w); maintenance NR	Randomization with remote delivery; risk unclear for blinding; adherence tracked
Zhu et al. (2025) AR+TENG prototype	AR system with wearable TENG sensors	Adolescents (N NR)	PA participation/ steps (feasibility); physiological estimates	Wearable sensors; cloud analytics	None (system description)	Feasibility evidence only; not designed to detect between-group effects	NA	Descriptive/engineering report; high risk for efficacy bias
Fowler et al. (2024) Pilot RCT (immersive VR go-kart)	Immersive HMD VR go-kart game + brief psychoeducation	Children 6–12 y with BMI ≥85th percentile; dyads	Self-reported active days; PA intentions/ attitudes	Survey scales; brief exposure (10 min)	Psychoeducation/ control content	PA behaviour: short-term intention/active-days signal (directional); effect size NR	2-week follow-up	Small sample; brief exposure; self-report; some risk of bias
Lee & Jin (2024) Quasi-experimental	Clinic-based VR + gym-based PA sessions	Children with developmental disability; supervised sessions	In-session PA minutes; motor/ social skills	Wearable PA monitor (e.g., GENEA); standardized scales	Pre–post / usual therapy	PA: increased sessional activity; Motor/social: improvement on standardized measures	Immediate post; longer-term NR	Moderate quality; no randomization; therapist fidelity noted
Flôres et al. (2024) Comparative (VR vs tennis vs control)	VR exergame vs tennis training vs control	School adolescents (~15.6 y)	Reaction time (secondary: exertion)	Reaction-time tests; RPE	Active sports training / control	Cognitive/RT: improvement after brief VR bout; PA volume not primary	Immediate	Short, single-session; limited external validity
Köse et al. (2023) Home telerehab (multi-session)	Home-based telerehabilitation VR/game-based program	Children with ADHD	Motor proficiency; incidental PA during tasks	BOT2; adherence logs	Pre–post / wait-list	Motor: improvements on BOT2 subtests; PA: sessional engagement reported	Post-program	Non-randomized; small sample; moderate risk
Menekşeoğlu et al. (2023) Rehab cohort with assessments	Clinic-based VR gamified upper-limb rehabilitation	Children with hemiplegic CP	Upper-limb function; QoL; activity capacity	AHA, ABILHANDKids, QUEST; ROM	Pre–post	Function: significant improvements at +1 and +3 months; PA behaviour not primary	1 and 3 months	Non-randomized; clinical measures robust; moderate quality
Hocking et al. (2022) Feasibility (6×20 min)	Custom low-cost VR motor game + motion capture	Youth with ASD (10–17 y)	Gross motor efficiency/ synchrony; feasibility/ acceptability	Custom motion-capture metrics; standardized tests	None (single-group feasibility)	Motor metrics: favourable change trends; Feasibility: acceptable	Immediate	Feasibility design; high risk for efficacy
Reis et al. (2022) Gamified mHealth (program roll-out)	Gamified web/ mobile mHealth platform	Adolescents in prevention program	Platform engagement; PA logs (steps/min)	App/web analytics; self-report	None or historical	Engagement: good uptake; PA: mixed/ variable changes	Program end	Implementation focus; confounding likely
Khaledi et al. (2022) Controlled program	VR-assisted Montessori-based games	Children with spastic hemiplegia (~6.4 y)	Motor proficiency; self-control	LincolnOseretsky; self-control scale	Usual activities / standard therapy	Motor: improvements vs control; PA: not primary	Post-intervention (8 w)	Small N; potential assessor bias
González-González et al., (2021) Clinic program	Kinect-based active games + biometric sensors	Children with obesity	PA behaviour change indicators; satisfaction	Kinect sensors; questionnaires	Outpatient routine care	PA/behaviour: positive trends reported; satisfaction high; objective PA limited	Program end	Uncontrolled; risk of reporting bias

4. Implementation, Equity, Safety, and Sustainability Considerations

The studies summarized in Table 4 provide important insights into implementation feasibility, equity considerations, safety requirements, and long-term sustainability of VR and gamified physical activity (PA) interventions for children. Consistent with earlier theoretical discussions on autonomy, competence, relatedness, and environmental facilitators, intervention effectiveness was closely linked to real-world logistical factors, including resource availability, staffing intensity, cost, accessibility, and participant diversity (Chen et al., 2024; Elaheebocus & Grant, 2023; Tersa-Miralles et al., 2025; Xu et al., 2022).

Implementation contexts varied widely, spanning clinical rehabilitation settings, home-based telerehabilitation, schools, laboratories, and community programs, demonstrating substantial contextual flexibility. However, clinical settings predominated, with nearly half of studies implemented in therapy or rehabilitation environments. Resource demands differed markedly across intervention types, ranging from high-cost immersive VR and motion-capture systems to consumer-grade devices and mobile platforms. Staffing intensity also varied, with therapist-led models requiring substantial human resources, whereas app-based or remote interventions reduced staffing demands. Figure 6 synthesizes these patterns, illustrating how setting, cost, staffing, and infrastructure interact to influence equity and long-term sustainability of VR and gamified PA interventions.

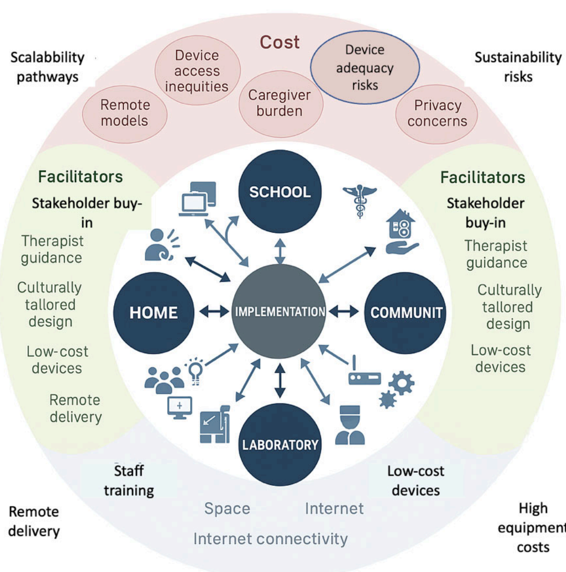

Fig. 6. Implementation Ecosystem

Equity and safety considerations were prominent determinants of implementation success. Barriers related to digital access, device affordability, connectivity, and sensory sensitivities were reported across multiple studies. Clinical interventions targeting vulnerable populations required supervised environments to manage physical safety and sensory overload, while home-based programs depended on caregiver and therapist involvement. Engagement patterns varied, with social support and therapist guidance consistently associated with higher adherence, whereas self-directed app-based interventions exhibited declining engagement over time, highlighting the challenge of sustaining motivation without ongoing support (Chen et al., 2024; Tobaiqi et al., 2023).

Scalability was primarily constrained by cost, infrastructure, and staffing demands. Remote and low-cost interventions demonstrated greater scalability potential, whereas equipment-intensive or therapist-led models posed barriers to widespread implementation. Several interventions remained at prototype or feasibility stages, underscoring the need for cost reduction, system refinement, and implementation trials before large-scale deployment.

Overall, these findings indicate that although VR and gamified PA interventions are feasible across multiple contexts, their sustainability and equitable reach depend on deliberate attention to cost, accessibility, safety protocols, and human-resource requirements. This underscores the importance of implementation-focused and equity-oriented research alongside efficacy evaluations.

Discussion

The findings synthesized from Tables 1–4 reveal systematic and theoretically coherent patterns in how virtual reality (VR) and gamified physical activity (PA) interventions influence children's engagement, motivation, and health-related outcomes. Across populations and settings, interventions consistently enhanced enjoyment, competence, and self-efficacy, mechanisms central to both Self-Determination Theory and Social Cognitive Theory (Tersa-Miralles et al., 2025; Tobaiqi et al., 2023; Wang et al., 2025). his review extends prior evidence by integrating effectiveness outcomes with behavioural mechanisms and implementation characteristics, demonstrating that immersive and gamified features—such as feedback, adaptive challenge, rewards, and social interaction—are key drivers of engagement and motor-related gains (Bowling et al., 2025; Lee & Jin, 2024; Menekşeoğlu et al., 2023). However, effect magnitude varied considerably, with intensive, theory-driven, and supervised interventions producing more consistent outcomes than brief or prototype-stage programs (Flôres et al., 2024; Zhu et al., 2025)

Methodological quality and theoretical alignment emerged as central determinants of intervention effectiveness. Studies employing robust designs, validated outcome measures, and explicit theoretical frameworks reported more consistent improvements in PA-related and motor outcomes (Korkmaz & Çoruh, 2025; Lin & Chang, 2025). In contrast, interventions with limited theoretical articulation or weaker designs yielded mixed finding (Eng et al., 2023; Gkintoni et al., 2024). Compared with earlier reviews that focused primarily on engagement or feasibility, this review highlights the importance of theoretical fidelity and measurement rigor in explaining outcome variability. Beyond efficacy, implementation constraints—including cost, technological access, staffing demands, and infrastructure requirements—substantially influenced real-world feasibility (Table 4). These barriers are particularly salient in low-resource settings, where high equipment costs and limited digital access may exacerbate health inequities (Gasteiger et al., 2022).

Table 4. Implementation, Equity, Safety, and Sustainability Characteristics of VR & Gamified PA Interventions in Children

Study/ Country	Implementation setting	Resource requirements (hardware, software, staffing, training, costs if reported)	Participant inclusion characteristics (age, condition, SES/region if reported)	Reported facilitators	Reported barriers/ risks	Adherence/ drop-out/ engagement	Scalability & sustainability notes
Bowling et al. (2025) GamerFit RCT/ Country NR	Home & community with remote coaching	Smartphone app; Fitbit/ actigraphy; exergame access; remote coaching platform; data plan; moderate coach training; subscription/ maintenance costs	Adolescents (13–17 y) with heterogeneous mental-health comorbidity; recruited via clinics/ schools; mixed demographics; SES/region NR	Remote support; personalized goals; high acceptability of app; seamless integration into daily routines	Device access inequality; sync/ connectivity issues; potential privacy and data-governance concerns	Engagement tracked in-app; adherence associated with coaching touchpoints; attrition NR	High potential for scale via remote, low-contact model; constrained by recurring costs for wearables/ subscriptions and need for robust data governance frameworks
Zhu et al. (2025) / Country NR	Lab/prototype	AR-capable smartphone/ glasses; custom TENG wearables; cloud analytics back-end; development and technical staff; calibration tools	Adolescents; early feasibility/ volunteer users; not targeted for specific clinical diagnoses; SES/ region NR	Adaptive difficulty; novelty of sensors; rich real-time feedback	Hardware cost/ availability; durability of wearables; calibration burden; data security issues	Feasibility usage only; adherence not systematically evaluated	Prototype stage; requires industrial-grade manufacturing, cost reduction, and maintenance plans before large-scale deployment
Fowler et al. (2024) / Country NR	Laboratory exposure (single session)	High-end HMD VR system; custom go-kart race software; facilitator; dedicated safe play space	Children 6–12 y with BMI ≥85th percentile; caregiver-present dyads; obesity risk group; SES/ region NR	High immersion and enjoyment; brief psychoeducation integrates easily into clinic visits	Cybersickness risk (though low with short exposure); cost of HMD; limited physical space and staff time	Single-dose exposure; adherence NA; only short-term follow-up	Low near-term scalability without repeated, structured modules; feasible for limited use in pediatric clinics if equipment and staffing are available
Lee & Jin (2024) / Country NR	Clinic/gym with supervised sessions	VR setup; gym equipment; one or more therapists; scheduled 60-min sessions; moderate staff training; facility access	Children with developmental disability; screened for safety and suitability; caregiver consent; SES/ region NR	Structured progression; close therapist guidance; cooperative play; strong therapeutic alliance	High staffing intensity; transport/ time burden on families; cost and maintenance of equipment	Good attendance reported across 12-week program; adherence supported by therapist involvement; drop-out NR	Scalable mainly within funded therapy services; sustainability dependent on staffing stability, reimbursement structures, and upkeep of VR/gym equipment

Table 4 (continued)

Study/ Country	Implementation setting	Resource requirements (hardware, software, staffing, training, costs if reported)	Participant inclusion characteristics (age, condition, SES/region if reported)	Reported facilitators	Reported barriers/ risks	Adherence/ drop-out/ engagement	Scalability & sustainability notes
Flôres et al. (2024) / Country NR	School setting (comparative sessions)	VR console/HMD or equivalent; PE teacher supervision; small cleared play area; minimal training for staff	School adolescents (~15–16 y); typical classrooms; school-based cohorts; SES/ region NR	Short, engaging VR sessions; novelty effects support immediate buy-in from students	Limited PE time; need for teacher training; potential motion sickness in some students	Single/short sessions; engagement reported as high during trials	Scalable as an enrichment tool in schools using relatively low-cost consoles/HMDs; sustainability linked to curriculum integration and teacher capacity
Köse et al. (2023)/ Country NR	Home (telerehabilitation)	Consumer-grade devices; home internet; telehealth platform; therapist tele-hours; guidance materials for families	Children with ADHD; require parental involvement and support; home environments variable; SES/ region NR	Convenience of home use; therapist guidance at a distance; structured, gamified tasks	Variability in home environments; inconsistent internet connectivity; increased caregiver load	Multi-session participation feasible; adherence supported by therapist reminders and parental engagement	Promising scalability within telehealth infrastructures; sustainability linked to reimbursement models, digital access, and family capacity
Menekşeoğlu et al. (2023) / Country NR	Clinic (rehabilitation)	Dedicated VR rehab system; trained clinicians; scheduled clinic slots; ongoing equipment maintenance	Children with hemiplegic CP; clinical rehabilitation population; SES/ region NR	Real-time feedback; graded therapeutic tasks; continuous clinical oversight	High equipment cost; clinic time and travel demands; risk of fatigue in intensive sessions	Program completion generally good; attendance encouraged by routine follow-up	Scalable within specialized rehabilitation centers; requires capital investment and long-term maintenance budgets
Hocking et al. (2022) / Country NR	Lab/clinic feasibility	Low-cost motion capture hardware; custom VR game/ software; facilitator; small lab/clinic space	Youth with ASD (10–17 y); sensory considerations; caregiver consent required; SES/ region NR	Low-cost hardware; tailored tasks; predictable environment reduces anxiety	Sensory overload risk; need for individual customization; training needs for facilitators	Feasibility acceptable; most participants completed 6 × 20-min sessions	Suitable for small-scale pilots and community centers with trained staff; scalability contingent on staff training and ongoing technical support
Reis et al. (2022) / Country NR	School/community (program roll-out)	Web/mobile mHealth platform; administrator dashboard; notification system; optional wearables; basic IT support	Adolescents in a prevention program; typical school cohorts; group-based implementation; SES/region NR	Points and challenges drive initial uptake; easy onboarding through schools	Mixed device ownership; data privacy and parental consent requirements; decline in engagement over time	Good initial uptake; engagement fluctuates and tends to decay without ongoing stimulation	Highly scalable with SaaS-based model; requires continuous content updates, data protection policies, and school/community partnerships

Table 4 (continued)

Study/ Country	Implementation setting	Resource requirements (hardware, software, staffing, training, costs if reported)	Participant inclusion characteristics (age, condition, SES/region if reported)	Reported facilitators	Reported barriers/ risks	Adherence/ drop-out/ engagement	Scalability & sustainability notes
Khaledi et al. (2022) / Country NR	Clinic/home hybrid	VR-assisted Montessori games on consumer devices; instructor/therapist at clinic; parent facilitation at home	Children with spastic hemiplegia (~6.4 y); require caregiver support; SES/ region NR	Child-led, repetitive tasks can be continued at home; flexibility across clinic and home	Need for caregiver facilitation; risk of fatigue or frustration in longer tasks	Session completion feasible; good attendance across 8 weeks; families generally able to maintain participation	Scalable as an adjunct to conventional therapy; sustainability depends on caregiver training and access to suitable devices
González-González / Country NR	Outpatient clinic (group sessions)	Kinect/active game system; large display; biometric sensors; facilitator/instructor; appropriate space	Children with obesity in outpatient care; group-based sessions; SES/ region NR	Group enjoyment; peer support; immediate feedback from sensors and games	Space requirements; equipment failures; heterogeneous motivation levels	Attendance acceptable; high satisfaction reported; objective PA measurement limited	Scalable to clinics and community gyms with adequate space and staff training; sustainability relies on equipment maintenance and ongoing program funding

Several facilitators were identified that enhance acceptability, sustainability, and scalability, including stakeholder engagement, culturally responsive design, caregiver and staff training, and remote or hybrid delivery models (Hamilton et al., 2024; Lowell et al., 2023). Interventions using low-cost or consumer-grade technologies demonstrated greater feasibility for long-term adoption (Hocking et al., 2022; Reis et al., 2022). Nonetheless, important research gaps remain. Most studies assessed outcomes only in the short term, limiting conclusions regarding sustained behaviour change and habit formation (Kumwenda et al., 2024). Additionally, limited demographic diversity and inconsistent reporting of socioeconomic characteristics constrain generalizability (Allen et al., 2022; Tully et al., 2021). Although multiple Behaviour Change Techniques were commonly employed, the relative contribution of specific gamification elements to long-term adherence remains unclear, highlighting the need for comparative, mechanism-focused, and longitudinal research.

Conclusions

This systematic review demonstrates that virtual reality (VR) and gamification represent promising, theory-aligned approaches for promoting physical activity (PA) among children across diverse settings and populations. Synthesized evidence indicates that these interventions can enhance engagement, motivation, motor outcomes, and selected psychosocial indicators, particularly when designs explicitly support autonomy, competence, and social interaction. However, evidence for sustained PA behaviour change remains limited, and effectiveness is strongly influenced by methodological rigor, theoretical grounding, and implementation context. Persistent challenges—including cost, digital inequities, staffing demands, and limited long-term evaluation—constrain scalability and equitable reach. Addressing these gaps will require longitudinal, theory-driven trials; standardized objective PA measures; and inclusive implementation strategies. With these advances, VR and gamification have the potential to become scalable and equitable tools for supporting active lifestyles and child health worldwide.

Ethics Approval

Ethical approval was not required for this study, as it is a systematic review based exclusively on previously published and publicly available data.

Informed Consent

Not applicable.

Data Availability Statement

All data analyzed in this study are derived from published sources cited in the reference list. No new datasets were generated.

AI Transparency Statement

The authors did not use artificial intelligence–assisted tools in the preparation of this manuscript.

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Conflict of Interest

The authors declare no conflicts of interest.

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Віртуальна реальність і гейміфікація для сприяння фізичній активності дітей: систематичний огляд сучасних тенденцій та інновацій

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 17 с., 4 табл., 6 рис., 56 джерел.

Обґрунтування. Фізична неактивність серед дітей у всьому світі зростає, що зумовлено сидячою поведінкою та способами життя, опосередкованими цифровими технологіями. Нові дослідження свідчать, що віртуальна реальність (VR) і гейміфікація можуть слугувати ефективними цифровими інтервенціями для сприяння фізичній активності (PA) та покращення показників здоров'я дітей.

Мета. Метою цього систематичного огляду було узагальнити та критично оцінити сучасні докази щодо інтервенцій на основі VR і гейміфікації, спрямованих на підвищення рівня фізичної активності серед дітей, із фокусом на характеристики інтервенцій, теоретичні механізми, ефективність та особливості впровадження.

Методи. Рецензовані дослідження було відібрано з баз даних Scopus, ERIC та ACM Digital Library. До аналізу включали інтервенційні дослідження за участю дітей і підлітків віком 5–18 років, у яких застосовували VR, ексергеймінг або гейміфіковані цифрові інтервенції для сприяння фізичній активності чи пов'язаним із нею показникам здоров'я. Дані було екстраговано та синтезовано відповідно до типології інтервенцій, теоретичних засад, результатів та особливостей впровадження.

Результати. До огляду було включено 11 інтервенційних досліджень, опублікованих у період з 2021 по 2025 рік. Загалом інтервенції на основі VR та гейміфікації продемонстрували позитивний вплив на залучення до фізичної активності, моторні результати та окремі психосоціальні показники. Ефективні дизайни зазвичай інтегрували постановку цілей, зворотний зв'язок, соціальне порівняння та механізми винагороди, часто узгоджені з теорією самодетермінації та соціально-когнітивною теорією. Ключовими бар'єрами впровадження були вартість, доступність і кадрові вимоги, тоді як чинниками-сприятелями виступали моделі дистанційної реалізації, залучення зацікавлених сторін і використання апаратного забезпечення споживчого рівня.

Висновки. VR і гейміфікація мають значний потенціал для сприяння фізичній активності дітей за умови теоретично обґрунтованої та якісної реалізації інтервенцій. Водночас докази щодо довгострокової ефективності, сталості та рівного доступу залишаються обмеженими, що підкреслює потребу в лонгітюдних дослідженнях і масштабованих, інклюзивних моделях інтервенцій.

Ключові слова: віртуальна реальність, гейміфікація, фізична активність, діти, імерсивні технології.

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Review Article

Systematic Review of Exercise Interventions in Archery: Injury Management and Performance Outcomes

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Abstract

Background. Exercise-based interventions are increasingly incorporated into archery training to enhance performance and reduce injury risk. However, the extent to which these interventions directly contribute to injury management and performance improvement remains unclear.

Objectives. This systematic review aimed to examine the effects of exercise interventions on injury management and performance improvement in archers. The review synthesizes 10 years of evidence (January 2015–April 2025) to provide recommendations for developing targeted exercise programs that address both performance optimization and injury prevention.

Materials and Methods. A comprehensive search was conducted across PubMed, Scopus, Web of Science, and SPORTDiscus, yielding 767 articles. Studies were screened according to predefined inclusion criteria, resulting in 15 eligible studies. Extracted outcomes included shooting accuracy, postural control, muscle strength, and indicators relevant to injury management. Methodological quality was assessed using the SQAC, with all included studies scoring ≥50%, indicating acceptable-to-high methodological rigor. Due to heterogeneity in study designs, interventions, and outcome measures, a meta-analysis was not performed.

Results. Most studies focused primarily on performance enhancement rather than direct injury management. Nonetheless, several exercise interventions demonstrated indirect benefits relevant to injury management and prevention, including improvements in postural stability, neuromuscular control, and muscular endurance. Core stability training, Pilates-based balance training, circuit training, and strength conditioning consistently produced significant improvements in postural stability (moderate-to-large effect sizes), muscle strength, and shooting accuracy. Targeted exercises such as lower trapezius strengthening, compound weight training, and archery-specific drills further enhanced accuracy, endurance, and neuromuscular coordination.

Conclusions. Exercise interventions meaningfully improve key performance outcomes in archers and may provide indirect benefits for injury prevention through improvements in strength, balance, postural control, and neuromuscular stability. Future research should incorporate standardized exercise protocols and prioritize larger randomized controlled trials explicitly examining injury-related outcomes to strengthen evidence-based practice in archery.

Keywords: archery, injury prevention, performance, strength training, systematic review.

Introduction

Archery is a competitive sport that requires a high level of physical strength and endurance to maintain technical consistency during performance (Falaahudin et al., 2024; Lau et al., 2020; Mohd Saleh et al., 2022). In addition, optimal archery performance depends on postural stability, balance, accuracy, and well-developed fine motor skills (Patil & Koley, 2019; Putra, 2022; Sarro et al., 2021). The specific nature of archery involves prolonged and repetitive upper-limb movements, which place considerable mechanical demands on the musculoskeletal system (Yachsie et al., 2023; Niestroj et al., 2018). When combined with sustained static postures, these demands substantially increase the risk of musculoskeletal injuries among archers (Alberola-Zorrilla et al., 2022; Subramaniam et al., 2025).

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Although archery is generally regarded as safe sport, injury rates can reach as high as 4.4 per 10,000 participants (Agranovich et al., 2024). A recent study of Malaysian elite archers reported that over 80% had experienced at least one injury, predominantly affecting the shoulder (bow arm 56.4%, drawing arm 54.5%), upper back (38.8%), lower back (38.2%), and neck (37.6%) (Subramaniam et al., 2025). Contributing factors such as improper technique, high training volume, insufficient strength and poor balance have been identified as significantly increase injury risk (B. R. Prine et al., 2023; Subramaniam et al., 2025). These factors not only heighten susceptibility to injury but may also compromise performance consistency and athlete longevity. Accordingly, implementing effective injury management strategies comprising well designed exercise programs with appropriate volume and intensity, along with training and movement corrections could mitigate injury risks and sustain athlete's performance.

Optimal archery performance requires precise physical control and stability throughout the shooting process that require a good core strength and lumbopelvic stability along the kinetic chain system (Sarro et al., 2021; Spratford & Campbell, 2017). Core stability, involving the trunk muscles supporting spinal alignment and abdominal organs, plays a central role in maintaining postural control and enabling efficient limb movement (Akuthota et al., 2008; Sarro et al., 2021). Research indicates that exercises targeting core strengthening exercises can improve dynamic balance abilities and reduce injury risks among archers (Park et al., 2016; Suppiah et al., 2017). Furthermore, balance training plays a vital role in synchronizing body movements with bow sway, a factor that significantly influences shooting accuracy (Sarro et al., 2021). Balance performance itself correlates strongly with archery success (Mohd Saleh et al., 2022) and tests such as static balance and star excursion have been linked to athlete's anthropometric characteristics (Patil & Koley, 2019).

In addition to core and balance factors, both upper and lower limb strength are essential for performance and stability. Upper limb strength, particularly in the arms, enables effective bow drawing and holding, directly impacting shooting accuracy and endurance (Liao et al., 2022; Susanto et al., 2021; Yachsie, Pranata, et al., 2023). Concurrently, lower limb strength especially in the hip extensors, abductors and knee flexors has been shown to significantly enhance balance control, which is vital for maintaining a stable shooting posture (Inoue et al., 2013; Wilson et al., 2018). Despite the recognition of limb strength's importance in archery, most of the training still emphasize on upper limb strength, with comparatively less focus on concurrent lower limb or trunk strengthening (Agranovich et al., 2024; Jogi et al., 2024; Subramaniam et al., 2025). It is essential to emphasize the integration of the upper limbs, trunk, and lower limbs, as the kinetic chain concept illustrates that effective movement in archery depends on the coordinated interaction of the shoulder–elbow–wrist force chain, trunk stabilization, and lower limb support (Liu, 2025) together with both static and dynamic postural stability (Fan et al., 2025; Kesilmiş et al., 2024). Previous systematic reviews in archery have explored biomechanical and performance related factors (Jogi et al., 2024; Lau et al., 2020), but they have placed less emphasis on exercise interventions that concurrently address injury management and performance enhancement. Consequently, a need exists for an integrated review synthesizing evidence on exercise interventions designed to improve both injury outcomes and performance in archers.

This systematic review aims to address these gaps by critically evaluating exercise interventions that support both injury management and injury prevention, while also enhancing performance in archery. By synthesizing current research, the review provides evidence-based recommendations for designing targeted exercise programs that can optimize performance and reduce the risk of injury among the archers.

Materials and Methods

Study Design and Protocol

This review adhered to the PRISMA-P (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009) and registered in PROSPERO (The International Prospective Register of Systematic Reviews) with identification number - CRD42023445770. The evaluation process was conducted according to the following: (1) preliminary, (2) identification, (3) screening, (4) eligibility, and (5) analysis. The review adhered to the pre-specified protocol without deviations; no amendments were made following registration.

Study Process

Preliminary Phase

In the initial phase, the research questions were formulated using the PICO framework (Population, Intervention, Comparison, and Outcome measures), as outlined in Table 1 (Aromataris & Riitano, 2014). Utilizing this framework, a preliminary search was conducted by

Table 1. PICO concept table

Research question: What exercise interventions are most effective for managing injuries and enhancing performance in archery athletes?	
PICO FRAMEWORK	
Population	The participants consisted of healthy female and male archers of all ages and competitive levels, with no restrictions.
Intervention	Any form of exercise intervention without constraints on training length, such as strength training, stretching exercises, circuit training, etc.
Comparison	Comparing against pre- or post-intervention data or a control group
Outcomes	Injury prevention, injury management, and skill performance Treatment effects or pre- and post-test values on injury prevention, management, or performance skills should be reported in the research, and at least one effect of the exercise intervention should be included. Actions involving a particular task or objective and requiring the synchronization of many motor skills in a given context and time period were deemed as technical skill outcomes.

combining the following terms: archer (population), exercise (intervention), and injury prevention, injury management, and skill performance (outcome measures). Keywords derived from the titles and abstracts of the selected articles were further refined utilizing a thesaurus and arranged into an organized grid table (Table 2).

Table 2. Logic grid with identified keywords

Logic grid with identified keywords		
Population	**Intervention**	**Outcomes**
Archer*	Exercise	Injury prevention
Archer* athlete	Training	Injury management
Shooting sport	Physiotherapy	Athlet* performance
Shooting game	Rehab*	Technical skill
	Resistance	Technique

Identification phase

The current study primarily employed the databases PubMed, Web of Science (WOS), SPORTDiscus, and Scopus, covering publications from January 2015 to April 2025. The keywords in the titles, abstracts, or topics of papers were matched in advance searches using a key search strategy that used Boolean operators, phrases, truncations, and wildcards (Table 3).

767 records were found overall as a result of the search, including 95 articles from PubMed, 223 from WOS, 72 from SportDiscus, and 377 from Scopus. In addition to database searches, we included a grey literature search using Google Scholar, ProQuest Dissertations, and relevant sport science repositories to identify unpublished theses and conference proceedings. Handsearching of reference lists from included articles and relevant reviews was also performed to ensure completeness.

Screening phase

The articles from all the databases were exported to Mendeley software to remove duplicates. Only 607 were screened in the third phase after eliminating duplication. During the initial part of this phase, all articles were evaluated based on (1) document type, (2) publication year, (3) language, and (4) topic area. (Table 4). The researchers restricted their selection to journal publications with empirical data, omitting master's theses, book chapters, conference proceedings, prefaces, and articles of opinion. In addition, only papers pertaining to archery or shooting disciplines, published in English between 2015 and 2025, were considered, yielding a total of 111 articles.

A second evaluation of the articles was conducted in accordance with their abstracts and titles during the second stage of the screening procedure. Articles were removed if they: (1) centered on psychological, mental, attention, arousal, concentration, or medication aspects, (2) were unrelated to exercise interventions or performance enhancement, (3) involved technology, or (4) pertained to Paralympic athletes. As a result, 18 articles were selected in this phase. Two researchers (AS and FFZ) independently evaluated the titles and abstracts of the discovered documents, subsequently conducting a full-text review. All experimental and quasi-experimental research were considered. All differences were addressed through discussions with the third author (MR).

Table 3. Databases and key search strings

Database	Strings	Results
PubMed	(“Archer*”[Title/Abstract] OR “Archer* athlete*”[Title/Abstract] OR “Shooting sport”[Title/Abstract] OR “Shooting game”[Title/Abstract]) AND (“Exercise”[Title/Abstract] OR “Training”[Title/Abstract] OR “Physiotherapy”[Title/Abstract] OR “Rehab*”[Title/Abstract] OR “Resistance”[Title/Abstract] OR “Strength”[Title/Abstract] OR “Physical activity”[Title/Abstract]) AND (“Injury prevention”[Title/Abstract] OR “Injury management”[Title/Abstract] OR “Athlet* performance”[Title/Abstract] OR “Technical skill*”[Title/Abstract] OR “Technique”[Title/Abstract] OR “Performance”[Title/Abstract] OR “Injur*”[Title/Abstract] OR “skill*”[Title/Abstract])	95
Web of Science	TS = (“Archer*” OR “Archer* athlete*” OR “Shooting sport” OR “Shooting game”) AND (“Exercise” OR “Training” OR “Physiotherapy” OR “Rehab*” OR “Resistance” OR “Strength” OR “Physical activity”) AND (“Injury prevention” OR “Injury management” OR “Athlet* performance” OR “Technical skill*” OR “Technique” OR “Performance” OR “Injur*” OR “skill*”)	223
SPORTDicus	AB ((“Archer*” OR “Archer* athlete*” OR “Shooting sport” OR “Shooting game”)) AND AB ((“Exercise” OR “Training” OR “Physiotherapy” OR “Rehab*” OR “Resistance” OR “Strength” OR “Physical activity”)) AND AB ((“Injury prevention” OR “Injury management” OR “Athlet* performance” OR “Technical skill*” OR “Technique” OR “Performance” OR “Injur*” OR “skill*”))	72
SCOPUS	TITLE-ABS-KEY (“Archer*” OR “Archer* athlete*” OR “Shooting sport” OR “Shooting game”) AND (“Exercise” OR “Training” OR “Physiotherapy” OR “Rehab*” OR “Resistance” OR “Strength” OR “Physical activity”) AND (“Injury prevention” OR “Injury management” OR “Athlet* performance” OR “Technical skill*” OR “Technique” OR “Performance” OR “Injur*” OR “skill*”)	377
TOTAL		767

Eligibility phase

A full-text screening of all 18 articles was conducted. Three articles were excluded because they were case studies or focused on validity and reliability. Figure 1 presents a

Table 4. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Investigated exercise interventions targeting performance improvement and/or injury prevention or management in archers	Non-exercise-based interventions – Articles focusing on psychological, nutritional, pharmacological, or surgical interventions without an exercise component.
Involved competitive or recreational archers of any age	Low methodological quality – Articles with major flaws in study design, insufficient reporting, or no control/comparison group (for experimental designs).
Used experimental or quasi-experimental	Master's theses, book chapters, conference proceedings, prefaces, and articles of opinion
Year published; between January 2015 to April 2025	Paralympic athlete populations.
Studies published in English	
Reported outcome measures related to physical performance, postural control, or injury profiles in archery	

summary of the four stages of the systematic review. Ultimately, 15 articles remained for analysis.

There are several rationales for considering 15 publications sufficient for the present systematic literature review (SLR), which collectively demonstrate that this number is consistent with both methodological norms and existing evidence in the field. First, drawing on the concept of study maturity articulated by Kraus et al., 2020, it is recognized that immature research fields often yield a relatively small number of articles, largely due to the scarcity of studies addressing exercise interventions for archers in the context of injury management and performance improvement.

There are several rationales for considering 15 publications sufficient for the present systematic literature review (SLR), which collectively demonstrate that this number is consistent with both methodological norms and existing evidence in the field. First, drawing on the concept of study maturity articulated by Kraus et al. (2020), it is recognized that immature research fields often yield a relatively small number of articles, largely due to the scarcity of studies addressing exercise interventions for archers in the context of injury management and performance improvement. Second, Robinson and Lowe (2015) observed that SLRs commonly examine fewer than 50 articles, and in many cases fewer than 10, thereby supporting the adequacy of a smaller dataset. Third, precedents in the literature reinforce this point: published SLRs focusing on exercise and physical training among archers, such as those by Jogi et al. (2024) and Lau et al. (2020) each reviewed only 10 studies. Collectively, these considerations justify the selection of 15 studies as a sufficient and methodologically sound basis for the present review.

Quality Appraisal

The methodological quality of the included studies (n=15) was assessed using the Standard Quality Assessment Criteria (SQAC), which evaluates key domains such as sample selection, intervention design, outcome measurement, and reporting clarity. The SQAC was selected as it allows consistent methodological evaluation across both randomized and non-randomized designs, which were prevalent in this review. This approach enabled comparability across heterogenous intervention studies without excluding relevant quasi-experimental evidence. However, it is acknowledged that SQAC does not provide the same level of bias domain specificity as randomized control trial focused tools such as RoB 2 or Robins-I. Therefore, while SQAC was appropriate for this mixed design reviews, its use represents a methodological limitation that may reduce sensitivity in detecting certain area of bias.

Two independent reviewers assessed each study's quality. Any discrepancies were resolved through discussion with a third reviewer. Each study was evaluated based on the checklist, with scores assigned as follows: Y = fully met the criteria (score 2), P = partially met the criteria (score 1), and N = did not meet the criteria (score 0). If a criterion was inapplicable to a specific research, it was designated as 'n/a.' A cumulative quality score was calculated for every article and changed to a percentage following the grading process.

A quality threshold of ≥50% was used to denote acceptable methodological rigor, consistent with earlier reviews employing SQAC (Kmet, 2004). Although this threshold is inherently arbitrary, this cutoff provides a practical compromise by eliminating studies with inadequate methodology while keeping those with adequate internal validity (Kmet, 2004). All 15 articles scored above 50% and were therefore included in this phase (Table 5).

Results

Study Selection, Screening and Eligibility

The systematic review process for study selection is illustrated in Figure 1. A total of 767 articles were initially obtained from numerous databases. Following the elimination of duplicates, 607 articles were retained and evaluated according to the established inclusion and exclusion criteria, as well as the criteria pertaining to exercise interventions. This screening process resulted in 18 relevant articles. Upon further review of the full-text articles, 3 were excluded because they were either case studies or studies focused on validity and reliability. Ultimately, 15 articles met the final eligibility criteria, each scoring over 80% in the quality assessment and were considered in the current review. A meta-analysis was not performed due to the diversity in the training protocols utilized for injury management and performance development in archers. Table 6 presents the primary findings.

Study Characteristics

All 15 publications considered in the present analysis are published in English and were published between 2015 and 2025.Two studies were conducted in India (Chatla et al., 2023; Khan et al., 2024), five studies in Indonesia (Nasrulloh et al., 2022; Prasetyo et al., 2023; Subekti et al., 2023; Yachsie et al., 2024; Yachsie, Pranata, et al., 2023)3-4 sets, 15-25 repetitions, and 1-2 minutes of rest between sets. The study population was Yogyakarta State University archery athletes selected via purposive sampling. The instrument used to measure muscle strength is the hand grip strength test. Meanwhile, to measure the upper, lower, and middle body for the endurance of muscular test, four kinds of test items were used namely bench jump, bent leg curl-ups, abdominal crunches, modified dips (man and one each in Japan (Shinohara et al., 2023)side bridges are performed in a posture similar to archery shooting for training the muscles around the shoulder joint and the shoulder girdle of the pusher. Aim The purpose of this study was to determine whether a low-tremor side-bridge exercise for 4 weeks improves bow tremor during archery movements. Methods Participants were 20 male college students. First, we measured the tremor during side bridges performed with trunk inclinations of 25°, 40°, 55°, and 70° using an accelerometer attached to the elbow joint and identified low-tremor side bridges. The participants were then randomly divided into intervention and non-intervention groups, and the low-tremor side bridges were performed for 4 weeks. Results The effect of the intervention was determined by measuring the total tremor value using an accelerometer attached to the bow and changes in the median power frequency (MdPF, Korea (Park et al., 2016), Turkey (Beyaz et al., 2024), Thailand (Hemara et al., 2021), China (Geng et al., 2023), Ukraine (Sergiy et al., 2017), Malaysia (Suppiah et al., 2017) and Taiwan (Liao et al., 2022).

Three studies focused on international and national levels (Chatla et al., 2023; Hemara et al., 2021; Khan et al., 2024), two studies addressed beginner levels (Beyaz et al., 2024; Shinohara et al., 2023)these interlimb asymmetries have been shown to associate with spatial patterns of hand selection behavior. Importantly, these interlimb asymmetries can be modified systematically by occlusion of visual feedback, or a long-term sports training. In this study, we asked about the effects of a short-term training on interlimb asymmetries. Eighteen healthy young participants underwent a 12-week novice traditional archery training (TAT, while high school level was examined in two studies (Park et al., 2016; Suppiah et al., 2017) and university level in two studies (Liao et al., 2022; Nasrulloh et al., 2022). One study investigated both national level and basic training archers (Sergiy et al., 2017) and five studies did not specify the level of the archers (Geng et al., 2023; Prasetyo et al., 2023; Subekti et al., 2023; Yachsie et al., 2024; Yachsie, Pranata, et al., 2023)this paper also explores the relationship between attention and performance in competitions. Methods: By random sampling method, 24 archery athletes were investigated. They were divided into three groups: A, B, and C. Group A represented excellent scores (8).

Outcome Measures

In the analysis of outcome variables of each study, shooting accuracy were the most assessed variables (Chatla et al., 2023; Geng et al., 2023; Khan et al., 2024; Liao et al., 2022; Prasetyo et al., 2023; Sergiy et al., 2017; Suppiah et al., 2017; Yachsie et al., 2024; Yachsie, Pranata, et al., 2023), followed by posture (Hemara et al., 2021; Sergiy et al., 2017; Suppiah et al., 2017), balance and stability (Hemara et al., 2021; Park et al., 2016; Prasetyo et al., 2023), arm muscle strength (Nasrulloh et al., 2022; Sergiy et al., 2017; Yachsie, Pranata, et al., 2023), arm muscle endurance (Nasrulloh et al., 2022; Subekti et al., 2023)to increase arm muscle endurance of archery athletes. This type of research is an experiment with a "Two Groups Pretest-Posttest Design" design. The population is archery athletes, totaling 20 males sex with ages 12-15 years. The exercise was carried out for six weeks. The instrument uses the Holding Bow Digitec Test. The data analysis technique was a t-test. The results showed: 1 and one study on each of the following variables; lumbopelvic stability (Khan et al., 2024), tremor (Shinohara et al., 2023) side bridges are performed in a posture similar to archery shooting for training the muscles around the shoulder joint and the shoulder girdle of the pusher. Aim The purpose of this study was to determine whether a low-tremor side-bridge exercise for 4 weeks improves bow tremor during archery movements. Methods Participants were 20 male college students. First, we measured the tremor during side bridges performed with trunk inclinations of 25°, 40°, 55°, and 70° using an accelerometer attached to the elbow joint and identified low-tremor side bridges. The participants were then randomly divided into intervention and non-intervention groups, and the low-tremor side bridges were performed for 4 weeks. Results The effect of the intervention was determined by measuring the total tremor value using an accelerometer attached to the bow and changes in the median power frequency (MdPF, muscle activities of upper trapezius, lower trapezius and serratus anterior (Shinohara et al., 2023)side bridges are performed in a posture similar to archery shooting for training the muscles around the shoulder joint and the shoulder girdle of the pusher. Aim The purpose of this study was to determine whether a low-tremor side-bridge exercise for 4 weeks improves bow tremor during archery movements. Methods Participants were 20 male college students. First, we measured the tremor during side bridges performed with trunk inclinations of 25°, 40°, 55°, and 70° using an accelerometer attached to the elbow joint and identified low-tremor side bridges. The participants were then randomly divided into intervention and non-intervention groups, and the low-tremor side bridges were performed for 4 weeks. Results The effect of the intervention was determined by measuring the total tremor value using an accelerometer attached to the bow and changes in the median power frequency (MdPF, arm reaching movement performance (Beyaz et al., 2024), precision (Hemara et al., 2021), attention (Geng et al., 2023), core strength and endurance (Suppiah et al., 2017), lower trapezius strength and shoulder kinematics (Liao et al., 2022) (Table 6).

Duration of the Study

The highest duration of intervention among the studies was six weeks (Khan et al., 2024; Prasetyo et al., 2023; Sergiy et al., 2017; Subekti et al., 2023; Yachsie et al., 2024; Yachsie, Pranata, et al., 2023)ip 2 = 0.159, p = 0.03, twelve weeks (Chatla et al., 2023; Liao et al., 2022; Park et al., 2016), eight weeks (Nasrulloh et al., 2022; Suppiah et al., 2017), four weeks (Shinohara et al., 2023)side bridges are performed in a posture similar to archery shooting for training the muscles around the shoulder joint and the shoulder girdle of the pusher. Aim The purpose of this study was to determine whether a low-tremor side-bridge exercise for 4 weeks improves bow tremor during archery movements.

Methods Participants were 20 male college students. First, we measured the tremor during side bridges performed with trunk inclinations of 25°, 40°, 55°, and 70° using an accelerometer attached to the elbow joint and identified low-tremor side bridges. The participants were then randomly divided into intervention and non-intervention groups, and the low-tremor side bridges were performed for 4 weeks. Results The effect of the intervention was determined by measuring the total tremor value using an accelerometer attached to the bow and changes in the median power frequency (MdPF, 12 to 16 weeks (Geng et al., 2023), one day (Hemara et al., 2021) and one study did not mention the duration (Beyaz et al., 2024).

Types of Exercise Intervention

Balance, Pilates and Core Training

A growing body of evidence highlights the effectiveness of balance, Pilates and core training, with four studies exploring various approaches (Khan et al., 2024; Park et al., 2016; Prasetyo et al., 2023; Suppiah et al., 2017). Specifically, these included Pilates and balance exercise (Khan et al., 2024), circuit training using a Bosu ball (Prasetyo et al., 2023), Pilates core stability (Park et al., 2016) and a core stability program using bodyweight exercises (Suppiah et al., 2017). All studies reported significant improvements ($p<0.05$) in performance outcomes, particularly in shooting accuracy (Khan et al., 2024; Prasetyo et al., 2023), balance (Park et al., 2016; Prasetyo et al., 2023) and reduction in postural sway (Suppiah et al., 2017).

Strength Training

Five studies have focused on strength training to improve the performance among the archers (Chatla et al., 2023; Liao et al., 2022; Nasrulloh et al., 2022; Subekti et al., 2023; Yachsie, Pranata, et al., 2023). Three studies have focused on arm muscle strength (Nasrulloh et al., 2022; Subekti et al., 2023; Yachsie, Pranata, et al., 2023), two studies on shooting accuracy (Chatla et al., 2023; Yachsie, Pranata, et al., 2023), one study on overall endurance of upper, lower, and middle muscle groups (Nasrulloh et al., 2022), and one study on lower trapezius muscle strength (Liao et al., 2022). Significant improvements were noted in all the outcome measures of the studies intervention ($p<0.05$).

Posture and Coordination

Three studies have investigated posture and coordination in archery (Beyaz et al., 2024; Hemara et al., 2021; Sergiy et al., 2017). The first study adopted traditional archery technique training to examine improvements in arm reaching movement performance (Beyaz et al., 2024). The second study utilized the archery skill analysis assessment form (ASAAF) to enhance posture, focus and muscle control among archers (Hemara et al., 2021). The third study implemented a specialized training program me targeting coordination, technical skills readiness as well as improvement in completion of complex tasks (Sergiy et al., 2017). All three studies reported significant improvement ($p<0.05$) in their post intervention scores.

Other Exercise Interventions

Yachsie et al. (2024) have examined the effects between fixed and changing drilling exercises on the archer's shooting accuracy with 18 sessions of training. The study has reported that both the fixed and changing drilling exercises have shown significant improvements in shooting accuracy ($p<0.05$). Shinohara et al. (2023) investigated how side bridge exercises with a 40-degree trunk inclination could reduce bow tremor during the archery sighting phase. The study revealed that following four weeks of interventions, significant improvements were seen in the tremor reduction and median power frequency of the middle deltoid. However, the serratus anterior, upper, and lower trapezius muscles did not show any significant improvements. Geng et al. (2023) investigated the impact of targeted archery training on attention stability and performance among 24 Chinese athletes. Over a controlled period, standardized practices focusing on posture and mechanical energy training were implemented, resulting in significant improvements in attentional stability for the highest-performing group. The study identified a strong correlation between focused attention and competitive outcomes. These findings underscore the role of mental focus in enhancing archery performance, providing valuable insights for optimizing athletic preparation.

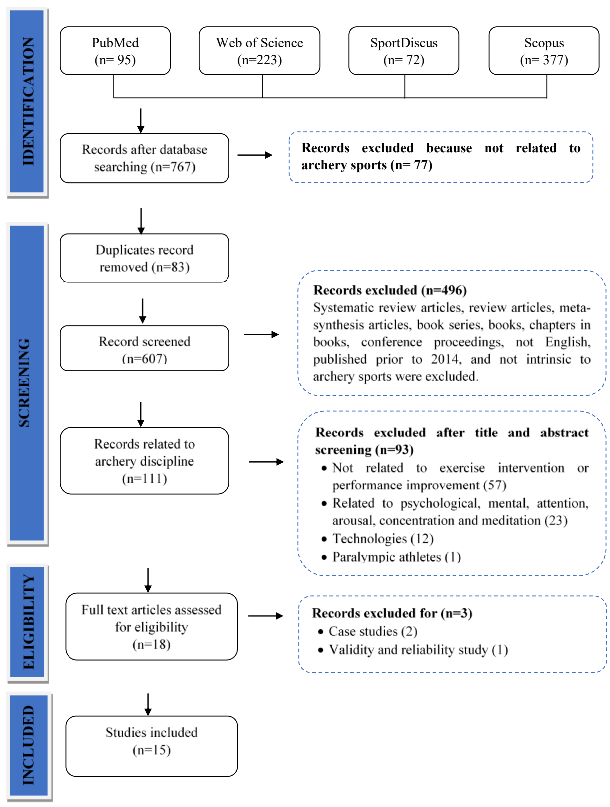

Fig. 1. PRISMA flowchat

Discussion

This systematic review consolidates the latest evidence on exercise interventions designed to enhance performance and manage injuries in archery athletes. Recent studies suggest that archers experience substantial musculoskeletal

Table 5. Quality assessment scores for the selected studies using the Standard Quality Assessment Criteria (SQAC)

Author(s)	Quality Assessment Criteria														Total Score	Quality Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
Khan et al., 2024 (Khan et al., 2024)	Y	Y	Y	Y	Y	P	N	Y	P	Y	Y	P	Y	Y	23/28	82.1%
Prasetyo et al., 2023	Y	Y	P	Y	n/a	n/a	n/a	Y	P	Y	Y	N	Y	Y	18/22	81.8%
Yachsie et al., 2024	Y	Y	Y	Y	Y	n/a	n/a	Y	P	Y	Y	Y	Y	Y	24	95.8%
Shinohara et al., 2023	Y	Y	Y	Y	Y	N	n/a	Y	P	Y	Y	Y	Y	Y	23	88.5%
Park et al., 2016	Y	Y	Y	Y	n/a	n/a	n/a	Y	P	Y	Y	Y	Y	Y	21	95.5%
Beyaz et al., 2024	Y	Y	Y	Y	Y	n/a	n/a	Y	P	Y	Y	Y	Y	Y	23	95.8%
Hemara et al., 2021	Y	Y	P	Y	n/a	n/a	n/a	Y	Y	Y	Y	P	Y	Y	20	90.9%
Subekti et al., 2023	Y	Y	Y	Y	P	n/a	n/a	Y	P	Y	Y	P	Y	Y	21	87.5%
Yachsie, Pranata, et al., 2023	Y	Y	P	Y	n/a	n/a	n/a	Y	P	Y	Y	P	Y	Y	19	86.4%
Geng et al., 2023 (Geng et al., 2023)	Y	Y	Y	P	n/a	n/a	n/a	Y	P	Y	Y	P	Y	Y	19	86.4%
Sergiy et al., 2017	Y	Y	Y	P	n/a	n/a	n/a	Y	P	Y	Y	P	Y	Y	19	86.4%
Chatla et al., 2023	Y	Y	Y	Y	n/a	n/a	n/a	Y	P	Y	Y	P	Y	Y	20	90.9%
Nasrulloh et al., 2022	Y	Y	Y	Y	n/a	n/a	n/a	Y	P	Y	Y	P	Y	Y	20	90.9%
Suppiah et al., 2017	Y	Y	Y	Y	Y	n/a	n/a	Y	P	Y	Y	P	Y	Y	22	91.7%
Liao et al., 2022	Y	Y	Y	Y	P	n/a	n/a	Y	P	P	Y	P	Y	Y	20	83.3%

Note. 1) Question/objective sufficiently described? 2) Study design evident and appropriate? 3) Method of subject/comparison group selection or source of information/input variables described as appropriate? 4) Subject (and comparison group, if applicable) characteristics sufficiently described? 5) If interventional and random allocation was possible, was it described? 6) If interventional and blinding of investigators was possible, was it reported? 7) If interventional and blinding of subjects was possible, was it reported? 8) Outcome and (if applicable) exposure measure(s) well defined and robust to measurement/misclassification bias? means of assessment reported? 9) Sample size appropriate? 10) Analytical methods described/justified and appropriate? 11) Some estimate of variance is reported for the main results? 12) Controlled for confounding? 13) Results reported in sufficient detail? 14) Conclusions support the by results? Y = fully met the criteria, P = partially met the criteria, and N = did not meet the criteria.

stress, particularly in regions such as the shoulder complex, spinal column and neck (B. Prine et al., 2016; Singh & Lhee, 2016; Subramaniam et al., 2025). The cumulative effects of high training volumes, technical errors, and insufficient physical preparedness can lead to tissue overload and a heightened susceptibility to both acute and chronic overuse injuries (Agranovich et al., 2024; Niestroj et al., 2018). While injury prevalence remains a pressing concern, the findings of this review indicate that exercise intervention have largely been employed with a primary focus on performance enhancement, rather than explicitly targeting injury management. Nonetheless, many of these interventions discussed in the current review indirectly reduce injury risk by correction biomechanical inefficiencies, improving neuromuscular control and enhancing tissue resilience.

The current review synthesizes results from 15 high quality studies involving various training approaches and provides valuables insight into the components of effective exercise programs for archers. The findings emphasize the multifaceted nature of effective archery training, revealing the significant contributions of intervention duration, strength conditioning, Pilates-based core engagement, balance training, and comprehensive core stability development. These elements work synergistically to improve shooting accuracy, minimize postural sway, and optimize musculoskeletal function, ultimately supporting superior performance and injury resilience in archers.

The duration of exercise interventions across the included studies ranged from a single-day protocol to programs lasting up to 12 weeks. Notably, most effective interventions spanned six to twelve weeks, delivered at a frequency of two to three sessions per week. Studies with shorter durations (e.g., 4-week side-bridge training) reported limited improvements in muscle activation patterns and neuromuscular stability (Shinohara et al., 2023). Conversely, interventions exceeding six weeks, such as the 12-week Pilates and strength training programs (Chatla et al., 2023; Khan et al., 2024), demonstrated significant improvements in lumbopelvic stability and shooting accuracy. Studies consistently show that 6-12-week interventions outperform shorter durations in developing neuromuscular adaptations and motor skills (Liao et al., 2022; Steib et al., 2017). This aligns with broader research on strength training, which indicates that untrained individuals benefit most from 3 sessions per week, while trained athletes see maximal gains with 2 weekly sessions (Rhea et al., 2003). Longer interventions allow for progressive loading and periodization, crucial for continued and maximized adaptation in strength as well as injury prevention (Severo-Silveira et al., 2021). Overall, evidence supports designing archery training programs with realistic

Table 6. Details of the included studies

Author (s)	Study design	Population	Intervention group	Control group	Protocol	Outcome measures	Result
Khan et al., 2024	RCT	30 national level athletes; male; 17-27 years.	Pilates exercises (PB) Balance training (B)	Did not receive any type of training	Pilates - 50 minutes with 10 minutes warm-up and 10 minutes cool down for 6 weeks (3 times per week). Balance - 20 minutes for 3 times per week (6 weeks)	Lumbopelvic stability - Knee Lift Abdominal Test (KLAT) and Bent Knee Fall-Out Test (BKFOT) Shooting accuracy	Significant difference in shooting accuracy ($F = 5.11$, $\eta_p^2 = 0.159$, $p = 0.03$), KLAT (Right) ($F = 8.51$, $\eta_p^2 = 0.240$, $p = 0.00$) KLAT (Left) ($F = 6.62$, $\eta_p^2 = 0.187$, $p = 0.01$) and BKFOT (Left) ($F = 6.31$, $\eta_p^2 = 0.195$, $p = 0.01$). No significant difference in BKFOT (Right) ($F = 0.99$, $\eta_p^2 = 0.035$, $p = 0.33$) among B, PB, and Control group pre and post intervention. Significant difference in shooting accuracy ($p = 0.03$) for PB group compared to the control and B training group. Significant changes in KLAT (Left and Right) between B group and control groups ($p = 0.03$ and 0.02). PB showed significant difference from control ($p = 0.05$). For BKFOT (Left), only the PB group demonstrated any significant difference ($p = 0.02$) compared to the other two groups.
Prasetyo et al., 2023	One group (pre-post test design)	12 archers; level and gender not specified; 14-17 years.	Circuit training sessions using a Bosu ball.	No control group	18 session of circuit training – Dosage and frequencies not mentioned	Shooting accuracy Balance tests	The pretest balancing score was 44.12 seconds, while the archery accuracy score was 216.50. After 18 bosu ball circuit training sessions, posttest balance score averaged 51.44 seconds and archery accuracy averaged 282.83. Significant increase in balance and accuracy was observed, with a p-value of 0.000.
Yachsie et al., 2024	One group (pre-post test design)	20 archers; level not specified; male; 15-20 years.	Drilling distance still Drilling distance changed	No control group	Still drilling: 30m, 65% intensity, 12 sessions, 6 children arrows, 45-minute recovery. Changed drilling distance: 10, 20, and 30m; 65% intensity; 12 sessions; 6 children arrow each session; 45-minute recovery.	Shooting accuracy	Fixed drilling training distance significantly improves archery accuracy in athletes (p-value < 0.05). Changing drilling training distance significantly impacts archery athletes' accuracy (p-value < 0.05). A significant difference in archery athletes' accuracy was found between constant and shifting drilling training distances (p-value < 0.05).
Shinohara et al., 2023	RCT	20 inexperienced archers; male; 20-22 years.	Side bridge exercises involving trunk inclination of 40° angle.	Did not receive any type of training	5 days/week for 4 weeks (20 days)	Tremor levels in the arm and bow during the sighting phase. Muscle activity changes in middle deltoid, upper trapezius, lower trapezius, and serratus anterior muscles.	Measurements obtained during shooting movements at baseline and after 4 weeks in the intervention group were compared, and significant differences were observed in the intensity of tremors and the MdPF of the middle deltoid. However, no significant intervention related differences were observed in the MdPF of the upper trapezius, lower trapezius, and serratus anterior muscles. In addition, none of the items in the non-intervention group showed significant differences in the findings obtained at the two evaluation points.

Table 6 (continued)

Author (s)	Study design	Population	Intervention group	Control group	Protocol	Outcome measures	Result
Park et al., 2016	Non-RCT	20 high school archers with experience of 5 years; gender not specified; 15-19 years.	Pilates core stability (PCS) exercises	Regular archery training	60 min work out (warm-up exercise for 10 min, main exercise for 40 min, warm down exercise for 10 min). 3 times/week (12 weeks). Intensity progressively increased over 12 weeks.	Static balance ability test Dynamic balance ability test	In static balance ability, there were no significant differences between pre- and post-values in the exercise group after completing the PCS program. Similarly, these results were also represented in the control group. In the aspect of comparisons between post values in both groups, there were significant improvements in only the exercise group. As for the dynamic balance ability, there were significant differences between pre- and post-values in the exercise group, except for up-right and left postures, whereas, there were no changes or decreases between pre- and post-values in the control group after completing the PCS program. Meanwhile, in the aspect of comparisons between post values in both groups, there were significant improvements in up, and up right, and downright part and overall dynamic scores of the exercise groups.
Beyaz et al., 2024	Non-RCT	36 inexperience archers, 7 males and 11 females in both groups; 18-23 years.	Traditional archery technique (TAT)	Regular archery training	1 training session (60 mins) every day for a total of 84 sessions (12 weeks).	Arm reaching movement performance	Movement accuracy, movement precision, and movement efficiency in the experimental group have all improved significantly as a result of TAT ($p < .05$). These improvements were comparable across both arms, thus the interlimb differences in movement performance were not affected by the short-term TAT and remained similar.
Hemara et al., 2021	Non- RCT	31 national and international competitive archers, gender not specified; 15-31 years.	Preferred Form Group: Archers who received training based on archery skill analysis assessment form (ASAAF). Training emphasized posture, focus, and muscle control across 10 standardized archery skills, such as aiming and release.	Actual Form Group: Archers' untrained, original shooting form served as a baseline, reflecting their usual skill levels prior to intervention.	Same day training and assessment based on guidance by experts and video.	Performance Scores: Average scores from both forms (Actual and Preferred) across 10 shooting trials. Skill Analysis (ASAAF): Ten core skills, with specific focus on precision, posture, and stability.	Significant improvement: Preferred form scores averaged 86%, compared to 79% in the Actual form, indicating a statistically significant improvement in archery performance post-training. Efficiency Indicators: Regression analyses showed ASAAF's R^2 values of 51% and 69% for actual and preferred forms, respectively, supporting the efficacy of posture training in enhancing archery skills.
Subekti et al., 2023	Non- RCT	20 archers; gender and level of experience not specified, 12-15 years.	Free Weight Training Group: (dumbbell presses, lateral raises, and incline bench exercises).	Gym Machine Training Group: (gym machines, with exercises such as pulley lateral raises, pec deck laterals, and shoulder presses).	6 weeks with a total of 18 training sessions.	Arm muscle endurance	Free weight training had a statistically significant effect on arm muscle endurance in archery athletes ($p < .001$). Gym machine–based weight training had a statistically significant effect on arm muscle endurance in archery athletes ($p = .002$). A statistically significant difference in arm muscle endurance was observed between free weight training and gym machine–based training ($p = .019$).

Table 6 (continued)

Author (s)	Study design	Population	Intervention group	Control group	Protocol	Outcome measures	Result
Yachsie, Pranata, et al., 2023	One group (pre-post test design)	12 archers; male; level of experience not specified, 16-18 years.	Circuit Plank Training	No control group	Exercise dose: 1 RM, 60-70% with 30 seconds recovery, 3-5 reps, 1-3 sets, and 3-minute breaks between sets. 3 times/week with 18 sessions (6 weeks).	Arm muscle strength Shooting accuracy	The analysis of the arm muscle strength data resulted in a t-count value of (41,894) > t-table (1.80) and a p-value of (0.000) < 0.05. Meanwhile, the archery accuracy analysis obtained a t-count value of (55,001) > t-table (1.80), and a p-value of (0.000) < 0.05. There was an increase in the strength and accuracy of archery athletes after having circuit plank training and increased endurance component of the arm muscles.
Geng et al., 2023	Non-RCT	24 archers; gender, age and level of experience not specified.	Physical fitness training Standardized archery movement Posture training Mechanical energy stretching exercises Static and dynamic exercises Arm position awareness and correction	Routine training	The protocol of each exercise not mentioned clearly in the methodology.	Archer's attention using EEG assessment Archer's performance and accuracy	Athletes in group A had the greatest increase in attention after training, showing statistical significance (P<0.01). The comparison between groups B and C also showed statistical significance (P<0.01). Significant differences were found in the stability of attention between the experimental and control groups. *Athletes were categorized based on the performance level; Group A achieved excellent results (n=8), group B had good results (n=8), and group C had average results (n=8).
Sergiy et al., 2017	Non-RCT	70 archers, gender and age not specified; 25 national level and 45 basic training archers.	Specialized training programme (Coordination skills, technical precision, reduced maximum strength training)	Usual training	The training protocol- 80% of training on coordination and technical skill enhancement.	Arm strength Muscle sensitivity Shooting accuracy Angles of body positioning before and after the shot.	Improved Coordination The experimental group showed significant enhancements in coordination tasks, such as the "Laser hold in target field," with results improving by 50.55–72.18% (p < 0.01). Muscle sensitivity deviations decreased by 29.42–146.59% (p < 0.01). Enhanced Technical Skills Skills like "stretching to the chin" and "traction phase" improved significantly in the experimental group. Shot execution time reduced, and elbow angle, hand positioning, and shoulder movement speed increased by 5.05–39.94% (p < 0.01). Physical and Technical Readiness Experimental group outperformed in exercises like "Shooting 18x18" and challenging conditions (e.g., platform or closed eyes), with gains of 1.41–24.49% (p < 0.01). The focus on coordination and stability in experimental training led to better precision performance compared to traditional methods. Training Program Comparison The experimental program delivered more significant improvements in complex tasks requiring fine motor control and stability, crucial for elite archery.

Table 6 (continued)

Author (s)	Study design	Population	Intervention group	Control group	Protocol	Outcome measures	Result
Chatla et al., 2023	Non-RCT	60 national level archers, both male and female; aged between 16 to 25 years.	Specific strength training (SSTG) General strength training (STG) Combined Training (CTG)	Usual training	SSTG – received strength training on alternate days. STG – followed a general strength training regimen on alternate days. CTG – received a combination of specific and general strength training on alternate days. *12 weeks training protocol with specific strength training protocol	Shooting accuracy	Training methods significantly improved the scoring performance index in archer groups (SSTG < 0.05, STG < 0.05, CTG < 0.05). The CTG achieved the highest performance index after strength and specific strength training. The control group showed no significant improvement in scoring performance index.
Nasrulloh et al., 2022	One group (pre-post test design)	15 university archers, gender not specified; age between 17 – 22 years.	Compound set training protocol (weight training sessions)	No control group	60-80% of the one-repetition maximum (1 RM), 3-4 sets with 15-25 repetitions, with 1-2 minutes of rest between sets.	Arm muscle strength Endurance across upper, middle, and lower body muscle groups	The t-test results showed a t-value of 14.532 with a significance of 0.000 ($p < 0.05$), indicating that compound set weight training significantly improves arm muscle strength in archery athletes. For muscle endurance, the t-test showed a t-value of 13.396 with a significance of $p < 0.05$. These results confirm that compound set weight training significantly enhances muscle endurance in archery athletes.
Suppiah et al., 2017	RCT	12 adolescent archers, 6 males and 6 females; aged between 13 to 18 years; level of experience not specified.	Core stability program (bodyweight exercises)	Usual training	45 minutes including warm up (8 weeks)	Postural sway Core strength and endurance Shooting accuracy	Mixed factorial ANOVA revealed significant time-based interactions in push-up performance, plank, archery performance, and postural sway. Postural sway differed significantly between experimental and control groups on both planes at T2 (CoP range x: $F(1,10) = 7.952$, $p < .05$, $d = 1.302$; CoP range y: $F(1,10) = 7.887$, $p < .05$). Similar results were observed at T3(CoP range x: $F(1,10) = 7.952$, $p < .05$; CoP range y: $F(1,10) = 11.105$, $p < .05$).
Liao et al., 2022	Non-RCT	14 university level archers, 5 males and 9 females; average age of 19 years.	Lower trapezius centered exercise	Usual training	12 weeks training	Lower trapezius muscle strength Shoulder kinematics Upper /lower trapezius muscle activity Shooting accuracy	The exercise group improved their simulated game score from 628 to 639 ($p = 0.045$), while the control group showed no changes. Lower trapezius strength increased from 8 to 9 kg-force in the exercise group ($p = 0.045$). Horizontal abductor strength improved from 81% to 93% of body weight ($p = 0.048$). The UT/LT ratio decreased from 2.2 to 1.1, indicating better shoulder stability during archery shots.

RCT- Randomized trial control; UT/LT- Upper trapezius/lower trapezius timeframes of 6-12 weeks for meaningful performance improvements (Je, 2016).

Strength training has consistently proven effective in enhancing archery performance, particularly when both upper and lower limb muscle groups are targeted (Chatla et al., 2023; Liao et al., 2022; Nasrulloh et al., 2022; Sergiy et al., 2017; Subekti et al., 2023; Yachsie, Pranata, et al., 2023). Such interventions have led to marked improvements in arm endurance, postural stability, and shooting precision. Notably, compound set training protocols (Nasrulloh et al., 2022) and integrated general-specific strength programs (Chatla et al., 2023) have outperformed isolated routines, offering superior performance gains. These findings align with biomechanical principles, as archery demands coordinated, multi-joint control and stability (Vendrame et al., 2022). Evidence also shows that free weight exercises offer a slight edge over machine-based training, particularly in improving muscle endurance (Subekti et al., 2023). This advantage likely stems from the greater neuromuscular activation required by free weights due to their stabilization demands (Schwanbeck et al., 2020), an effect consistent with recent meta-analyses showing superior strength gains with free-weight training (Haugen et al., 2023; Heidel et al., 2021). Because archery involves complex three-dimensional movement and precise control, training methods that replicate these demands, such as free weights, are more effective than machines, which limit movement patterns and stabilization.

Archery is a full-body discipline that relies on a coordinated kinetic chain beginning from the lower limbs and progressing through the trunk to the upper body. While the upper extremities perform the final action of drawing and releasing the bow, the generation and transfer of force originate from the ground up, beginning with the legs and pelvis and progressing through the trunk to the shooting arm (Ertan et al., 2003). This kinetic chain mechanism is essential for optimizing shooting performance and stability in archery. The lower limbs play a crucial role in establishing postural stability and initiating movement, which then transmits through the pelvis and trunk before reaching the bow arm (Azhar et al., 2021; Serrien et al., 2018). Enhancing lower limb strength contributes to greater neuromuscular control and stability, thereby minimizing energy dissipation along the kinetic chain and improving overall performance efficiency (Simsek et al., 2014; Vendrame et al., 2022). Research shows that elite archers who emphasize core and lower extremity conditioning experience more consistent shot accuracy and postural control (Kim et al., 2019; Liao et al., 2022). From a practical standpoint, the inclusion of comprehensive training program inclusive of posture correction, correcting the muscles imbalance, core activation and stabilization, balance training, and also development of strength program should prioritize multi-joint exercises that involve dynamic stability, apply progressive overload across different movement planes, and combine general strength with archery-specific patterns. Future protocols should adopt a more comprehensive approach, addressing both upper and lower body muscular demands to prevent compensatory strategies that lead to overuse injuries.

Core stability interventions delivered through Pilates-based, circuit plank training or bodyweight-focused led to measurable improvements in balance, postural control, trunk endurance, and shooting accuracy among archers (Khan et al., 2024; Park et al., 2016; Suppiah et al., 2017). While each study emphasized different outcome measures, the findings support the conclusion that enhancing core function translates into better shooting performance and potentially reduced injury risk. These findings align with the kinetic chain theory, which posits that force generation initiates from the lower limbs and is transmitted through a stable core to the upper extremities (Kibler et al., 2006). A well-conditioned core not only provides a stable base for efficient force transfer but also minimizes compensatory movements that can contribute to common overuse injuries in the shoulder and lumbar regions (Akuthota et al., 2008). Furthermore, enhanced core stability improves energy efficiency, delaying fatigue during prolonged shooting sessions, a critical factor in competitive archery where sustained precision is required (Spratford & Campbell, 2017).

A key limitation of the current evidence base is that injury-related outcomes were rarely measured directly across the included studies. Most interventions did not report injury incidence, injury severity, or time-loss data. Consequently, conclusions regarding injury management and injury prevention are primarily derived from indirect indicators such as improvements in balance, postural control, neuromuscular stability, core endurance, and muscular strength. While these parameters are well established contributors to injury risk reduction, their interpretation as injury-related outcomes should be viewed as inferential rather than definitive.

Conclusions

This systematic review demonstrates that exercise-based interventions consistently improve crucial performance determinants in archers, including shooting accuracy, postural stability, neuromuscular coordination, core strength and upper-limb endurance; however, implications for injury prevention and injury management should be interpreted as indirect and inferential, as most studies did not directly assess injury related outcomes. Although most interventions were primarily designed for performance enhancement, the observed improvements in trunk stability, balance control, and muscular endurance suggest meaningful secondary benefits that may help reduce injury risk through better kinetic-chain efficiency and movement control. These findings support the integration of structured, multi-week exercise programs as an effective strategy for enhancing overall performance capacities among archery athletes.

Despite these demonstrated benefits, there remains a clear lack of a systematic, integrated training module that concurrently incorporates strength development (both upper and lower body), core stability, balance and proprioception, postural re-education, and archery-specific neuromuscular training. Moreover, most studies did not explicitly measure injury outcomes, underscoring the need for future research employing longitudinal designs, injury surveillance, and functional movement assessments to better capture injury risk and recurrence. Moving forward, future studies should adopt standardized intervention protocols, larger sample sizes, and multidimensional outcome measures, including explicit injury metrics to strengthen the evidence base and inform more comprehensive training guidelines for coaches, therapists, and sport scientists working with archers.

Ethics Approval

Ethical approval was not required for this study, as it is a systematic review based exclusively on previously published and publicly available data.

Informed Consent

Not applicable.

Data Availability Statement

All data analyzed in this study are derived from published sources cited in the reference list. No new datasets were generated.

AI Transparency Statement

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Conflict of Interest

The authors declare no conflicts of interest.

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Систематичний огляд фізичних вправ у стрільбі з лука: профілактика та лікування травм і вплив на показники результативності

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 16 с., 6 табл., 1 рис., 55 джерел.

Обґрунтування. Тренувальні інтервенції на основі фізичних вправ дедалі частіше інтегруються у підготовку стрільців з лука з метою підвищення результативності та зниження ризику травм. Однак ступінь, до якого ці інтервенції безпосередньо сприяють управлінню травмами та покращенню спортивних показників, залишається недостатньо з'ясованим.

Мета. Цей систематичний огляд мав на меті проаналізувати вплив фізичних тренувальних інтервенцій на управління травмами та підвищення результативності у стрільців з лука. Огляд узагальнює 10 років наукових доказів (січень 2015 – квітень 2025) з метою надання рекомендацій щодо розроблення цільових програм вправ, спрямованих одночасно на оптимізацію результативності та профілактику травм.

Матеріали і методи. Комплексний пошук було проведено в базах даних PubMed, Scopus, Web of Science та SPORTDiscus, у результаті чого було виявлено 767 публікацій. Дослідження відбиралися відповідно до заздалегідь визначених критеріїв включення, що зрештою дало 15 прийнятних досліджень. До аналізованих показників належали точність стрільби, постуральний контроль, м'язова сила та індикатори, релевантні для управління травмами. Методологічну якість оцінювали за шкалою SQAC; усі включені дослідження набрали ≥50 %, що свідчить про прийнятний або високий рівень методологічної строгості. Через гетерогенність дизайнів досліджень, інтервенцій та показників результативності метааналіз не проводився.

Результати. Більшість досліджень були зосереджені переважно на підвищенні спортивної результативності, а не на безпосередньому управлінні травмами. Водночас низка тренувальних інтервенцій продемонструвала опосередковані ефекти, релевантні для управління та профілактики травм, зокрема покращення постуральної стабільності, нейром'язового контролю та м'язової витривалості. Тренування стабілізації корпусу, вправи на баланс за методикою пілатесу, кругові тренування та силова підготовка стабільно забезпечували суттєве покращення постуральної стабільності (ефекти помірного–великого розміру), м'язової сили та точності стрільби. Цільові вправи, зокрема зміцнення нижніх пучків трапецієподібного м'яза, багатосуглобові силові вправи та спеціалізовані стрілецькі вправи, додатково покращували точність, витривалість і нейром'язову координацію.

Висновки. Фізичні тренувальні інтервенції суттєво покращують ключові показники результативності у стрільців з лука та можуть забезпечувати опосередковані переваги для профілактики травм за рахунок підвищення сили, балансу, постурального контролю та нейром'язової стабільності. Подальші дослідження мають передбачати стандартизовані протоколи фізичних вправ і надавати пріоритет масштабнішим рандомізованим контрольованим дослідженням, які прямо оцінюють травматологічні результати, з метою зміцнення доказової бази у стрільбі з лука.

Ключові слова: стрільба з лука, профілактика травм, результативність, силова підготовка, систематичний огляд.

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Review Article

Wearable Technologies in School Physical Education: A Systematic Review of Pedagogical Implications

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Abstract

Background. Wearable technologies such as heart rate monitors, accelerometers, and fitness trackers are increasingly integrated into school-based physical education (PE) to enhance instructional strategies, student engagement, and personalised learning. Yet empirical evidence on their pedagogical effectiveness remains fragmented.

Purpose. This systematic review synthesises research on wearable technology applications in school-based PE, examining their integration into teaching strategies, student motivation and participation, and personalised feedback.

Methods. A systematic search across Web of Science, Scopus, ERIC, SPORTDiscus, and PsycINFO identified 12 peer-reviewed studies published between 2000 and 2025. Methodological quality was assessed using the Mixed Methods Appraisal Tool (MMAT), and results were synthesised.

Results. Wearable technologies facilitated diverse instructional strategies including real-time feedback, self-monitoring, gamification, and goal setting. Their use increased student motivation, participation, and enabled personalised feedback, although data privacy and ethical concerns were noted. Teacher digital literacy and pedagogical competence influenced implementation effectiveness.

Conclusions. Wearable technologies offer significant pedagogical benefits for school-based PE by enhancing motivation, participation, and personalisation. Successful implementation requires thoughtful instructional design, teacher readiness, and careful ethical management of student data. Future research should investigate long-term outcomes and professional development models for educators.

Keywords: wearable technologies, school-based physical education, student motivation, personalised learning, technology integration.

Introduction

In recent years, the application of wearable technology in physical education (PE) has increased steadily, and it is now becoming a standard teaching tool in PE classrooms. Devices such as heart rate monitors, accelerometers and smart bracelets can record students' physiological and motor data in real time, providing a more objective basis for teachers to understand students' classroom participation and exercise intensity (Lin et al., 2021, 2023; Wort et al., 2021). The use of these technologies makes it easier for teachers to carry out personalised feedback and differentiated teaching and also helps students gradually form self-monitoring and self-regulation learning ability (Boiché et al., 2020). Therefore, wearable technology has not only altered the teaching methods of traditional PE classrooms to some extent but also provided new ideas for enhancing the quality of PE teaching, particularly in sports intensity monitoring, real-time feedback, and sports performance evaluation (Xu et al., 2024).

In PE classes, wearable technology is no longer just a health monitoring tool. However, it has gradually become an important resource to support teaching and promote students' learning. By obtaining students' motor and physiological data in real-time, teachers can more accurately assess students' exercise intensity, skill performance, and classroom participation. For example, heart rate monitoring can guide students to participate in activities within the appropriate intensity range and adjust the amount of exercise in real-time according to feedback, thereby improving the exercise effect (Cunningham-Rose et al., 2024; Gråstén et al.,

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2019). At the same time, accelerometers and other devices can record students' activities under different exercise intensities, providing teachers with more comprehensive classroom information (Zhang & Wang, 2024). For students, instant feedback helps them gain a clearer understanding of their own motor state, thereby enhancing self-regulation ability and improving learning motivation (Gråstén et al., 2019; Siacor et al., 2024). In general, wearable technology can help students adjust their exercise strategies based on real-time data, promoting improvements in exercise performance and learning outcomes.

Although the application of wearable technology in PE classes is increasing, the relevant research is still relatively scattered. Existing research focuses more on changes in the technical performance, health effects, or sports performance of the equipment itself. It less systematically analyses how these technologies are effectively utilised in the teaching process and their impact on students' learning outcomes (Boiché et al., 2020). Some studies explain students' learning motivation and participation using self-determination theory or social and cultural learning theory; however, a comprehensive analysis of how wearable technology supports the explicit teaching of strategies, classroom management, and students' self-regulation remains insufficient (Esmonde, 2019). Therefore, there is still a lack of a systematic overview of the teaching application of wearable technology in PE and its learning effect (Zhang et al., 2025).

Based on this, this study aims to systematically review the application of wearable technology in school PE situations, focusing on how these technologies support teaching strategies, promote students' learning motivation and classroom participation, and provide personalised feedback for students. By integrating existing research, this study aims to provide a practical reference for PE teachers and educational researchers, helping them utilise wearable technology more effectively in PE classes to enhance the quality of teaching. This review aims to address these research questions: 1) How are wearable devices used in school physical education classes? What are the most common teaching strategies and classroom designs? 2) What is the overall impact of wearable devices on students' motivation, participation, and learning in physical education classes? Under what kind of classroom and teaching conditions are these influences more likely to promote learning or bring negative effects?

Theoretical Framework

Self-Determination Theory (SDT) is used to explain how the learning environment influences the "quality of motivation" in students, and how this motivation, in turn, affects participation and the learning experience. SDT believes that people have three basic psychological needs: autonomy (feeling of choice and control), sense of competence (feeling that one can do well and make progress), and relatedness (feeling respected, accepted, and connected with others). When classroom teaching supports these needs, students are more likely to form autonomous motivations, that is, to participate because of interest or recognition of the value of learning, which is usually more stable and sustainable. On the contrary, when the teaching method oppresses or thwarts these needs, students are more likely to experience controlled motivation (to avoid criticism, participate for the sake of a score, or due to external pressure), and may even experience a lack of motivation and withdrawal. The advantage of SDT is that it not only focuses on "whether the amount of exercise has increased" but also pays more attention to "this increase is driven by interest or pressure", so it is more suitable for explaining technical intervention in physical education classes (Deci & Ryan, 2000; Viciana et al., 2019).

In this review, we use SDT to understand how wearable devices affect students' learning through "teaching methods", rather than attributing the effect to technology itself. Wearable devices can support a sense of competency by providing clear, timely, and linked feedback to learning goals, helping students see progress and adjust their strategies (Gråstén et al., 2019). When teachers provide explanation and guidance, and give students space to set personal goals, choose rhythms, and understand data, devices may also support autonomy (Kerner & Goodyear, 2017; Siacor et al., 2024). If the use of data in the classroom emphasizes cooperation, encouragement, and inclusion, equipment may also enhance the relationship. This review focuses on the analysis under the framework of SDT: (1) the teaching mechanism of equipment uses (feedback design, goal setting, teacher language, and interaction), and (2) the key situational conditions that determine their promotion or suppression of psychological needs (Deci & Ryan, 2000; Kerner & Goodyear, 2017).

Methodology

This systematic review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure the standardisation and transparency of the research process (Page et al., 2021). In view of the significant differences in equipment type, research object, teaching strategy, and learning results, this study employs a systematic review with narrative synthesis to integrate and analyse the relevant research findings (Rodgers et al., 2009). In this way, this study strives to comprehensively present the application of wearable technology in PE and provide a theoretical reference for subsequent educational technology research and practice (Keogh et al., 2021).

Search Strategy

The literature retrieval strategy of this study follows the standard practice of systematic reviews, selecting five core databases for retrieval: ERIC, SPORTDiscus, Web of Science, Scopus, and APA PsycINFO (Page et al., 2021). The retrieval time range is set to 2000-2025 to cover as much research as possible on the application of wearable technology in school PE (Keogh et al., 2021). To enhance the comprehensiveness of retrieval and minimise the risk of missing relevant research, this study develops a more systematic retrieval strategy grounded in Boolean logic, drawing on best practice suggestions from systematic reviews (Siddaway et al., 2019; Higgins, 2019). Different forms of keyword expression are included in the search process, including synonyms, variations in spelling, changes between singular and plural forms, and common expressions related to teaching. For example, in terms of wearable technology, terms such as "heart rate monitor", "fitness tracker" and "smartwatch" are used; in the teaching dimension, "teaching strategies" is covered. Expressions such as "instructional approaches" and "learning outcomes".

To adapt to the retrieval rules of different databases, this study employs intercepts (such as strateg*, technolog*) and Boolean operators (AND/OR), adjusting the retrieval fields accordingly based on the syntactic characteristics of each database. For example, this approach utilises abstracts in ERIC (AB), use the TITLE-ABS-KEY in Scopus (Page et al., 2021). In addition, through manual consultation of the list of references included in the literature, relevant research that may be omitted in the initial retrieval is also supplemented to identify (Stone et al., 2023). For example, we design a search strategy of Web of science: TS=("wearable technolog*" OR smartwatch OR Fitbit OR "heart rate monitor" OR accelerometer) AND TS=("physical education" OR "PE class" OR "school-based physical activity") AND TS=(teaching OR pedagogy OR "teaching strateg*" OR "learning outcome*" OR motivation OR engagement). Table 1 summarises the classification structure of search words and the changes in their terms.

Table 1. Search Term

Consider Different Terminology	Key Word
Synonyms	wearable technology, heart rate monitor, fitness tracker, smartwatch, activity tracker
Different Spelling	physical education, PE, teaching strategies, instructional approaches, classroom feedback
Singular versus plural forms	device/devices, student/students, teacher/teachers, outcome/outcomes
Final Searching Equations	("wearable technolog*" OR "heart rate monitor*" OR "fitness tracker*" OR "smartwatch*") AND ("physical education" OR "PE") AND ("teaching strateg*" OR instruction* OR feedback OR engagement OR outcome*)

This study has formulated explicit inclusion and exclusion standards to ensure that the selected literature is consistent with the research purpose. The included research must be published in an English peer-reviewed journal. For empirical research, the research design can be qualitative, quantitative or mixed methods, as long as it has specific educational or practical value for PE. The research content should involve the application of wearable devices in primary or secondary school PE classrooms, focusing on their role in teaching strategies, classroom monitoring, or student learning feedback, rather than just for health monitoring or behaviour records.

Only pay attention to the technical performance of the equipment; literature that does not belong to the school PE classroom is excluded. To enhance the transparency and repeatability of the research process, the specific inclusion and exclusion criteria are outlined in Table 2. Given that this study focuses on the application of teaching in school PE classes during the compulsory education stage, the intervention research conducted in colleges and universities or with adult groups is not included in the scope of this review due to the significant differences in teaching situations.

Table 2. Inclusion and Exclusion Criteria

Inclusion Criteria	
Topic:	Pedagogical applications of wearable technologies in school physical education
Language:	English
Publication Types:	Peer-reviewed journal articles
Data Range:	2000-2025
Study Type:	Empirical research (qualitative, quantitative, or mixed methods)
Setting:	Formal, school-based physical education classes (primary and secondary levels)
Target Participant:	School-aged students, PE teachers
Intervention Purpose:	Use of wearable technologies to support teaching strategies or learning outcomes
Exclusion Criteria	
Publication Types:	Conference abstracts, editorials, book reviews, dissertations, non-peer-reviewed works, grey literature
Setting:	Informal, extracurricular, elite training, clinical or university-based studies
Intervention purpose:	Use of wearables solely for health monitoring or technical validation
Study Focus:	Studies without analysis of teaching strategies or pedagogical outcomes

Literature Selection

This study strictly follows the PRISMA 2020 system overview reporting guidelines, and its screening process is shown in Figure 1 (Page et al., 2021). In the initial stage, 10,523 documents were retrieved through five databases, and the document management software Zotero was uniformly introduced for sorting and preliminary weighting (Gee, 2024). After the automatic removal of duplicate records (n = 493), the remaining 10,030 documents were imported into Rayyan, a system review collaboration platform, and entered the formal screening link (Siddaway et al., 2019).

Two authors jointly conducted the literature screening, using independent double review and discussion. Both reviewers screened each record based on predefined inclusion and exclusion criteria in the title and abstract phase. Uncertain or conflicting cases were marked using Rayyan's "maybe" function, then resolved through discussion (Kellermeyer et al., 2018). At this stage, 9,871 irrelevant records were excluded, leaving 159 articles for full-text review. During full-text screening, both authors made independent judgments again, using Rayyan's "conflict" alerts to resolve any disagreements. One additional relevant study was identified through a literature search. Finally, 12 studies met all criteria and were included in the synthesis. This review followed a two-person screening protocol supported by Rayyan's conflict resolution tools to ensure transparency, consistency, and reproducibility.

Quality Appraisal

This review used the Mixed Methods Appraisal Tool (MMAT, 2018) to assess all 12 included studies to ensure research quality and analytical credibility. MMAT is suitable for evaluating qualitative, quantitative, and mixed-method designs, matching the diversity of the selected literature (Hong et al., 2018). Two authors independently conducted the appraisal after agreeing on scoring criteria. Each study was assessed using five design-specific questions, rated as "yes," "no," or "cannot tell." (See Appendix A) Discrepancies were resolved through discussion, and all results were documented in a standardised scoring table. Notably, no studies were excluded based on quality scores; instead, the ratings informed the interpretation of findings to enhance credibility (Souto et al., 2015). Using MMAT adds methodological transparency and rigour to this review (Hong et al., 2019). MMAT results are used to control the certainty of conclusions: if a topic mainly comes from multiple "unjudged/unsatisfied" studies, we will regard it as a preliminary discovery and express it more carefully in the discussion.

Data Extraction and Synthesis

In this study, a systematic review with narrative synthesis was employed to investigate the impact of wearable technologies on students' motivation, participation, and learning outcomes in physical education. Key information—including study aims, device types, research designs, and contexts—was extracted from 12 included studies to establish a systematic analytical basis (see Appendix B) (Page et al., 2021; Souto et al., 2015).

Given the substantial heterogeneity in study designs, samples, and wearable devices, conducting a statistical meta-analysis was not appropriate (Keogh et al., 2021; Siddaway et al., 2019). Instead, a narrative approach was adopted to synthesise findings across studies. Each article was coded in Microsoft Excel 16 according to its objectives, methods, and key outcomes, allowing recurring patterns and thematic similarities to be identified across different educational contexts. This process enabled the comparison of convergent and divergent findings, revealing consistent trends in how wearable technologies support student motivation, participation, and skill development (Hong et al., 2019). Results were therefore reported descriptively, with an emphasis on pedagogical implications and directions for future research.

This review establishes a standardized data extraction table in Microsoft Excel and first selects a small number of them to be included in the literature for trial extraction to unify the field meaning and extraction rules. The extracted content includes: author and year, research country and school situation, sample characteristics, such as grade/age/number of people, research design and duration, wearable device type and data indicators, teaching purpose and teaching strategy, such as feedback, goal setting, gamification, self-monitoring, etc., outcome indicators, such as, motives, participation, classroom activity volume, learning-related results, and core findings related to research problems. The first author completes the data extraction of all literature, and the second author checks the extraction results item by item. When differences arise, an agreement is reached through discussion, and the extraction rules are refined as needed.

To enhance the trustworthiness of the synthesis, all identified themes were reviewed through team discussions to ensure the evidence well supported them. Following this iterative process, three core themes were confirmed: (1) the application of wearable technology in physical education; (2) its role in enhancing student motivation and participation; and (3) the use of wearable devices to provide personalised feedback.

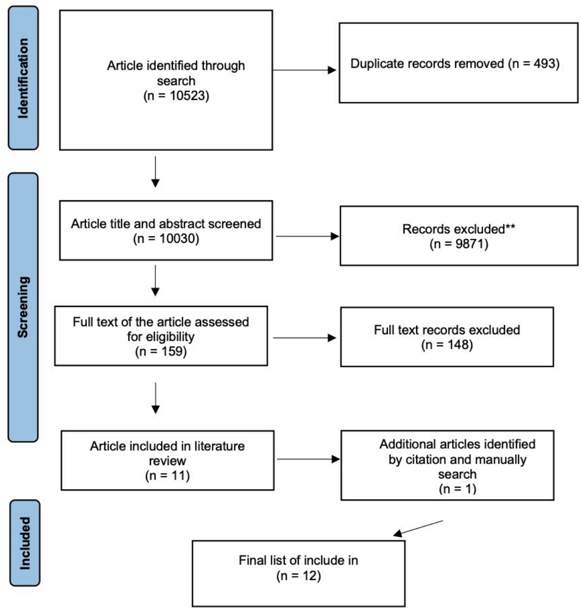

Fig. 1. PRISMA flow chart

Results

This review encompassed a total of 12 empirical studies on wearable technology in school PE classrooms. The research designs included quantitative description, qualitative interviews with control trial teachers, and a small number of mixed methods and technology evaluation studies (Almusawi et al., 2021; Boiché et al., 2020; Cunningham-Rose et al., 2024; Gråstén et al., 2019; Guijarro-Romero et al., 2025; Layne et al., 2022; Lindberg et al., 2016; Sit et al., 2019; Smith et al., 2019; Stöckel & Grimm, 2021; Wort et al., 2021; Zhang & Wang, 2024) The device includes heart rate monitoring, accelerometers/activity trackers, pedometers, and smart sports glasses, etc. The results are presented according to the three themes of the original draft.

The Application of Wearable Technology in Physical Education

Wearables were rarely used as pedagogy in isolation; instead, they were integrated into existing teaching structures (Layne et al., 2022; Cunningham-Rose et al., 2024; Guijarro-Romero et al., 2025). When wearable data are used to communicate clear lesson intentions and provide understandable performance information, they can function as competence-supportive scaffolds. For example, investigate the influence of heart rate projection on classroom effort (Cunningham-Rose et al., 2024), integrate the heart rate system with the sports education model and evaluate classroom activity volume and rope skipping performance (Layne et al., 2022), it provides real-time heart rate feedback in the classroom and simultaneously measures physiological and motivational indicators (Stöckel & Grimm, 2021). Studies mainly based on accelerometers have mostly been used to objectively measure MVPA sedentary time or activity patterns, and to investigate the relationship between these indicators and classroom/school context (Boiché et al., 2020). In addition, a group randomized controlled trial evaluated the effect of gamified interval units on students' weekly activity levels (Guijarro-Romero et al., 2025). Technology integration research also includes classroom solutions for wearable motion-sensing games (Lindberg et al., 2016) and classroom evaluation based on real-time feedback from smart glasses (Zhang & Wang, 2024). Research indicates that the implementation of wearable devices is significantly influenced by teacher readiness resource conditions and classroom feasibility (Almusawi et al., 2021; Wort et al., 2021).

The teacher's perspective study points out that the implementation of wearable devices is significantly affected by teachers' readiness, resource conditions and classroom feasibility (Almusawi et al., 2021; Wort et al., 2021). If teachers lack time, confidence, or data interpretation routines, wearable integration may become fragmented and harder for students to understand, limiting its pedagogical value (Almusawi et al., 2021; Wort et al., 2021).

Improving Motivation and Participation

The research results indicate that wearable technology can indeed enhance students' participation motivation and activity input to a certain extent in PE classes, primarily through real-time feedback that concretises and visualises sports efforts, thereby improving students' perception of their own performance (Stöckel & Grimm, 2021; Wort et al., 2021). When such technologies are combined with gamified design or clear goal setting, it becomes easier for students to understand classroom requirements and maintain participation, especially in the short term, resulting in a higher level of activity (Guijarro-Romero et al., 2025; Viciana et al., 2019).

There are two main ways to present motivation and participation in research: one type reflects classroom effort and participation (such as heart rate interval time and moderate-to-vigorous physical activity, or MVPA) through objective intensity/activity indicators; the other directly measures motivation or motivation-related variables. The heart rate projection study reported classroom intensity and effort indicators (Cunningham-Rose et al., 2024), and the real-time heart rate feedback study also reported the results of psychophysiology and motivation (Stöckel & Grimm, 2021). Research shows that motivation variables are related to school activities measured by accelerometers (Boiché et al., 2020), and SDT-related variables can predict physical education classes and total MVPA (Gråstén et al., 2019). Additionally, studies have examined the differences in activity patterns of depicting school hours (including physical education) among various groups and under different seasonal conditions (Sit et al., 2019). Technology integration research also reveals classroom effects, including "learning experience/sense of participation" and "learning-related results" (Lindberg et al., 2016; Zhang & Wang, 2024).

However, this motivational improvement is not stable or universal, and its effect is highly dependent on the logic of using teaching situations and techniques. Many studies have shown that when wearable technology is used to compare, rank, or continuously monitor student behaviour, the motivation structure in the classroom may shift from interest- and experience-oriented to data-driven and externally controlled (Kerner & Goodyear, 2017). In this case, although students may temporarily increase the amount of activity, it is accompanied by a decrease in stress, anxiety and motivation, weakening the autonomy and positive experience that should have been emphasised in PE classes.

Providing Personalised Feedback through Wearable Devices

The research results indicate that wearable technology offers a new support pathway for differentiated teaching, formative evaluation, and students' self-regulation in PE classrooms through real-time and personalised data feedback (Goodyear et al., 2019; Wort et al., 2021; Zhang & Wang, 2024). When feedback is directly related to students' own performance, it is easier for students to understand learning goals and adjust behaviour, thus improving skill learning efficiency and classroom participation to a certain extent (Goad et al., 2019; Cunningham-Rose et al., 2024). This mechanism enables students to gradually participate in the self-regulated learning process, no longer relying entirely on the teacher's immediate instructions.

The most consistent function of cross-research is "feedback," including classroom real-time intensity feedback, activity feedback, and action/posture feedback. Heart rate projection provides real-time visual data and collects effort indicators accordingly (Cunningham-Rose et al., 2024); real-time heart rate feedback research takes data as part of the classroom experience and evaluates relevant results (Stöckel & Grimm, 2021); The integrated research of sports education model uses the heart rate system for classroom monitoring and connects it to the evaluation of activity and skill performance (Layne et al., 2022). The study of smart glasses uses real-time posture feedback in the classroom and reports skill-related results (Zhang & Wang, 2024). Device measurement research reveals differences in the accuracy of pedometers across various action tasks, suggesting that the step index may be unstable in certain physical education class contents (Smith et al., 2019). Teacher research also highlights that data can be of potential value for feedback and informed decision-making in teaching, but the feasibility of implementation and the ability to interpret data are key conditions (Wort et al., 2021; Almusawi et al., 2021).

However, research also clearly shows that the teaching value of personalised feedback is not automatically generated by technology. First of all, the data generated by wearable devices is not equivalent to the quality of learning. Its measurement results have obvious situational limitations. If they are directly used to evaluate students' performance, it is easy to simplify or even misjudge the learning process

(Smith et al., 2019). Secondly, students' ability to understand data is not a priori, and the lack of teaching-guided data feedback may be transformed into a cognitive burden, thus weakening their original intention to support learning (Casey et al., 2017; Creaser et al., 2022).

Discussion

The results of this review indicate that wearable technology is more akin to a "classroom infrastructure" than a neutral teaching tool in school physical education classes. It often enters the classroom through the data process of "monitoring-feedback-display" and affects how teachers organize teaching, how students understand effort and performance, and how classroom relationships are redefined (Layne et al., 2022; Cunningham-Rose et al., 2024; Wort et al., 2021). Therefore, we need to analyze this phenomenon using a theoretical framework that can explain why the same technology produces different consequences in different classrooms. Self-determination theory (SDT) provides a clear entry point: whether technology truly promotes learning, the key is not the equipment itself, but whether it supports or hinders students' autonomy, sense of competence, and relationships in the classroom (Deci & Ryan, 2000). From this perspective, your three themes are not simply the linear logic of "application-effect-feedback", but three groups of motivational mechanisms that may reinforce or offset each other.

In teaching integration and teaching strategy, the study generally points out that wearable devices rarely constitute teaching methods alone, but are superimposed on existing teaching structures, such as sports education models, game units, or intensity-centered lessons (Layne et al., 2022; Guijarro-Romero et al., 2025; Cunningham-Rose et al., 2024). The critical point of SDT is that this "superposition" does not necessarily mean better learning. It may not only provide clear goals and informative feedback to support the sense of competency; it may also become a fragmented monitoring process due to teachers' lack of data explanation and classroom routines but also increase students' confusion and pressure (Almusawi et al., 2021; Wort et al., 2021). More importantly, there is a natural risk of a mismatch between equipment indicators and classroom tasks. The underestimation of pedometers in non-walking tasks reminds us that data is not equivalent to effort, let alone the quality of learning; once teachers or students regard data as "expressing the truth", the sense of competence may be continuously frustrated by wrong feedback (Smith et al., 2019). This means that in practice, "technical integration" must be redefined as a teacher's professional judgment ability: teachers need to know when data is informational support and when it is just noise; and they should be able to put the data back into the teaching objectives and action tasks to explain, instead of letting the data reverse define that the classroom should teach What (Casey et al., 2017).

Motivational engagement and participation are most likely to be misinterpreted because some studies have indeed reported higher intensity indicators or higher MVPA, especially in the context of heart rate projection or gamification design (Cunningham-Rose et al., 2024; Guijarro-Romero et al., 2025). However, according to the SDT, a more crucial question arises: What is the quality of motivation underlying the same greater effort? If the data presentation in the classroom resembles a publicly visible supervisory device, students may increase their intensity due to the pressure of being evaluated, which is closer to controlled motivation. It may seem effective in the short term, but in the long run, it may weaken autonomy and continuous participation (Deci & Ryan, 2000) This is also why critical research would remind us that heart rate monitoring and feedback loops may reshape classroom power relations, slide physical learning towards data compliance, and impose an additional burden on students who are unwilling to be shown or perform poorly (Esmonde, 2019) Meanwhile, the research also suggests that there is a connection between motivational variables and objective activity levels, and the differences are presented among different groups (Boiché et al., 2020; Gråstén et al., 2019). This means that, at the practical level, one should not merely focus on increasing the intensity but rather pay more attention to how to make students feel that they have the choice and ability to be accepted through classroom language, goal setting, and interaction methods. If the main consequence of using technology is comparison rankings or implicit humiliation, then even MVPA Ascent may also come at the expense of autonomy and a sense of relationship, ultimately being detrimental to learning and long-term sports engagement (Kerner & Goodyear, 2017).

Personalized feedback and data evaluation are the most educational and critical parts of wearable technology. Whether it is heart rate real-time feedback, intensity interval visualization, or posture feedback provided by smart glasses, the core is to transform "imperceptible performance clues" into actionable feedback, so as to support a sense of competence and self-regulation (Stöckel & Grimm, 2021; Zhang & Wang, 2024). However, personalized feedback is not inherently equivalent to "learner centered." When feedback is overly dataized or bound to evaluation, it may change from "promoting understanding and improvement" to "code of conduct and performance monitoring", which will frustrate autonomy and make students treat data as objects to be judged rather than self-regulating resources (Kerner & Goodyear, 2017; Esmonde, 2019). In addition, data-driven feedback also raises privacy and ethical concerns, especially in the K-12 scenario, where the scope, storage, and use boundaries of data are unclear, directly affecting students' psychological safety and participation experience (Jovanovic & Kay, 2022). Therefore, the practical significance can be very specific: teachers should position wearable data as auxiliary evidence for formative evaluation, not the basis for scoring; at the classroom level, give priority to the strategy of "private feedback, goal selection, and emphasis on progress" to protect autonomy and relationship; at the school level, clear consent mechanisms and data are needed. Access and storage rules and improve data literacy and interpretation ability through teachers' professional development, otherwise technology is easy to slide from "supported learning" to "defined learning" (Almusawi et al., 2021; Wort et al., 2021; Goodyear et al., 2019). Overall, this review supports a "cautious and optimistic" conclusion: the educational value of wearable technology stems from the teaching mechanism that requires support, rather than from more intensive data production.

Conclusion

This system review shows that wearable technology has the potential to support differentiated teaching, formative evaluation and student self-regulation in PE, especially promoting student participation and skill learning through personalized feedback. However, its teaching effectiveness does not come from technology itself but depends on how teachers interpret and use data. A key contribution of this review is that we move beyond describing devices and instead explain how wearables work in PE through a simple mechanism-and-conditions lens. Across studies, wearables matter mainly because they change feedback, make lesson goals more visible, and increase the visibility of performance data. Using SDT, we show that these pathways shape students' autonomy, competence, and relatedness, which helps explain why similar technologies produce mixed outcomes (Deci & Ryan, 2000). Wearables are most likely to support PE aims when data are used as formative feedback, metrics fit the task, and routines protect privacy and inclusion; they are more likely to hinder learning when data are used for ranking, comparison, or control (Esmonde, 2019; Smith et al., 2019; Wort et al., 2021). Therefore, wearable technology should be used as an auxiliary tool to serve teaching judgment, not a mechanism to dominate classroom operation. Future research needs to pay more attention to its teaching integration method and the ethical boundaries of data use.

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Ethics Approval

Ethical approval was not required for this study, as it is a systematic review based exclusively on previously published and publicly available data.

Informed Consent

Not applicable.

Data Availability Statement

All data analyzed in this study are derived from published sources cited in the reference list. No new datasets were generated.

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Conflict of Interest

The authors declare no conflicts of interest.

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Appendix A. Mixed Methods Appraisal Tool

Category of study designs	Methodological quality criteria	Almusawi et al. (2021)	Cunningham-Rose et al. (2024)	Gråstén et al. (2019)	Boiché et al. (2020)	Lindberg et al. (2016)	Sit et al. (2019)	Guijarro-Romero et al. (2025)	Layne et al. (2022)	Stöckel and Grimm (2021)	Wort et al. (2021)	Zhang and Wang (2024)	Smith et al. (2019)
Screening	S1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
questions	S2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Qualitative	1.1	Y									Y		
	1.2	Y									Y		
	1.3	Y									Y		
	1.4	Y									Y		
	1.5	Y									Y		
Quantitative	2.1							Y	Y	Y			
randomized	2.2							Y	Y	Y			
controlled trials	2.3							Y	Y	Y			
	2.4							Y	C	C			
	2.5							Y	Y	Y			
Quantitative	3.1					C							C
non-randomized	3.2					Y							Y
	3.3					Y							Y
	3.4					C							N
	3.5					Y							Y
Quantitative	4.1			Y	Y		Y					C	
descriptive	4.2			C	C		C					C	
	4.3			Y	Y		Y					Y	
	4.4			C	C		C					C	
	4.5			Y	Y		Y					Y	
Mixed methods	5.1		Y										
	5.2		Y										
	5.3		Y										
	5.4		C										
	5.5		Y										

Note: Y Yes, N No, C Cannot tell. S1: Are there clear research questions? S2: Do the collected data allow to address the research questions? 1.1: Is the qualitative approach appropriate to answer the research question? 1.2: Are the qualitative data collection methods adequate to address the research question? 1.3: Are the findings adequately derived from the data? 1.4: Is the interpretation of results sufficiently substantiated by data? 1.5: Is there coherence between qualitative data sources, collection, analysis, and interpretation? 2.1: Is randomization appropriately performed? 2.2: Are the groups comparable at baseline? 2.3: Are there complete outcome data? 2.4: Are outcome assessors blinded to the intervention provided? 2.5: Did the participants adhere to the assigned intervention? 3.1: Are the participants representative of the target population? 3.2: Are measurements appropriate regarding both the outcome and intervention (or exposure)? 3.3: Are there complete outcome data? 3.4: Are the confounders accounted for in the design and analysis? 3.5: During the study period, is the intervention administered (or exposure occurred) as intended? 4.1: Is the sampling strategy relevant to address the research question? 4.2: Is the sample representative of the target population? 4.3: Are the measurements appropriate? 4.4: Is the risk of nonresponse bias low? 4.5: Is the statistical analysis appropriate to answer the research question? 5.1: Is there an adequate rationale for using a mixed methods design to address the research question? 5.2: Are the different components of the study effectively integrated to answer the research question? 5.3: Are the outputs of the integration of qualitative and quantitative components adequately interpreted? 5.4: Are divergences and inconsistencies between quantitative and qualitative results adequately addressed? 5.5: Do the different components of the study adhere to the quality criteria of each tradition of the methods involved?

Appendix B. Summary of Data Extraction from Included Studies

NO	Author (Year)	Device(s)	Study Design	Sample & Context	Purpose	Main Findings
1	Layne et al. (2022)	Polar HRM; Accelerometer	Quantitative Randomised Controlled Trials	130 fourth-grade students (61Famle, 69Male)	Examine effects of Sport Education model + HRM on MVPA and jump rope performance	Sport Education Model+ HRM yielded higher MVPA and improved jump rope performance
2	Boiché et al. (2020)	Accelerometer	Quantitative Descriptive	319 middle school students (ages 9–13)	Explore links between motivation (SDT) and PA during PE	Motivation correlated more strongly with PA during active periods
3	CunninghamRose et al. (2024)	Polar H10 HR Monitor	Mixed Methods	20 students (12.3±0.9 years) in HIIT sessions	Assess impact of HR projection on exercise effort	HR projection increased peak HR and time in RED zone
4	Gråstén et al. (2019)	Accelerometer	Quantitative Descriptive	490 elementary students (264 Female,226 Male)	Relate motivational needs (SDT) to in-class & total MVPA	Social relatedness predicted total MVPA in girls; competence predicted in-class MVPA in boys
5	GuijarroRomero et al. (2025)	Accelerometer; Smartwatch	Quantitative Randomised Controlled Trials	203 primary students (9–12 years)	Evaluate gamified teaching unit effects on weekly MVPA	Gamified unit increased MVPA, steps, and adherence to guidelines
6	Lindberg et al. (2016)	Smartphone; Smart wristband	Quantitative non-randomised	61 third-grade students in South Korea	Evaluate “Running Othello 2” exergame with wearables	Exergame increased engagement, learning efficiency, and HR
7	Sit et al. (2019)	ActiGraph GT3X Accelerometer	Quantitative Descriptive	270 children with disabilities (9–12 years)	Explore seasonal PA & sedentary time variations at school	Higher MVPA in winter; no significant sedentary differences
8	Smith et al. (2019)	Pedometers	Quantitative non-randomised	53 5th–6th graders	Assess pedometer accuracy & metabolic cost of locomotor movements in the PE class	Accurate in walking; underestimated in skipping; higher cost for non-walking
9	Stöckel & Grimm (2021)	Polar H10 HR Monitor	Quantitative Randomised Controlled Trials	40 adolescents (16–17 years)	Test real-time HR feedback effects on motivation & effort	Increased enjoyment and intrinsic motivation in experimental group
10	Wort et al. (2021)	Moki Accelerometer	Qualitative	26 UK primary teachers	Explore teacher perspectives on wearable technology for PA practices	Positive acceptability; data interpretability; interest in reducing inequalities
11	Zhang & Wang (2024)	Sports Smart Glasses	Quantitative Descriptive	PE students in smart glasses sessions	Evaluate smart glasses for real-time monitoring & feedback	Improved motor skills, posture feedback, high student acceptance
12	Almusawi et al. (2021)	Smartwatches; Chest straps; VR setups	Qualitative	38 public school PE teachers in Kuwait	Explore PE teachers’ readiness for wearable tech integration	Identified eight readiness themes from attitudinal to environmental factors

Note: PA = physical activity; PE = physical education; HR = heart rate; HRM = heart rate monitor; MVPA = moderate-to-vigorous physical activity; HIIT = high-intensity interval training; SDT = Self-Determination Theory; VR = virtual reality

Носимі технології у шкільному фізичному вихованні: систематичний огляд педагогічних аспектів

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 11 с., 4 табл., 1 рис., 36 джерел.

Обґрунтування. Носимі технології, зокрема монітори серцевого ритму, акселерометри та фітнес-трекери, дедалі частіше інтегруються у шкільне фізичне виховання з метою вдосконалення навчальних стратегій, підвищення залученості учнів і забезпечення персоналізованого навчання. Водночас емпіричні докази їхньої педагогічної ефективності залишаються фрагментованими.

Мета. Метою цього систематичного огляду є узагальнення досліджень щодо застосування носимих технологій у шкільному фізичному вихованні з аналізом їх інтеграції в навчальні стратегії, впливу на мотивацію та участь учнів, а також використання персоналізованого зворотного зв’язку.

Методи. Систематичний пошук у базах Web of Science, Scopus, ERIC, SPORTDiscus та PsycINFO дозволив ідентифікувати 12 рецензованих досліджень, опублікованих у період з 2000 по 2025 рік. Методологічну якість досліджень оцінювали за допомогою інструмента оцінювання змішаних методів, після чого результати було синтезовано.

Результати. Носимі технології сприяли реалізації різноманітних навчальних стратегій, зокрема наданню зворотного зв’язку в реальному часі, самоконтролю, гейміфікації та постановці цілей. Їх використання підвищувало мотивацію й участь учнів, а також забезпечувало персоналізований зворотний зв’язок, хоча водночас було відзначено проблеми, пов’язані з конфіденційністю даних та етичними аспектами. Рівень цифрової грамотності вчителів і їхня педагогічна компетентність суттєво впливали на ефективність упровадження.

Висновки. Носимі технології мають значний педагогічний потенціал у шкільному фізичному вихованні, сприяючи підвищенню мотивації, участі та персоналізації навчання. Успішне впровадження потребує продуманого навчального дизайну, готовності вчителів і ретельного етичного управління даними учнів. Подальші дослідження мають бути спрямовані на вивчення довгострокових ефектів та моделей професійного розвитку педагогів.

Ключові слова: носимі технології, шкільне фізичне виховання, мотивація учнів, персоналізоване навчання, інтеграція технологій.

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The Effects of Structured School-Based Physical Activity on Fitness and Psychosocial Well-Being in Pre-Adolescents

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Abstract

Objectives. The study aimed to identify the impact of structured school-based physical activity program on physical fitness and psychosocial well-being of pre-adolescent students.

Materials and Methods. The quasi-experimental pre-test post-test control group research was utilized. Intact schools were used to assign a total of 100 and 120 students (between 10-12 years old), who were to be placed either in Intervention (n = 60) or Control group (n = 60). The intervention course was a 8-week structured physical activity programme carrying out three sessions a week (45 minutes/session), and involved progressive endurance, strength, agility and cooperative activities. The results of the physical fitness were aerobic endurance (PACER), muscular endurance (push-up test), and agility (pro-agility shuttle run). The variables based on psychosocial factors were estimated by self-perception, intrinsic motivation, peer support, and mental well-being through culturally adjusted and validated questionnaires. Data analysis was performed using paired t-tests, mixed ANOVA, and ANCOVA. Effect sizes and confidence intervals were also provided.

Results. The intervention group demonstrated statistically significant improvements across all physical fitness and psychosocial outcomes ($p < .01$), accompanied by large effect sizes (Cohen's $d > 1.60$; partial $\eta^2 > .40$). In contrast, the control group showed no statistically significant changes and negligible effect sizes. In addition, strong positive correlations were observed among psychosocial variables, suggesting coordinated improvements across psychological domains.

Conclusions. The findings of this study suggest that the structured school-based physical activity significantly enhances the physical fitness and psychosocial well-being of pre-adolescents, thus making it reasonable to incorporate it into the routine school programs.

Keywords: physical fitness, school-based intervention, psychosocial well-being, motivation, children.

Introduction

A child's regular participation in physical activities is a major contributor to their physical, mental, and social growth of the best quality. The current literature is unanimous in asserting that a regular asthmatic lifestyle (physical activity) leads to an increase in one's ability to run long distances, as well as muscular endurance, and a better overall ability to move, and at the same time, to a better emotional control, mental health, and social adaptability in the case of children and adolescents (Carson et al., 2016; Donnelly et al., 2016; Poitras et al., 2016). The above-mentioned advantages are grounded with empirical data but the worldwide monitoring data pointed out that a large portion of the children of school age do not reach the threshold of the recommended physical activities, especially in the developing countries and economies that are in transition (Guthold et al., 2020; Aubert et al., 2021). The trend of increasing physical inactivity has already raised a number of very serious concerns about the health, fitness, and psychosocial stress of people in the reducing age groups and about the risk of them getting sick early in life.

Schools are the most important places for such problems to be solved since they allow the establishment of an interface between children of different socioeconomic backgrounds. Physical activity programs at schools have been reported to yield benefits to children's cardiorespiratory endurance, muscular fitness, and basic movement skills if they were properly administered in terms of frequency and progression (Donnelly et al., 2017; Love et al., 2019). Besides the physical effects, being a part of school-based activity has been correlated with better cognitive functioning, self-esteem,

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intrinsic motivation, peer relationships, and emotional well-being, all of which contribute to holistic development and academic engagement (Lubans et al., 2016; Rodríguez-Ayllon et al., 2019; Lang et al., 2023).

The power of such projects can be explained through the widely accepted motivational theories, in particular, the self-determination theory (SDT), which perceives the satisfaction of the basic needs for autonomy, competence, and social involvement as the primary factors of long-lasting participation and psychological well-being (Deci & Ryan, 2017; Standage & Ryan, 2020). If the physical activity environments provide cooperation, gradual challenges and peer interaction as the main features, then not only will the children's intrinsic motivation be fostered but also the good self-images will be created (Vasconcellos et al., 2020; Owen et al., 2022). For instance, the pre-adolescence period can be marked with the multi-component training consisting of endurance, strength, agility, and cooperative play that will be highly effective since the kids at that age go through very fast and enormous physical and emotional changes.

The evidence from around the world has pointed to the advantages of physical activities in schools that are structured as they should be, however, there are still not many research works done in Indian contexts. A number of Indian schools are dependent on infrequent or unstructured physical education sessions, which do not allow a very limited opportunity for skill development or psychosocial growth (Singh et al., 2018; Kumar & Joshi, 2021). Furthermore, only a few empirical studies have tried to observe both physical fitness and psychosocial outcomes simultaneously among Indian pre-adolescent children. This, in turn, has left a very small evidence base that is necessary for the culturally relevant policy and curriculum decisions to be made (Sahoo et al., 2017; Ramesh et al., 2022). It is a pressing issue considering that the problem of physical inactivity, the pressure of academic workload, and mental health problems among Indian youngsters are increasingly getting the attention of researchers and practitioners alike (Patel et al., 2018; WHO, 2020).

It is, therefore, possible that the combined school-based programs focused on endurance, strength, agility, and teamwork could be a practical and large-scale solution for enhancing both the physical and mental aspects of children. The development of movement skill and physical fitness has been associated with the increase of self-perception, confidence, and social acceptance, which in turn, lead to better motivation and emotional health (Bailey et al., 2020; Cairney et al., 2019). Investigating the connections between psychosocial factors also sheds light on the situation whether the increase in motivation, self-belief, and mental health happens in a synchronized developmental pattern rather than being separate (Guérin et al., 2021; Mancini et al., 2024).

Therefore, the current research has been conducted with the goal of evaluating the effects of an eight-week structured school-based physical activity intervention on children's physical fitness (aerobic endurance, muscular endurance, and agility) and psychosocial outcomes—such as self-perception, intrinsic motivation, peer support, and mental well-being—among Indian pre-adolescent students. The combination of progressive physical challenges with socially supportive activities was the means through which the intervention provided a model that was both contextually relevant and feasible for enhancing youth health outcomes in school settings. The findings also add to the body of literature by providing empirical data from a non-Western educational context, thus filling a major gap in the current research on school-based physical activity.

Hypotheses

H1: Students in the intervention group will demonstrate significantly greater improvements in physical fitness (PACER endurance, push-up performance, and pro-agility speed) compared with the control group.

H2: Students in the intervention group will exhibit significantly greater improvements in psychosocial outcomes (self-perception, intrinsic motivation, peer support, and mental well-being) than students in the control group.

H3: Psychosocial variables will be positively correlated at post-test, indicating coordinated enhancement in self-belief, motivation, and emotional well-being.

Materials and Methods

Research Design and Participants

The study introduced a quasi-experimental, two-group pre-test-run experimental design to determine the impact of a designed physical activity program in school in increasing physical fitness and psychosocial success in pre-adolescent students. Intervention and Control groups were used to assign intact schools in order to prevent cross over of participants and also to ensure implementation fidelity. G*Power 3.1.9.7 (Faul et al., 2009) was run a priori; it was a mixed ANOVA with f = 0.30, 0.05, and an estimated desirable power of.80. Findings showed that 88 study subjects were needed. The last sample (N = 120) was above this number and this guaranteed sufficient statistical power to find significant effects. Since the cluster assignment would potentially create a dependency between scores, intraclass correlation coefficient (ICC) was considered. The ICC values on the key outcomes were less than .05 which mean that there was little impact of clustering. Because there were only two clusters (two schools), it was not possible to perform multilevel modelling, and analyses at individual level were kept. It is recognized that this, along with design considerations is a limitation to the project since small clustering effects might still be left. The participants had to be between the age of 10 -12, be in the Grade 5-7, and medically fit to undertake physical activity. Before collection of data, written parental permission and oral consent by the participants were secured. In the end, the sample was composed of students who had different levels of activity activities and socioeconomic backgrounds that reflected on the school population.

Intervention Protocol

The intervention plan was based on 3 supervised sessions a week with a 45 min long duration conducted by physical education teachers who undergo training. Session structure included: Warm-up (5 minutes): active stretching and rhythm aerobic to increase the pulse rate and prepare majorly muscle groups. Core activity (30 minutes): o Endurance exercises: modified PACER shuttle running with the increment in frequency and repetition. o Strength workouts: push-ups, planks, routine on resistance bands, and medicine-ball passes. o Agility race: 5-10-5 shuttle race, cone snowballs, and cooperative relay based. Cool-down (10 minutes):

Table 1. Description of Physical Fitness and Psychosocial Measures

Domain	Variable	Instrument / Test	Outcome / Unit	Reliability (α / r)
Physical Fitness	Aerobic Endurance	PACER Test (20-m shuttle run)	Total laps completed	r = 0.91
	Muscular Endurance	Push-Up Test (FITNESSGRAM protocol)	Number of correct repetitions	r = 0.89
	Agility	Pro-Agility 5-10-5 Shuttle Test	Time (s); lower = better	r = 0.87
Psychosocial	Self-Perception	Self-Perception Profile for Children	5-point Likert mean score	α = 0.86
	Intrinsic Motivation	Intrinsic Motivation Inventory (IMI)	5-point Likert mean score	α = 0.88
	Peer Support	Peer Support Scale for Children	5-point Likert mean score	α = 0.82
	Mental Well-Being	Warwick-Edinburgh Mental Well-Being Scale (Short Form)	Composite mean score	α = 0.90

Higher scores denote better performance or well-being. All measures demonstrated acceptable reliability (α / r ≥ 0.80). All psychosocial measures underwent linguistic and cultural validation to ensure appropriateness for Indian pre-adolescent students.

gentle stretching in position and facilitated breathing as a way of encouraging recovery and stimulating reflection. The intensity of the session was matched to the OMNI 10-point Rate of Perceived Exertion (RPE) scale (which targeted 5-7, i.e. moderate-vigorous). The developments were done weekly and involved an increase in repetitions, reduction of rest periods or create more difficult motion activities. Attendance and compliance were monitored by instructors. Control group carried on with the normal school activities without any physical training outside of regular physical activities.

Measures

The study assessed physical fitness (aerobic endurance, muscular endurance, and agility) using standardized field tests, and psychosocial functioning (self-perception, intrinsic motivation, peer support, and mental well-being) using validated questionnaires with acceptable reliability (α / r ≥ 0.80)(Table 1).

Procedure

There were baseline assessments (T1) that were done in the week before the intervention. The final week saw the post-test evaluations (T2) that were administered in the same procedures and evaluators. The testing was to be done in the morning hours so as to reduce fatigue. Anonymization and storage of all data were safe.

Statistical Analysis

The SPSS 27.0 was used to analyse the data. All variables were calculated using the descriptive statistics. Inferential testing was carried out after checking normality, homogeneity of variance and the outliers. Paired-sample t-tests were used to assess within-group changes, and mixed ANOVA and ANCOVA were done to assess between groups and take into consideration baseline values. Cohen d was used to report the effect size of t -tests, and partial 2 was used to report effect size of ANCOVA with the calculation of 95 a confidence interval (CI) to facilitate the interpretation of effect size. Even though the level of clustering was low (ICC < .05), its possible effect on the estimates of be it variance is recognized. The level of significance was determined to be p =.05 in which the adjustments were indicated where applicable.

Results

The Intervention and Control groups showed similar scores at the baseline, both at the physical fitness and

Table 2. Means and Standard Deviations of Study Variables at Pretest and Post test

Variable	Group	Pretest M ± SD	Post test M ± SD	Change (Δ)
PACER (laps)	Intervention	24.60 ± 10.2	39.10 ± 10.6	+14.5
	Control	24.80 ± 9.8	26.00 ± 10.0	+1.2
Push-Up (reps)	Intervention	12.30 ± 5.1	21.50 ± 5.8	+9.2
	Control	13.00 ± 5.3	14.20 ± 5.5	+1.2
Pro-Agility (sec)	Intervention	19.70 ± 1.8	17.90 ± 1.7	-1.8
	Control	19.60 ± 1.8	19.30 ± 1.8	-0.3
Self-Perception	Intervention	2.95 ± 0.68	4.05 ± 0.61	+1.10
	Control	3.15 ± 0.66	3.27 ± 0.65	+0.12
Intrinsic Motivation	Intervention	3.02 ± 0.73	4.28 ± 0.58	+1.26
	Control	3.08 ± 0.71	3.24 ± 0.70	+0.16
Peer Support	Intervention	3.15 ± 0.66	4.32 ± 0.53	+1.17
	Control	3.40 ± 0.64	3.55 ± 0.62	+0.15
Mental Well-Being	Intervention	13.90 ± 3.3	20.20 ± 3.5	+6.3
	Control	14.80 ± 3.4	15.90 ± 3.3	+1.1

Values are mean ± standard deviation. Positive Δ values indicate improvement; negative Δ (Pro-Agility) indicates faster performance. Significance level α = .01 (two-tailed).

psychosocial scales. The beneficial effects of the eight-week intervention on the Intervention group were significant in the endurance, muscular endurance, agility, and the psychosocial indicators, but the changes were very slight in the Control group.

The Intervention group recorded significant differences in all the physical and psychosocial measures between pre- and post-tests compared to the Control group who showed small variations as indicated in Table 2. These trends show that the routine of schools was not adequate to bring meaningful development without formatted activity.

The comparisons made between pre-test and post-test showed significant impact of Intervention on all physical fitness and psychosocial outcomes ($p < .001$). The effect sizes were between d =1.62 and d=2.21 which shows big practical improvements that support intensive and structured training. These effects were corroborated by confidence intervals (95% CI), which showed there was strong positive change in all measures. However, by contrast, the Control group showed the small non-significant changes (all $p > .05$), which points to the inability of regular school activities to have a significant impact.

Table 3. Paired-Sample t-Test Results for Within-Group Changes

Variable	Group	$t_{(59)}$	p	Cohen's d
PACER (laps)	Intervention	16.27	< .001	2.10
Push-Up (reps)	Intervention	14.93	< .001	1.92
Pro-Agility (sec)	Intervention	11.86	< .001	1.53
Self-Perception	Intervention	13.45	< .001	1.74
Intrinsic Motivation	Intervention	12.88	< .001	1.68
Peer Support	Intervention	11.62	< .001	1.50
Mental Well-Being	Intervention	15.07	< .001	1.95
Control (all variables)	-	ns	> .01	-

Two-tailed significance α = .01. p < .001, p < .01, ns = not significant

Table 3 presents statistically significant changes in outcomes of all Intervention group (all $p < .001$, $d > 1.60$) with reference to strong physiological and psychosocial adaptation. There were no media changes in the Control group. These results support the quality of the designed program. ANOVA and ANCOVA adjusted on the values at baseline indicated that there were significant Group x Time interactions in all resultant outcomes (all p =.001). Adjusted means of post-tests were always better than control group in terms of physical fitness and psychosocial constructs. The values of partial eta 2 were between.42 and.58 indicating very high effects.

Even though the size of effects was high, 95% CI and adjusted models justify its validity. The observed magnitudes can be indicators of high levels of adherence, intense session and novelty of some structured program in the school setting. Minor values on ICC (< .05) limit interest in the possibility of clustering bias.

As shown in Table 4, the Intervention group obtained much greater adjusted post-test means in all the outcomes. Partial η^2 values of 0.40 and above represent extremely large practice effects. With the results, the study ascertains the intervention as having a powerful and independent effect on top of differences in the baseline. Post test psychosocial

Table 4. ANCOVA Results Comparing Post-test Scores Between Groups

Variable	$F_{(1,117)}$	p	Partial η^2
PACER (laps)	59.41	< .001	0.51
Push-Up (reps)	54.86	< .001	0.48
Pro-Agility (sec)	43.12	< .001	0.42
Self-Perception	38.74	< .001	0.40
Intrinsic Motivation	45.62	< .001	0.44
Peer Support	47.85	< .001	0.45
Mental Well-Being	63.23	< .001	0.52

Post-test group means adjusted for pretest scores. Significance level α = .01 (two-tailed). p < .001. Partial η^2 indicates effect size magnitude

variables demonstrated strong positive relationships revealed on Pearson correlations (Table 4). Greater self-perception related to more intrinsic motivation (r = .81), peer support (r =.67) as well as mental wellbeing (r = .78). These findings suggest a combination of psychosocial enhancement, which confirms the hypothesis of the changes to happen in a correlated trend.

Table 5. Intercorrelations Among Psychosocial Variables at post-test

Variable	1	2	3	4
1. Self-Perception	-	.81	.76	.78
2. Intrinsic Motivation		-	.79	.74
3. Peer Support			-	.72
4. Mental Well-Being				-

Pearson r coefficients (two-tailed). p < .001.

Table 5 shows that there are strong positive relationships between psychosocial constructs. There were especially strong correlations between self-perception and intrinsic motivation and mental well-being. The findings imply the need to mutually support psychological benefits and consistent psychosocial growth after the intervention.

Figure 1 presents the interaction between the Group and Time on PACER, push-up performance and mental well-being. The Intervention group indicates strong positive trends in all the outcomes and the Control group indicates no or slight increase. This visual effect is a clear back-up of the statistical results of the significant effects of intervention.

The organized physical activity program held in school brought about notable effects in all physical fitness and psychosocial fitness among pre-adolescent students. These findings are robust with big effect sizes, which are supported by adjusted models and confidence intervals. The slight alterations in the Control group once again confirm that the normal school schedules in themselves were not good enough to generate the same benefits.

Discussion

The present investigation studied the impact of an 8-week structured physical activity program in school on the fitness and psychosocial health of youngsters aged 11-12 years. The

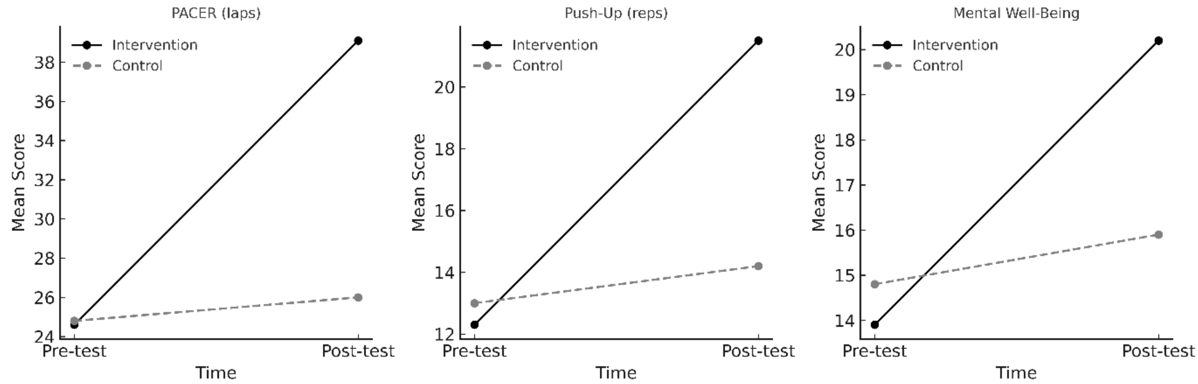

Fig. 1. Group × Time Interaction for PACER, Push-Up, and Mental Well-Being scores

results showed that the pupils in the Intervention group had significantly higher increases in aerobic endurance, muscular endurance, and agility than the pupils in the Control group, who only had slight and non-significant changes. The new evidence is in line with the already existing and strong body of evidence that structured, age-appropriate physical activity programs rolled out in school settings can significantly improve the basic physical fitness components in children. The magnitude of change is highlighted by large effect sizes and narrow confidence intervals, implying that the intervention was powerful enough to create a training stimulus that triggered meaningful physiological adaptations.

In addition to physical benefits, the research also suggested a lot of improvements in the psychosocial aspects such as self-acceptance, internal drive, support from friends, and mental health. The results are in agreement with the Self-Determination Theory, which claims that the learning settings allowing for autonomy, skill, and social connection are the main sources of intrinsic motivation and good psychological functioning in children and teenagers (Deci & Ryan, 2017; Standage & Ryan, 2020). The main features of the intervention were the progressive challenges, cooperative activities, and peer-supported tasks, which probably catered to the psychological needs and thus were responsible for the favorable psychosocial outcomes. In the literature, similar effects have been observed in previous school-based interventions that reported the benefits of motivating, self-esteem, and emotional well-being improvements through structured physical activity (Lubans et al., 2016; Owen et al., 2022).

The very strong positive correlations between psychosocial constructs that were observed point to the same conclusion that there was a coordinated improvement in the self-perception, motivation, and mental well-being of the participants. This was already implied by the current physical literacy models which state that the physical ability, self-confidence, and motivation to be active grow together to promote the long-term participation in physical activities (Cairney et al., 2019; Bailey et al., 2020). Such relationships stressed the fact that physical activity interventions should not be considered just fitness enhancement tools but rather as all-around approaches to the development of social and emotional skills during critical periods of growth.

Even though the intervention's effects were massive, different contextual factors could be the reason behind the size of the effects. The structured program in itself was a significant increase in the amount of activity done compared to the usual school physical education practices, which can be a reason for the higher responsiveness to training (Love et al., 2019). Also, very little prior exposure to organized physical activity and rather low baseline variability among the participants might have had a hand in the larger standardized effect sizes, as indicated in similar studies of youth-based Intervention (Rodríguez-Ayllon et al., 2019; Vasconcellos et al., 2020). However, the fact that there were consistent improvements in different physical and psychosocial domains gives more confidence in the effectiveness of the intervention.

Significantly, the current study's results broaden the very scant evidence coming from Indian school settings where often structural limitations, curricular priorities, and a lack of instructional time keep systematic physical activity restricted (Singh et al., 2018; Kumar & Joshi, 2021). The substantial progress made in both physical fitness and psychosocial wellness is an endorsement of the coexistence and the necessity of structured physical activity programs in the mainstream school schedules. Their coexistence is in agreement with the global and national prescriptions that support school-based strategies to counteract the declining physical activity levels and the growing mental health issues of the young people (Guthold et al., 2020; World Health Organization, 2020).

Conclusions

The school-based physical activity intervention that was institutionalized had a major influence on both physical fitness and psychosocial health of the elementary school children. The kids not only became more physically active and fit, but also more confident, motivated, supported by peers, and mentally healthy. This indicates that school, where the above mentioned positive psychosocial changes took place, can be a good environment for physical activity implementation that is progressive and socially facilitating, and even medium-period interventions can offer great improvements. The simultaneous increasing of psychosocial results also indicates the organized activity's potential in promoting the whole child development in the school setting.

The findings have clear practical implications for school practice and educational policy. The results support the curricular integration of structured physical activity programs (40–45 minutes, three times per week) with a progressive focus on endurance, strength, and agility. Effective implementation requires targeted professional development for physical education teachers, particularly in applying Self-Determination Theory–based strategies that foster autonomy, competence, and relatedness. Given the minimal equipment requirements, the program is feasible within existing school infrastructure and scalable across educational settings. Moreover, the integration of cooperative tasks and reflective activities may contribute to holistic development by simultaneously enhancing physical fitness and psychosocial well-being. At the policy level, these findings align with national and international initiatives promoting comprehensive school-based health and wellness frameworks.

Ethical Approval Statement

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (2013 revision). Ethical approval was obtained from the Institutional Research Ethics Committee of Hindustan Institute of Technology and Science, Chennai, India (Approval ID: HITS/CRC/004/20603034). Written informed consent was obtained from the parents or legal guardians of all participating students prior to data collection. In addition, age-appropriate oral assent was obtained from the students themselves. All procedures were designed to ensure the confidentiality, anonymity, and voluntary participation of the participants.

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Conflict of Interest

The authors declare that there are no financial or non-financial conflicts of interest related to this study.

AI Transparency Statement

The authors declare that no generative artificial intelligence tools were used in the design of the study, data collection, data analysis, interpretation of results, or preparation of the manuscript.

Data Availability Statement

The data supporting the findings of this study are not publicly available due to ethical and privacy considerations related to research involving minors. De-identified data may be made available from the corresponding author upon reasonable request and subject to approval by the relevant ethics committee.

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Вплив структурованої шкільної фізичної активності на фізичну підготовленість та психосоціальне благополуччя дітей передпідліткового віку

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Реферат. Стаття: 8 с., 5 табл., 1 рис., 26 джерел.

Цілі. Дослідження мало на меті визначити вплив структурованої шкільної програми фізичної активності на фізичну підготовленість та психосоціальне благополуччя учнів передпідліткового віку.

Матеріали та методи. Застосовано квазіекспериментальне дослідження з контрольною групою, що включало проведення претесту та посттесту. Загалом було залучено 100 та 120 учнів (віком від 10 до 12 років) з інтактних шкіл, яких розподілили на інтервенційну ($n = 60$) та контрольну ($n = 60$) групи. Курс інтервенції складався з 8-тижневої структурованої програми фізичної активності, що проводилася тричі на тиждень (45 хвилин/заняття) і включала в себе прогресивні вправи на витривалість, силу, спритність та кооперативні активності. Результатами фізичної підготовленості були аеробна витривалість (PACER — тест з бігу для визначення прогресивної аеробної серцево-судинної витривалості), м'язова витривалість (тест на віджимання) та спритність (човниковий біг). Змінні, засновані на психосоціальних факторах, оцінювалися через самосприйняття, внутрішню мотивацію, підтримку однолітків та психічне благополуччя шляхом використання культурно адаптованих та валідованих анкет. Аналіз даних проводився за допомогою t-критеріїв для парних вибірок, змішаного дисперсійного та коваріаційного аналізів. Також наведено розміри ефекту та довірчі інтервали.

Результати. Група втручання продемонструвала статистично значущі покращення за всіма показниками фізичної підготовленості та психосоціальними результатами ($p < .01$), що супроводжувалися великими розмірами ефекту (d Коена > 1,60; часткова $\eta^2 > .40$). Натомість у контрольній групі статистично значущих змін не виявлено, а розміри ефекту були незначними. Крім того, між психосоціальними змінними спостерігалися сильні позитивні кореляції, що свідчить про скоординовані покращення в межах психологічних доменів.

Висновки. Результати цього дослідження показують, що структурована фізична активність на базі шкіл значно покращує фізичну підготовленість та психосоціальне благополуччя дітей передпідліткового віку, тому є доцільним її впровадження до стандартних шкільних програм.

Ключові слова: фізична підготовленість, інтервенція на базі шкіл, психосоціальне благополуччя, мотивація, діти.

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Understanding the Relationship between Self-esteem and Motor Creativity in Ecological PE Contexts at Adolescence

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Abstract

Background. In current studies, it is generally admitted that creativity is an important asset in performing in sports and Physical Education (PE). Based on the multivariate framework, authors have also investigated the influence of motivation, intelligence and cognitive abilities on creative motor performance. However, data surrounding self-esteem and its association with motor performance in ecological domains is scant.

Objectives. This study aimed to understand the relationship between self-esteem and motor creativity, focusing on ecological motor contexts in PE at adolescence.

Materials and Methods. The experiment population comprised three groups of 20 children in total (N= 60), with 31 girls and 29 boys aged 12 years old. First, self-esteem was assessed using the Rosenberg Self-Esteem Scale (RSES), which demonstrated excellent internal consistency in the sample (Cronbach's α = .94). Subsequently, participants engaged in a 20 minute ecological game task called "Sitting ball". Rooted in the multivariate framework, the study measured motor fluency and flexibility by using praxic communication as key indicators of creativity. Once the data was gathered, a factorial analysis was put into place using the Trideux.cloud tool to establish the relationship between self-esteem and motor creativity.

Results. The factorial map indicates that self-esteem levels are correlated to motor creativity scores in ecological situations. Analysis conducted at the individual level (N = 60) using a Pearson correlation calculation confirmed these results, associating self-esteem and ecological motor creativity positively with r = .734. Moreover, the findings are statistically significant as the 95% confidence intervals (CI) for self-esteem were between 21.55–25.81 and 48.43–57.90 for ecological motor creativity. The intervals are sufficiently narrow to indicate good precision of the estimated means and results.

Conclusions. This study revealed that creative motor abilities seem to be highly related to self-esteem. Low self-esteem levels tend to be strongly linked to weaker motor creativity performances and strong self-esteem levels relate to increased motor creativity. The present novel ecological framework underlines the pedagogical importance of assessing and understanding such intrapersonal characteristics in order to favor motor development and well-being in PE.

Keywords: creativity, physical education, motor performance, self-esteem, adolescents.

Introduction

Nowadays, creativity is considered to be a desirable asset in sports and Physical Education (PE) to improve performance (Büning et al., 2020; Oboeuf et al., 2024). Indeed, creativity is often described as the skill to perform new, original work in a meaningful environment (Runco & Jaeger, 2012). Moreover, it is the ability to express numerous and different answers (divergence) while being capable of selecting the optimal one (convergence) to solve a problem (Hatchuel & Weil, 2009; Zhang et al., 2020). In line with these definitions of creativity, creative motor performance refers to the capacity of one or several individuals to produce a solution that is both novel and appropriate in a motor situation (Oboeuf et al., 2020). In PE, motor "productions" are carried out "in real life", requiring in-situ interaction with the physical and social environment (Besançon & Lubart, 2011). Consequently, creative performance in PE is strongly linked to the task and domain of activity in which the individual is immersed

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(Memmert, 2015). For instance, performing creatively in team sports such as football requires different cognitive, emotional or motor abilities than in boxing or track and field (Lubart et al., 2015).

Therefore, ecological environments—being unstable, complex and changing environments with social, physical and technical constraints—are optimal to develop motor creativity (Bonnardel et al., 2023; Memmert, 2015). Nonetheless, not all students engage in the same way in PE, especially in ecological settings where decision-making and motor skills are continuously disrupted by social interference from teammates or opponents. Therefore, if findings have shown that intrapersonal characteristics such as motivation, empathy levels, ego or risk-taking also influence motor creativity (Kokkonen, 2018; Versace et al., 2018), the importance given to self-esteem on creative motor performance in ecological settings is meager.

Indeed, self-esteem—described as overall feelings of self-worth and well-being (Harter, 2012)—can also be narrowed to a representation of one's value in areas as broad as academic, social, physical or creative domains (Kaufman, 2012). The "image" that the individual has of oneself can fluctuate and evolve, impacting performance in a given domain. For instance, studies have shown that successfully completing physical tasks and engaging in motor development can enhance motivation, catalyse positive emotions, thus, increasing self-esteem and well-being (Rubeli et al., 2020). On the other hand, physical experiences associated with negative emotions or trauma could lower self-esteem and inhibit the expression of motor skills (Rinaldi, 2023). Therefore, important stakes appear to be at play surrounding self-esteem in PE (Bailey, 2006), especially at adolescence, where self-esteem is in decline (Schaffhauser, Allemand, & Schwarz, 2017).

If there seems to be a link between the physical experiences of individuals and the development of self-esteem, the knowledge regarding the impact of self-esteem on creative motor performance in PE is scant, with only few studies taking interest in this matter (Barbot, 2018; Deng & Zhang, 2011). Consequently, we wish to address this gap by exploring the research question: What is the impact of self-esteem on creative motor performances in ecological contexts in PE? To answer this question, we will be quantifying self-esteem of adolescents. Supported by the multivariate framework (Palmiero et al., 2019) we will then assess motor creativity performance in an ecological setting.

Adolescence: A crossroads in developing self-esteem and creative motor performance

It is during adolescence—marked by pubertal changes—that creative skills can take shape and crystallise themselves in various domains (Barbot & Lubart, 2012). In the same way, self-esteem—which has no distinguishable facet in childhood—will also spread and nurture itself in various and specific domains at this period of age (Barbot & Heuser, 2017). In this way, adolescence could be a lever for developing motor creativity and self-esteem, because of the individual's willingness to transgress certain rules, to oppose adults and to prove themselves in the face of peers (Lubart & Besançon, 2015). Nonetheless, this period of change and uncertainty can also be a creative inhibitor, as the gaze of others can prove unbearable at times, also negatively impacting self-esteem in case of failure (Scharmann, 2011). This ambiguous relationship between individual assertion and the gaze of the group is therefore particularly significant. It constitutes a crucial period in the development of creativity and self-esteem for adolescents (Besançon & Lubart, 2011).

Further, if self-esteem and motor creativity stakes are salient during puberty Barbot & Heuser, 2017; Rothenberg, 1990), pedagogical choices from teachers could strongly improve or downgrade creative performance and self-esteem. Indeed, research like the Creative Habits Of Mind (CHOM) framework show that implementing collaborative work, imaginative tasks or collective games at school could enhance creativity in adolescents (Fakhour & Ghareeb, 2020). On the other hand, in situations where they are repeatedly unsuccessful, where they feel anguished or mocked, students can physically disengage themselves from PE. Indeed, low confidence and negative motor experiences could nurture decreased motor performances and habits for students, which would limit motor adaptability in ecological situations (Barker et al., 2023). Therefore, taking into account individual self-esteem in relation to creative performance in ecological environments could lead to a better understanding of motor and social behaviour of students. Consequently, gathering data on self-esteem and creative motor performances in ecological domains could lead to improved pedagogical choices from PE teachers, to lead learners towards personal and academic success.

Nonetheless, what do empirical studies show regarding the relationship between self-esteem and performance?

Self-esteem and creative motor performance: an undervalued relationship?

Even though scientific literature surrounding movement and motor learning has increased in recent years (Barker et al., 2023), creative motor performance and self-esteem have received meagre attention. Moreover, the studies that have provided some data have given heterogeneous results (Barbot & Heuser, 2017). Some authors have found a positive link between self-esteem and physical performance (Noordstar et al., 2016). While it seems to be the dominating consensus, other works outline the absence of a significant relationship between self-esteem and physical activity (Baumaster et al., 2018), therefore, leading to inconclusive results. One of the explanations to this lack of clear knowledge is that self-esteem and creativity are generally explored in non-motor domains. Indeed, even if intrapersonal functions have spun interest, authors have studied self-esteem in fields as broad as work, school or creative thinking (Orth & Robins, 2022). Nevertheless, authors have pointed out that the relationship between self-esteem and motor abilities has rarely been discussed (Barbot & Heuser, 2017). More, while the multivariate theories assert the importance of complex and unstable environments to develop and study creative motor skills, motor creativity performances are often focused on psychomotor settings—being stable environments without social interaction (Parlebas, 1999)—rather than ecological settings (Lee et al., 2023). Indeed, if some data has shown a positive correlation between self-esteem and motor creativity (Bournelli et al., 2009), studies are rarely undertaken in dynamic social and physical environments. While acknowledging the insights gathered from the studies in psychomotor environments, our study wishes to endeavour a novel approach. With a broader and more holistic perspective using the multivariate framework, we wish to establish a new scope for the understanding of creative motor performances in PE.

Praxic communications and divergent indicators: tools for creative motor performance assessment in ecological situations

In France, Bertsch (1983) was one of the first to include divergent indicators to measure creative motor performance in PE, based on the works of previous authors such as Guilford (1967) or Torrance (1981). These divergent indicators are fluency (number of overall motor responses), flexibility (diversity of the motor responses) and originality (rarity of the motor response). These indicators are strongly valued in assessing motor creativity performances (Buning et al., 2020; Mendez-Martinez & Fernandez-Rio, 2018). Nonetheless, they are still rarely used to assess creativity in ecological settings at school—noticeably because PE evaluation and teaching strongly relies on technique. Indeed, authors have shown that PE teaching in France is still strongly sport-centred, where pleasure, collaborative work, exploration and curiosity have a minor role to play (Bordes, 2020; Lubart & Besançon, 2015). The lack of emphasis on motor creativity in PE and a rather normative pedagogy through sports are limiting factors in understanding and including motor creativity at school (Beghetto, 2010). Indeed, PE teachers often assess performance as a result of physical, technical, and tactical criteria (Clemente et al., 2016; Coutts, 2014). While these traditional indicators are necessary conditions for performance, they are not sufficient to be fully accountable for it (Furley & Memmert, 2018). To address this issue, and to surpass Bertsch's study that was set in a psychomotor setting, authors have used praxic communications as ways of assessing creative motor performances in ecological settings (Oboeuf et al., 2020). Praxic communications refer to the communications and interactions that are expressed by players during an ecological task, such as in collective games or sports (Parlebas, 1999). The communications that are observed between players have been divided in various categories such as direct communications (essential motor actions without which the game cannot be played such as shooting or passing for example) and praxemes (behaviours that surround and add to the direct communications such as a call for the ball or feints) (Bordes, 2020; Oboeuf et al., 2024). Therefore, the normative frame in which the player evolves—generated by the rules of the game, the game objectives, as well as physical and social constraints—will catalyse different behaviours and communication channels during the game. In consequence, to assess a player's creative motor performance during a specific ecological setting, it is crucial that the spectrum of motor possibilities and praxic communications are clearly identified. In other words, a roster of game-specific communications must be established to meaningfully assess creative motor performance. In football for instance, a call for the ball is a praxeme. If a player does a sudden run in an opponent-free area, the behaviour (running) is the signal that conveys the message (calling for the ball) to the teammate ball-bearer. In handball, 75 % to 85 % of overall praxic communications are indirect channels such as praxemes. This illustrates the importance of properly coding and identifying the various communications for each ecological activity. As an example in table 1, here are the registered praxic communications in football (Oboeuf et al., 2020).

Table 1. Example in football: List of direct communications and praxemes

Type	Description
Interception	When an opponent stops the ball from reaching its destination by cutting the pass line or shot.
Tackle	Defensive physical act that aims to recover the ball when the opposing player is in possession.
Contact	Shoulder-to-shoulder contact between two players who wish to take the ball.
Pass	Technical action that aims to transmit the ball to a teammate.
Shot	Direct ball attempt aimed at the opponent's goal.
Praxeme	**Motor Action Description**
Body feint	A motor action that makes opponents believe the player will move in one direction while moving in another.
Passing feint	A motor action that makes opponents believe a pass will be made, while another action is performed.
Shooting feint	A motor action that suggests a shot but leads to a different action.
Returning run	The run of a player who just lost the ball and returns quickly to a defensive position.
Tracking run	A player follows a direct opponent to reduce maneuvering space.
Holding run	The player behind the bearer runs to offer a pass solution.
Supporting run	The player in front of the bearer runs to offer a pass solution.
Focusing run	A run toward the rival bearer to limit their maneuvering margin.
Cross run	A player crosses in front of a teammate to destabilize the opposing defense.
Recolocation	Movements to occupy a suitable position relative to teammates, opponents, and the ball.
Ball call	A player accelerates toward the goal to anticipate a pass.
Ball countercall	A player accelerates in another direction to create free space.
Fixation	A run into an area defended by two opponents to create a numerical advantage.
Slip	A movement in which a player from behind or the side of the bearer creates space for the next action.

Across the various studies that have been conducted, evaluating creative motor performance in ecological settings relies on the identification of divergence, being the number of praxic motor communications (fluency) and the diversity of the praxic motor communications (flexibility) (Memmert, 2015; Orth et al., 2022). Therefore, if we have shown that methods and indicators exist to assess motor creativity performance, it isn't designed to explain or interpret creative motor performance disparities within students. By embracing the multivariate theory framework, we feel that understanding the dynamics between self-esteem and creative motor performance is an important step in allowing a more thorough motor knowledge for adolescents in PE.

Materials and Methods

Rooted in the multivariate framework, our study wishes to establish relationships between self-esteem and creative motor performance in ecological settings. Below, the full description of the experiment will give information about the participants, the material and the procedure that allowed us to obtain quantitative results. This section includes a consideration of ethics for this study.

Recruitment and Context

The main author, who is a PE teacher, conducted the experiment in a French middle school in collaboration with the PE teachers that were assigned to each studied class group. The first phase of the experiment began on the first day of school, when students and parents were informed of the upcoming study. Parental authorizations were sent out by e-mail, filled in by the legal tutors and collected by the main author for safekeeping. An e-mail detailing the study was also sent to the parents, explaining the objectives of the study, its duration, as well as the withdrawal rights (possibility of withdrawing from the study at any time). Elements relating to video rights and data confidentiality (anonymization, right to obtain study results etc.) were also included. Only the students who were willing and able to take part in the creativity tests, and those who had authorizations to do so, were included in the study.

Participants

The data collected for this study involved 60 adolescents aged 12, including 31 girls and 29 boys, all coming from the same school. The 60 students were assigned to their usual class groups (three different groups in total) and were not mixed during the study. Adolescents excluded from the test were those who were unable to participate in physical activities at the time of the experiment, and those who did not have parental authorization to participate. A total of 64 individuals were initially enrolled in the study. Of these, 2 did not provide consent and 2 more couldn't participate in the ecological creativity test and were therefore also excluded. The final sample consisted of 60 participants who completed all study measures appropriately.

Prior to the empirical test, our protocol — listed under No. 2024-82 — was approved by the Comité d'Ethique de la Recherche (CER), enabling us to conduct the experiment within the framework of legal and institutional regulations. Finally, let us note that the data collected is anonymised and stored securely, in compliance with the latest RGPD (Règlement général sur la protection des données) regulations (EU 2016/679).

Table 2. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Participation and authorization	Participation document signed by parents	Authorization documents unreturned or refusal of participation
Image rights	Image authorization signed by parents	Children without returned image authorization
Attendance	Child present for the entire study	Absence during any part of the assessments
Physical condition	Physically fit to practice at the time of the experiment	Unfit to practice physical activity at the time of the experiment

Measure Procedures for Self-esteem

To evaluate self-esteem, we used the Rosenberg (1965) Self-Esteem Scale (RSES) which was also validated by other recent studies (Hafekost et al., 2017; Jurado et al., 2015). We used self-rated Likert scales, where the adolescent evaluated his self-esteem, from 1 being low and 4 being high (Rosenberg, 1979) for a total of 10 items. Therefore, the maximum score would be 40 points and the minimum 10. This method and grading scales have proven to be effectively used to collect data about self-esteem for adolescents (Gnambs et al., 2018). The form was sent out to each adolescent during PE class in paper format. The main author and the PE teacher of the class supervised the self-esteem evaluation, making sure that students understood the questions and the instructions. Each form was filled individually with no time pressure or limit. When all the forms were completed, the main author collected them. This was repeated in the same way for each class group. Subsequently, the main author gave a self-esteem score for each adolescent, based on the answers they had given. The Rosenberg Self-Esteem Scale demonstrated excellent internal consistency in our sample (Cronbach's $\alpha = .94$).

Table 3. Self-esteem questionnaire

Question	Scale
On the whole, I am satisfied with myself	1 2 3 4
I feel I have a bad opinion of myself.	1 2 3 4
I feel that I have a number of good qualities	1 2 3 4
I am able to do things as well as most other people	1 2 3 4
I feel I do not have much to be proud of	1 2 3 4
I certainly often feel useless	1 2 3 4
I feel that I am not a person of worth	1 2 3 4
I have respect for myself	1 2 3 4
All in all, I am inclined to think that I am not successful	1 2 3 4
I take a positive attitude toward myself	1 2 3 4

Procedures for assessing creative motor performance Ecological creativity assessment

The second phase of our experiment, the assessment of creative motor performance in ecological settings, took place the week after the self-esteem task. To measure ecological motor creativity performance, we chose to use the game "sitting ball", as several studies have identified a wide variety of praxic indicators which will facilitate the construction of the coding and analysis grid for observers (Oboeuf et al., 2010; Bordes, 2020). The aim of this game is to eliminate the other participants by throwing a ball at them in a defined area. If one player is hit, he must sit down and wait for a chance to catch the ball. If so, he can come back into the game. The game stops when only one player remains or if there is no time left. Authors have shown that assessing ecological motor abilities in games is optimal, as these non-normative settings provide more risk-taking, more freedom and less inhibitors compared to culturally gendered activities. Sports such as football for instance, tend to hinder the creativity of some practitioners (Vigneron, 2006). Therefore, instead of a technical, fragmented and cloistered view on physical activity, we wished to take motor development into account in a more global and holistic way.

For the assessment, each class group was divided in half. Therefore, for each class group, two subgroups were constituted, making it a total of six different groups for our study. For each assessment, ten players were filmed and played for 20 minutes on a 100m2 mat area. The awaiting participants were in a separate space with a PE teacher from the school. This was meant to limit external disruptions, thus limiting behavioral bias and interference during the assessment. Participants entered and exited through different doors to limit bias prior to the assessment. The groups were always mixed and heterogeneous in gender and motor ability to limit cluster effects.

The objective was to assess the creative motor performance and divergent abilities of the students by scoring the fluency and flexibility of the praxic communications (direct communications and praxemes) expressed during the game (Oboeuf et al., 2024).

In table 4, are listed the known direct communications and praxemes for the game "sitting ball".

Motor fluency was operationalized as the total number of responses generated by each participant, including redundant behaviors. In other words, fluency reflects the sum of all praxic communications provided by a participant within the task period.

Motor flexibility was measured by taking into account the sum of distinct praxic communication categories expressed during the game. For instance, a shot an interception and a dodge run would lead to a total score of three in flexibility.

To assess the motor behaviours, trained observers were recruited to establish a significant and reliable scoring system. Based on a previously developed protocol (Oboeuf et al., 2024; Oboeuf & Frachey, 2025), students in the field of sports education or PE teachers were recruited. In concordance with the past uses of the protocol, the observers selected all had at least five years of training in collective games or sports. Further, they had at least five years of French sports faculty (STAPS) experience and were experts in the motor and physical education field. Finally, to ensure proper direct communication and praxeme identification, all must have followed a six-hour theoretical training in praxic communications. In the table below, the content (Oboeuf et al., 2020; Oboeuf et al., 2022; Oboeuf et al., 2024) of the training is presented.

In order to assess sociomotor creativity in the most efficient and objective way, the observations made by the selected experts were conducted by viewing footage of the recorded games. For each player, the assessment was led by two experts, each separately assessing the different praxic communications expressed by a player. This dual approach was designed to enhance inter-rater reliability by balancing situated expertise with methodological neutrality. Also, to

Table 4. Direct Communications for the Game of Sitting Ball

Type	Description
Shot	Offensive action aiming at scoring or hitting a target.
Pass	Transmission of the ball to a teammate.
Interception	Stopping the ball from reaching its intended destination.
Ball recovery	Regaining possession of the ball after loss.
Praxeme	**Motor Action Description**
Call for the ball	A player signals for the ball with a hand gesture and body positioning toward the bearer.
Dodge run	Sudden change of rhythm or direction to become harder to target.
Replacement run	Slow repositioning steps to find a favorable location.
Supporting run	Running toward the ball bearer to offer a pass option.
Positioning step	Steps or jumps allowing the bearer to adjust before shooting.
Body feint	Misleading movement suggesting false intentions.
Pass feint	Pretending to pass while executing a different action.
Shooting feint	Pretending to shoot to gain advantage or switch action.
Dodge	Quick body movement to avoid a shot.
Elusive run	Fast run indicating clear space for receiving a pass.

Table 5. Training content

Format and Course Title	Objectives
Lecture 1 – Theoretical Foundations of Motor Communication	i) Contextualize motor communication within interactional analysis; ii) Distinguish motor communication and counter-communication; iii) Introduce motor signs.
Lecture 2 – Praxems, Gestems, and Indices: A Semiotic Approach	i) Define expressive mediations; ii) Illustrate use in team sports; iii) Explore tactical scope and ambiguity.
Lecture 3 – Observing, Coding, and Interpreting Motor Behaviours	i) Tools for reliable observation; ii) Present Lince software and coding grids; iii) Interpretative biases and challenges.

ensure the reliability of the data (Marquéz Jiménez & Martinez de Santos, 2014), inter-rater reliability and validity tests were performed using Pearson and Spearman correlation coefficients. In previous studies, values consistently exceeded .96, indicating strong inter-observer agreement (Oboeuf et al., 2020; Oboeuf et al., 2022; Oboeuf et al., 2024). In our study, we made sure that inter-rater reliability scores were consistently above .90. If the score was below this value for a player, a new paired-review was put into place to assess the participant. This choice was made to ensure high reliability for the creativity assessment. After viewing the entire game footage, each adolescent was given a fluency (number of praxic communications) and flexibility (diversity of praxic communications) score.

Motor creativity performance interpretation

If each student has a fluency and flexibility score, how can we identify or circumscribe the different creativity levels? In other words, how can we identify a player's motor performance as creative or non-creative? It is worth mentioning that a creative or non-creative performance level can only be quantified within the sample in which it was observed. Indeed, a player can be very adaptive or creative while in one group, but his creative performance score can evolve in another group and be more or less remarkable. Therefore, in our sample, a low-creativity student would have expressed 45 praxic communications or less during the 20-minute game time span, while a participant between 45 and 65 communications would demonstrate average creativity performance. Finally, a student with a score above 65 praxic communications expressed would be considered highly creative and adaptive.

Results

The Factorial Analysis Measurement

Results for self-esteem were collected by adding the total points that were obtained for each item, with a total perfect score being 40. Then, for each participant, creative motor performance was scored by using the praxic communications (direct communications and praxemes) and divergent indicators (fluency and flexibility). The gathered data were then encoded by the observers after they quantified the praxic communications empirically expressed during the game, using an Excel grid. After, a factorial analysis calculation was applied. To study the link between self-esteem and creative motor performance, we used the factorial analysis Trideux.cloud tool. This tool was used to calculate the correspondences and correlations between the data we collected and encoded. It was used to establish whether or not self-esteem was related to creative motor performance. The calculation then resulted in a figural representation that enables the interpretation of the data.

To understand the results, it is important to clarify our coding system. The estimcrea– value represents the students below the average self-esteem score (below 21 points in this case), while the estimcrea+ value represents students with the highest self-esteem values (between 30 and 40 points). The creasociom < 45 value indicates creative motor performance scores that are the weakest (below 45 points), the 65 > creasociom < 45 represent the average performance score while creasociom > 65 represents the students with the best motor scores (above 65 points). These score brackets each represent 1/3 of the total data distribution, which explains the choice of these values. It is important to note that these creative motor performance values are specific to this group, and that a student can be deemed highly creative in this group while being average in another. Therefore, creative motor performance scores are necessarily anchored in a specific context and aren't necessarily stable within other settings or groups.

Factorial analysis result graphic

Our factorial analysis visualises the relationship between individuals and variables in terms of distance, producing clouds of points (Cibois, 2018). The distance between each point is based on how similar they are in their distribution. The proximity between encoded variables indicate the strength of their correlation, while the size of an encoded variable represents its relative importance or influence on the overall results. Moreover, the cosine of the angle between variables shows the correlation between the two corresponding variables (Clarke et al., 2021). Thus, a small angle between two variables indicates that the two variables are highly correlated. If two variables form an angle of 90° or greater than 90° then corresponding variables are uncorrelated or negatively correlated. The principal component analysis yielded two dominant axes that together account for 82.92% of the total variance. The eigenvalue of F1 are 0.4014, (explaining 51.10% of total variance) while the eigenvalue of F2 represents 0.3500, (accounting for 31.82% of the variance). These values provide a compact and reliable representation of the data structure. The horizontal axis (F1), here designated as the "intrapersonal valence factor" captures a clear contrast between lower and higher levels of self-esteem. Categories associated with high self-esteem and high creativity scores load positively on this axis, whereas low self-esteem values load negatively. The vertical axis (F2) that we will refer to as the "performative magnitude factor" differentiates the mid-range group from both the lowest and highest creative categories. Therefore, the distribution of categories across the figural map suggests a coherent distribution between self-esteem and motor creativity performance, with the strongest creative profiles clustering within the positive sector of self-esteem, while lower or more heterogeneous profiles occupy the opposite side.

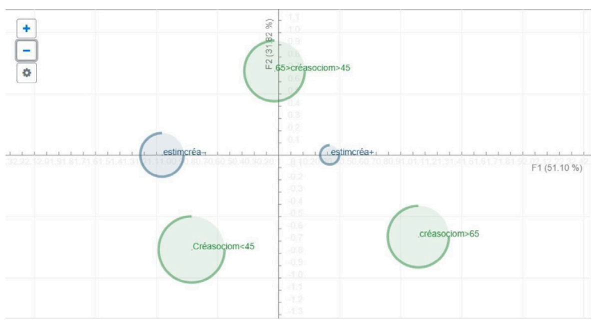

Fig. 1. Two-dimensional factorial analysis plot of variables and individuals

Indeed, as we can see from the results graphic, the highest creative motor performances (creasociom> 65) are clearly represented on the same side as the students with the highest self-esteem results (estimcrea+) and are close to one another. In addition, the angle formed between the sociomcrea>65 and esimcrea+ vectors is narrow, underlining the correlation between the two. In the same way, the lowest creative motor performances (Creasociom< 45) are related to the low self-esteem students (estimcrea–), as we can see from their proximity and narrow angles. However, the average creative motor performance scores (65>creasociom<45) seem to be insignificantly impacted by either self-esteem levels, as the angles formed between estimcrea+ and estimcrea- are of 90°.

Moreover, the estimcrea– circle is bigger than the estimcrea+, showing that low self-esteem is even more impactful on low motor performance than high self-esteem levels are on the best creative motor performances. Therefore, we can express the idea that indeed, self-esteem could be related to creative motor performance in ecological settings.

Additional statistic analysis

To reinforce the validity and rigor of our results, a Pearson correlation analysis conducted at the individual level ($N = 60$) also revealed a positive association between self-esteem and motor creativity where $r = .734$. This confirms the factorial analysis results, showing a significant relationship between self-esteem and ecological motor creativity.

Moreover, the self-esteem variable showed a mean score of 23.68. The standard deviation (SD) = 8.42 while the 95% confidence interval (CI) = 21.55–25.81. The motor creativity variable had a mean value of 53.17. The SD calculation showed that SD = 18.71 while the 95% CI = 48.43–57.90. We can see that the self-esteem variable displayed moderate dispersion, whereas the motor creativity variable showed a wider variability showing disparity in motor creativity scores. Nevertheless, the confidence intervals are sufficiently narrow to indicate good precision of the estimated means.

Discussion

Consistencies and Novelties of the Study

Our results indicate that higher self-esteem values were associated with high creativity scores, which is consistent with prior self-esteem and creativity studies in non-motor (Barbot, 2018) or psychomotor domains (Noordstar et al., 2016). However, this study is one of the first to offer a direct insight on the relation between self-esteem and creative motor performances in ecological settings.

The correlation between self-esteem and motor creativity in our study was first proven significant by the factorial analysis map which displayed a coherent distribution of self-esteem and motor creativity performance. The strongest creative profiles (creasociom>65) cluster within the positive sector of self-esteem (estimcréa+), while lower profiles (Creasociom<45) cluster on the opposite side. Moreover, the Pearson correlation analysis conducted at the individual level ($N = 60$) confirms the figural results of the factorial analysis, correlating self-esteem and ecological motor creativity positively with $r = .734$. The findings are statistically significant as the 95% confidence intervals for self-esteem were located between 21.55–25.81 and 48.43–57.90 for ecological motor creativity. These intervals are sufficiently narrow to indicate good precision of the estimated means and results.

Consequently, our study tends to show that self-esteem is related to motor creativity in ecological motor domains, hence indicating that intrapersonal singularities strongly affect ecological motor behaviour, habits and performance (Barker et al., 2023). In such changing and disruptive social environments, self-esteem seems to impair creative motor expression even more than in other domains. This highlights the fact that teaching and developing motor skills in ecological fields could be highly dependent on intrapersonal characteristics (Barker et al., 2023) such as self-esteem. The psychomotor environments which motor creativity studies tend to focus on (Lee et al., 2023) engage students in fewer emotional and cognitive disturbances (Memmert, 2015). Therefore, our data contributes to new empirical material which demonstrates that self-esteem could be an important predictor of motor performance in ecological settings. In contrast with existing studies which have studied intrapersonal characteristics such as motivation in individual motor contexts, our study encompasses a more complex and holistic environment.

Pedagogical implications

By using existing methods such as the RSES measure for self-esteem and divergent indicators paired with praxic communications for motor performance, we wish to put forward that accessible tools can be empirically used by PE teachers to recreate our protocol for pedagogical purposes. Indeed, the RSES, which demonstrated very good internal consistency, (Cronbach's $\alpha = .94$) ,could be of pedagogical use early in the learning sequence to identify the more fragile students in a proactive way, as psychological and intrapersonal characteristics are strongly related to motor behaviour (Barker et al., 2023). Identifying fragile students with lower self-esteem could allow teachers to adapt their tasks, activities and instructions during class to favour their physical investment and risk-taking, thus allowing better motor development. The results highlight that if self-esteem is linked to motor performance in ecological situations, pedagogical settings that encourage collaborative work and tolerance of mistakes could increase self-esteem (Fakhour & Ghareeb, 2020).

While our data shows that ecological settings could strongly affect the motor behaviour of low self-esteemed students, focusing on cooperative tasks could increase their motor abilities and performance (Ruiz-Ariza et al, 2017). Therefore, our study contributes to underlining the importance of elaborating specific ecological tasks for fragile adolescents in developing motor habits and performance. By fostering self-esteem, PE teachers would strive towards better motor development for all students, which could also, in a mutual and systemic relationship, increase self-esteem.

Limitations and perspectives

While this study provides important insight on the association of self-esteem and creative motor development, some limitations can be underlined. First of all, users of such methods must be advised that in order to reveal the adaptive performance of players, it is essential that a rigorous list of sport-specific praxic communications is established, as it has been done in our study for the game of sitting ball. Moreover, all the possible praxic communications must be included in the in-situ game, without changes or constraints made to the original setting so the players are able to express the global communication panels. Nonetheless, it is worth acknowledging that the theoretical training of the observers that are able to read these communications can be time-consuming, and that some specific training and background are necessary for the observers, which also explains the limited student sample provided for the study (N=60), which can also be seen as a limit. However, these requirements are necessary to study and assess motor development in an ecological environment thoroughly.

An additional limitation resides in the fact that the sample was drawn from a single educational context, which restricts the representativeness of the results. It is important to acknowledge that this study is rooted in a European and French school context, with a certain cultural history of PE and physical activity. Replication of our experiment in other cultural settings could also give a deeper understanding of the relationship between self-esteem and motor creativity. Similarly, participants were nested within classes, creating potential clustering effects. If the analysis conducted at the individual level was significant, the nested design may introduce intra-class correlations that could bias results. In addition, potential confounding variables such as socioeconomic background, academic performance or motivation were not measured, but could also partly account for the observed associations. If we advocate for self-esteem being a relevant lens to predict motor performance, it cannot be isolated or self-sufficient from other intrapersonal and interpersonal parameters (Kokkonen et al., 2018). By embracing the multivariate framework, a more global profiling of students would be needed for optimal understanding of creative motor performance, and is the subject of further research we are undertaking. Finally, it is worth mentioning that the self-report method to measure self-esteem could be prone to some constraints such as social desirability biases, that could influence the measurement. Despite this, the RSES scoring showed excellent internal consistency in our sample (Cronbach's $\alpha = .94$) showing that self-esteem was quantified in a significant manner.

Conclusion

In this study, by aligning with the multivariate framework (Versace & Vallet, 2018), we have suggested the importance of assessing self-esteem and creative motor performance in ecological settings for PE teachers. Indeed, by using a factorial analysis tool and a Pearson correlation calculation, we have shown that self-esteem and creative motor performance are related, with $r = .734$. Moreover, by discussing this relationship in terms of teaching practices for PE, the paper provides insight on available tools for identifying both self-esteem and creative motor levels in ecological settings. Further, we believe that our experiment underlines the importance of identifying fragile students with lower self-esteem, as they are less prone to engage and interact with their social and physical environment. Despite this, more studies regarding the intrapersonal parameters and their relationship with creative ecological motor performances would strengthen our data, hence being the perspective of our further research.

Ethics Approval

The study was approved by the French Research Ethics Committee (CER) and registered under IRB No. 00012024-82.

Informed Consent

Written informed consent was obtained from all participants and from their parents or legal guardians prior to participation in the study.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

AI Transparency Statement

The authors declare that no artificial intelligence (AI) tools were used in the collection, analysis, or interpretation of the study data. AI-assisted tools were used solely for language editing and grammatical refinement during manuscript preparation. All scientific content, study design, statistical analyses, and interpretation of results were performed solely by the authors.

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Conflict of Interest

The authors declare no conflicts of interest.

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Розуміння взаємозв'язку між самооцінкою та руховою творчістю в екологічних контекстах фізичного виховання в підлітковому віці

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 11 с., 5 табл., 1 рис., 55 джерел.

Обґрунтування. У сучасних дослідженнях загальновизнано, що креативність є важливим чинником результативності у спорті та фізичному вихованні (ФВ). На основі багатовимірної моделі автори також дослідили вплив мотивації, інтелекту та когнітивних здібностей на творчу рухову активність. Однак існує недостатньо даних щодо самооцінки та її зв'язку з руховою активністю в екологічних сферах.

Цілі. Мета цього дослідження полягала у розумінні взаємозв'язку між самооцінкою та руховою творчістю, зосередивши увагу на екологічних рухових контекстах у фізичному вихованні підлітків.

Матеріали та методи. Експериментальна популяція складалася з трьох груп загальною кількістю 20 дітей (N = 60), з них 31 дівчинка та 29 хлопчиків віком 12 років. На першому етапі дослідження самооцінку вимірювали за допомогою шкали самооцінки Розенберга (RSES), яка продемонструвала відмінну внутрішню узгодженість у зазначеній вибірці (α Кронбаха = .94). Потім учасники взяли участь у 20-хвилинній ігровій задачі з використанням гімнастичного м'яча під назвою "Sitting ball", що ілюструє концепцію взаємозалежності в екосистемі. Ґрунтуючись на багатовимірній моделі, у дослідженні оцінювали моторну плавність і гнучкість, використовуючи праксичну комунікацію в якості ключових показників креативності. Після збору даних проведено факторний аналіз за допомогою інструменту Trideux.cloud з метою встановлення взаємозв'язку між самооцінкою та руховою творчістю.

Результати. Факторна мапа показує, що рівні самооцінки корелюють з показниками рухової творчості в екологічних ситуаціях. Аналіз, проведений на індивідуальному рівні (N = 60) з використанням розрахунку кореляції Пірсона, підтвердив ці результати, встановивши позитивний взаємозв'язок між самооцінкою та екологічною руховою творчістю з r = .734. Крім того, результати є статистично значущими, оскільки 95% довірчі інтервали (ДІ) для самооцінки становили 21.55–25.81, а для екологічної рухової творчості — 48.43–57.90. Інтервали є достатньо невеликими, щоб вказувати на високу точність оцінених середніх значень і результатів.

Висновки. Це дослідження виявило, що творчі рухові здібності, судячи з усього, тісно пов'язані з самооцінкою. Низькі рівні самооцінки, як правило, сильно корелюють зі слабкими показниками рухової творчості, тоді як високі рівні самооцінки пов'язані із підвищеною руховою творчістю. Представлена нова екологічна модель підкреслює педагогічну важливість оцінки та розуміння таких внутрішньоособистісних характеристик для сприяння руховому розвитку та здоров'ю на заняттях фізичного виховання.

Ключові слова: творчість, фізичне виховання, рухова активність, самооцінка, підлітки.

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Original Scientific Article

Applicating Multivariate Adaptive Regression Splines (MARSplines) for Predicting Post-Traumatic Stress Disorder Risk in Military Personnel

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Abstract

Background. Risk prediction of post-traumatic stress disorder (PTSD), which has substantial social and economic consequences and affects military readiness, is an increasingly important challenge. Early identification of service members at elevated risk enables timely preventive strategies, including interventions based on physical culture, physical activity, sport, and rehabilitation.

Objectives. This study aimed to develop and validate a predictive model for assessing PTSD risk in military personnel and to substantiate its use as a decision-support tool for pedagogical planning in physical education and sport-based prevention and rehabilitation programs.

Materials and Methods. The study involved 4,403 military personnel (89.9% men) aged predominantly 21–50 years. PTSD severity was assessed using the Mississippi Scale for Combat-Related PTSD (military version), which demonstrated high internal consistency (Cronbach's $\alpha = 0.892$; Guttman split-half = 0.920). Statistical analyses included comparative and gender-based procedures, as well as machine learning modeling using Multivariate Adaptive Regression Splines (MARSplines) with progressive optimization, dataset balancing, and evaluation of classification performance.

Results. A MARSplines-based model predicting PTSD risk was developed using 18 dichotomous demographic, behavioral, and service-related variables. The final model for male military personnel included 300 basis functions with an interaction order of six and demonstrated sensitivity of 71.1%, specificity of 69.5%, accuracy of 70.3%, and moderate agreement between predicted and observed risk (Cohen's $\kappa = 0.405$).

Conclusions. Machine learning–based prediction of PTSD risk represents a promising approach for early prevention and targeted intervention in military populations. The proposed model supports identification of high-risk individuals and informs the design of preventive and rehabilitative programs, including those based on physical culture, sport, and e-sports, aimed at stress reduction and resilience enhancement.

Keywords: mental health, stress-related conditions, post-traumatic stress disorder, military personnel, predictive modeling, risk factors, physical culture and sport, physical activity.

Introduction

Predicting the risk of developing post-traumatic stress disorder (PTSD) among military personnel has become increasingly relevant in the context of modern armed conflicts. Stress-associated conditions in military populations arise from sustained exposure to extreme physical and psychological loads, life-threatening situations, and prolonged emotional tension during military service (Mulligan et al., 2010; Kulka, et al., 1990; Perconte & Wilson, 1994). Such conditions manifest in various forms, including chronic psychological stress, post-traumatic stress disorder, episodes of aggression or emotional dysregulation, and insufficient access to psychological support.

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In recent years, the number of military personnel requiring medical and psychological assistance due to PTSD has increased substantially, underscoring the urgent need for effective methods of early risk detection and prevention (Kulka, 1990; Perconte & Wilson, 1994; Steenkamp et al., 2015). PTSD not only affects the mental health and functional capacity of service members but also imposes a significant socio-economic burden, including reduced work capacity, increased healthcare costs, and deterioration of family and social well-being. Early identification of PTSD risk and the implementation of preventive strategies are therefore critical for preserving combat readiness and ensuring effective performance of military tasks (Imas et al., 2023; Shynkaruk et al., 2024).

Military service is frequently associated with prolonged separation from family and close social networks, exposure to morally challenging situations, and the necessity to perform tasks that may conflict with personal values or ethical norms. These factors contribute to the development of psychological stress, which is defined as a state of emotional and mental tension arising in response to adverse events, environmental conditions, or excessive load, accompanied by physiological and psychological changes (Smith & Jones, 2019; Thomas et al., 2010).

Epidemiological data indicate that approximately 7–8% of the general population in the United States experience PTSD, whereas its prevalence among active-duty military personnel and veterans may reach 14–16% (Gates et al., 2012). PTSD in military personnel typically results from exposure to combat-related traumatic events, including armed engagements, explosions, injuries, and the loss of comrades (Charles et al., 2004; Kang et al., 2003; Vasterling et al., 2010). The disorder is characterized by symptoms such as intrusive memories, nightmares, anxiety, depressive states, hyperarousal, and other stress-related reactions, which substantially impair daily functioning and quality of life and often require professional psychological intervention (Saar-Ashkenazy et al., 2024). Long-term psychological consequences of combat exposure have been documented across different military conflicts, including Vietnam, where elevated PTSD risk persisted years after service (Dohrenwend et al., 2006).

Contemporary research emphasizes that effective PTSD risk assessment among populations exposed to traumatic experiences enables the development of targeted preventive and early intervention strategies, thereby reducing individual suffering and broader social costs (Papini et al., 2023). However, incomplete understanding of PTSD symptom development and the complex interaction of risk and protective factors complicate the timely identification of individuals at increased risk (Wshah et al., 2019). To address these challenges, recent studies increasingly propose the use of machine learning models for automated prediction of PTSD risk based on self-reported psychological and behavioral data (Wshah et al., 2019).

Machine learning approaches for predicting mental health disorders in military populations are currently undergoing rapid development (Pareek et al., 2024; Rainio et al., 2024). Although this research field is relatively young, several studies have already demonstrated promising results (Hoge et al., 2006; Olff et al., 2019; Rzonca et al., 2024). For example, Sampson et al. (2021) applied random forest algorithms to data from 2,249 National Guard personnel and achieved prediction accuracies of 68% for women and 73% for men when modeling the risk of depression based on psychological, demographic, and military-related factors. Similarly, Papini et al. (2023) developed a machine learning model using data from 4,711 U.S. Army soldiers and 801 predictors across 17 domains to assess PTSD risk following combat exposure.

Within the field of physical education and sport sciences, the prediction of psycho-emotional risks should be viewed as a tool for pedagogical management of physical activity, sports training, and physical rehabilitation. Predictive models aimed at identifying PTSD risk create methodological prerequisites for evidence-based selection of physical activity interventions, individualization of training and rehabilitation loads, and prevention of maladaptive stress-related conditions. Thus, integrating predictive analytics into systems of physical culture, sport, and rehabilitation represents a promising direction for enhancing both mental health prevention and functional readiness in military populations.

The objective of this study was to develop and validate a predictive model for assessing the risk of post-traumatic stress disorder (PTSD) in military personnel and to substantiate its applicability as a tool for pedagogical decision-making in physical education, physical activity, and sport-based prevention and rehabilitation programs.

Materials and Methods

Research Methods

To assess the severity of post-traumatic stress reactions in military personnel, the Mississippi Scale for Combat-Related PTSD (military version) (Keane et al., 1988) was used, where each of the 35 statements is rated on a five-point Likert scale. The degree of impact of the traumatic experience on the military personnel was determined by summing the scores. It should be noted that current scientists point out that this scale is the best psychodiagnostic tool for measuring combat-related PTSD (Hastie et al., 2001; Hyer et al., 1991; Perconte & Wilson, 1994). Thus, the use of the Mississippi Scale can result in a PTSD assessment for military personnel ranging from 35 to 175 points.

The use of the Mississippi Scale for PTSD assessment as a screening tool among military personnel involved in combat actions is a self-assessment tool and cannot precisely determine whether a military personnel has PTSD. It evaluates the severity of PTSD symptoms rather than serving as a diagnostic tool. To improve approaches to interpreting the results of the Mississippi Scale, based on the method of equal intervals, we proposed the following gradation of scores obtained from the Mississippi Scale (see Table 1).

Table 1. Interpreting the results of the Mississippi Scale

Evaluation, Points	Risk Levels of PTSD	Description
35- 81	Low	Well-adapted veterans
82-111	Medium	рушення Risk of PTSD, mental health issues
112-175	High	High likelihood of PTSD, medical consultation needed

There was a need for further research and confirmation of the validity of our proposed PTSD rating scale using the Mississippi Scale. This validity can be demonstrated by comparing the results obtained using our scale with clinical PTSD diagnoses established by qualified mental health professionals. If our scale shows a high level of agreement with these clinical diagnoses, it will confirm its validity. However, since the armed conflict continues, it is currently impossible to organize additional research. Nevertheless, the use of the Mississippi Scale allowed us to obtain preliminary results aimed at providing a general understanding of the impact of combat participation on the mental health of military personnel, identifying potential issues, and determining individuals who may need further examination or early intervention.

The military version of the Mississippi Scale showed high internal consistency: Cronbach's alpha coefficient was 0.892, and Guttman's Split-half reliability was 0.920.

Study Participants

The studies involved 4,403 military personnel. The majority of the participants were men, accounting for 89.9% of the sample. Of these, 28.9% were in the age group of 21-30 years, 28.75% were 31-40 years old, and 24.9% were 41-50 years old. The remaining participants were military personnel either under 20 or over 50 years old. Of the respondents, 56.2% were enlisted personnel, and 69% were from the Air Force. One-third of the respondents, or 30.1%, had participated in combat operations in the last 6-12 months. In terms of education, 34.9% had secondary education, 27.1% had vocational education, and 38.0% had higher education. Additionally, 62.1% of the respondents were married, and 47% had minor children. The majority, 85.9%, had no prior experience working in other security agencies before joining the army.

Research Organization

The study was conducted at the National University of Physical Education and Sport of Ukraine as part of an applied research project funded by the state budget of the Ministry of Education and Science of Ukraine, titled «Reducing Stress-Associated Risks in Military Personnel and Youth of Ukraine through Health-Recreational Physical Activity» (state registration number 0124U000705). The study lasted from February 27 to April 15, 2024.

Participants were offered a psychological test and a questionnaire, the responses to which allowed us to identify potential risks to the physical and psycho-emotional health of military personnel associated with combat participation and the recovery period, as well as the presence and degree of stress states, anxiety, depression, and other psycho-emotional reactions.

The study was conducted in accordance with ethical principles. Participants were informed about the purpose of the study. Additionally, we obtained consent from the military personnel to participate in the study and took the necessary measures to protect the confidentiality of the provided information.

Statistical Analysis

During the statistical analysis, the frequency of affirmative ("yes") responses to individual questionnaire items among military personnel was calculated to provide a descriptive characterization of the dataset. Confidence intervals were applied solely for descriptive purposes to illustrate the distribution of proportions within the sample and were not used in subsequent analytical or modeling procedures.

Classical goodness-of-fit tests for assessing distribution uniformity were not applied, as subsequent stages of the analysis involved dataset balancing and machine-learning methods, for which such preliminary testing is methodologically redundant.

Comparative Analysis. To compare the frequency of selected characteristics (such as participation in combat operations, combat injuries, and chronic diseases) between two independent groups (men and women), a two-sample Z-test for proportions was applied. The null hypothesis (H_0) assumed no statistically significant difference between the proportions of the respective characteristic in men and women, while the alternative hypothesis (H_1) assumed the presence of such differences.

The Z-statistic was calculated using the standard formula for comparing two proportions:

$$Z = \frac{p_1 - p_2}{\sqrt{\frac{p_1(1-p_1)}{n_1} + \frac{p_2(1-p_2)}{n_2}}}, \quad (1)$$

where p_1 and p_2 represent the proportions of individuals with the given characteristic in the male and female groups, respectively, and n1 and n2 denote the corresponding sample sizes.

Statistical significance was set at $p<0.05$.

After calculating the Z-statistic, we could find the p-value (the probability of obtaining such an extreme value of Z or more under the assumption that the null hypothesis is true). If the p-value is less than the chosen significance level of 0.05, we rejected the null hypothesis in favor of the alternative.

Statistical Power Considerations. A formal a priori statistical power analysis was not conducted in the present study. This decision is methodologically justified by the large sample size (n = 4,403) and the exploratory–predictive nature of the research, which is focused on machine learning–based classification rather than hypothesis testing with predefined effect sizes.

In predictive modeling studies, model performance is primarily evaluated using empirical classification metrics (sensitivity, specificity, accuracy, and Cohen's kappa) and validation procedures such as generalized cross-validation (GCV), rather than traditional power calculations. The available sample size substantially exceeds commonly recommended thresholds for stable estimation of machine learning models with binary outcomes, supporting the robustness and reliability of the obtained results.

Method MARSplines (Multivariate Adaptive Regression Splines)

Machine learning methods are increasingly applied in sports medicine, physical education, and sport science to identify key factors influencing complex outcomes and to solve classification problems (Adeyemo et al., 2022; Friedman & Roosen, 1995; York et al., 2006).

In the present study, the Multivariate Adaptive Regression Splines (MARSplines) method was used to develop a predictive classification model. MARSplines is a nonparametric regression technique that allows flexible modeling of nonlinear relationships and interactions between variables by constructing piecewise linear basis functions.

The general form of the MARSplines model is expressed as:

$$f(x_i) = \sum_{j=1}^{J} \alpha_j \beta_j (x_1, x_2, \dots, x_k), \quad (2)$$

where $f(x_i)$– represents the predicted value of the dependent variable (binary outcome); j – is the number of basis functions; α_j– are the model coefficients; $\beta_j(x_1, x_2, \dots x_k)$ – are the basis functions.

Undersampling. To address class imbalance in the dataset, an undersampling procedure was applied to the majority class. Stratified random sampling was used to ensure proportional representation of classes based on the target variable (presence or absence of PTSD risk). This approach reduced classification bias and improved model stability while preserving the overall structure of the data.

Calculation of Classification Metrics

In this study, the presence of PTSD risk was explicitly defined as the positive class, as the primary objective of the predictive model was to identify military personnel with an elevated likelihood of developing post-traumatic stress disorder.

Model performance was evaluated using standard classification metrics derived from the confusion matrix: sensitivity, specificity, accuracy, and Cohen's kappa coefficient (Lever et al., 2016; Ruppert, 2004; Russell & Congalton, 1991).

In this study, the presence of PTSD risk was defined as the positive class, as the primary objective of the model was to identify individuals with an elevated likelihood of PTSD.

Sensitivity (true positive rate) reflects the model's ability to correctly identify individuals with PTSD risk:

$$\mathrm{Se} = \frac{\mathrm{TP}}{\mathrm{TP+FN}} \cdot 100\% \quad (3)$$

Specificity (true negative rate) reflects the model's ability to correctly identify individuals without PTSD risk:

$$\mathrm{Sp} = \frac{\mathrm{TN}}{\mathrm{TN+FP}} \cdot 100\% \quad (4)$$

Accuracy represents the overall proportion of correctly classified cases:

$$\mathrm{Accuracy} = \frac{\mathrm{TP + TN}}{\mathrm{TP + TN + FP + FN}} \cdot 100\% \quad (5)$$

where TP (True Positives) – number of cases where the model correctly predicts the positive class – PTSD risk is present; TN (True Negatives) – number of cases where the model correctly predicts the negative class – no PTSD risk; FN (False Negatives) – number of positive samples misclassified: PTSD risk is present, but the model identifies it as "No PTSD risk"; FP (False Positives) – number of cases where PTSD risk is absent, but the model identifies it as "PTSD risk."

Cohen's kappa coefficient (κ) was calculated to assess the level of agreement between predicted and observed classifications beyond chance: Kappa Coefficient κ, used

Table 2. Dataset for MARSplines Model Building

No.	Variable	Coding	Interpretation
1	Gender	Binary (0/1)	1 = Male; 0 = Female
2	Participation in combat	Binary (0/1)	1 = Yes; 0 = No
3	Hobbies or relaxation activities	Binary (0/1)	1 = Yes; 0 = No
4	Chronic diseases	Binary (0/1)	1 = Yes; 0 = No
5	Combat injuries or wounds	Binary (0/1)	1 = Yes; 0 = No
6	Harmful habits	Binary (0/1)	1 = Yes; 0 = No
7	Ability to engage in physical activity in combat zones	Binary (0/1)	1 = Yes; 0 = No
8	Systematic monitoring of psychological state	Ordinal	0 = Never; 1 = Rarely; 2 = Regularly
9	Support from comrades	Ordinal	0 = Unavailable; 1 = Difficult to access; 2 = Available
10	Availability of medical and psychological assistance	Ordinal	0 = Unavailable; 1 = Difficult to access; 2 = Available
11	Marital status	Binary (0/1)	1 = Married; 0 = Not married
12	Presence of minor children	Binary (0/1)	1 = Yes; 0 = No
13	Military rank (soldier)	Binary (0/1)	1 = Yes; 0 = No
14	Education level	Ordinal	0 = Secondary; 1 = Vocational; 2 = Higher
15	Physical fitness level	Ordinal	0 = Very low; 1 = Low; 2 = Average; 3 = Good; 4 = Excellent
16	Use of computer games	Ordinal	0 = Never; 1 = Occasionally; 2 = Regularly
17	Use of mobile games	Ordinal	0 = Never; 1 = Occasionally; 2 = Regularly
18	Availability of psychologist or chaplain	Binary (0/1)	1 = Yes; 0 = No
—	PTSD risk (target variable)	Binary (0/1)	1 = PTSD risk present; 0 = No PTSD risk

to measure agreement between categorical classification assessments, was calculated as:

$$\kappa = \frac{2 \cdot ((\mathrm{TP} \cdot \mathrm{TN}) - (\mathrm{FN} \cdot \mathrm{FP}))}{(\mathrm{TP + FP}) \cdot (\mathrm{FP + TN}) + (\mathrm{TP + FN}) \cdot (\mathrm{FN + TN})} \quad (6)$$

Statistical significance was set at $p < 0.05$.

Software

All calculations were performed using MS Excel. Model construction and data balancing were implemented using the Statistica software package, including the Multivariate Adaptive Regression Splines (MARSplines) module.

Description of the Dataset

The dependent variable in the MARSplines model was PTSD risk (binary outcome). Independent variables included gender, participation in combat operations, hobbies, chronic diseases, combat injuries, harmful habits, and other relevant characteristics (Table 2).

Ordinal variables were encoded to preserve the inherent ordering of response categories, while binary variables were coded using a 0/1 scheme.

Results

The analysis of the independent variables showed that male servicemen predominated in the sample, accounting for 90.0% of respondents. A substantial proportion of the participants reported systematic monitoring of their psychological state (69.3%), and 68.2% indicated the availability of a psychologist or chaplain within their unit. More than half of the respondents reported having hobbies or interests that helped them relax (62.4%), having minor children (61.7%), possessing higher education (56.4%), and

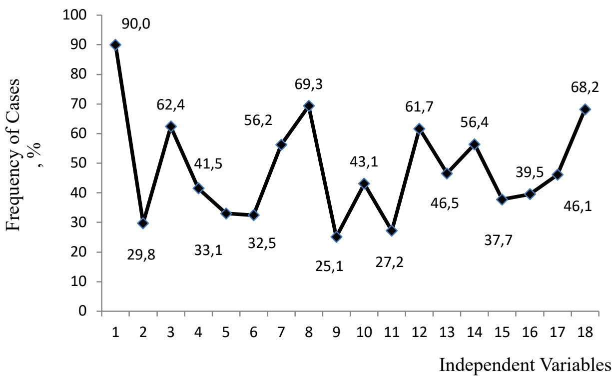

Fig. 1. Distribution of affirmative responses across the main descriptive variables, where: 1 – gender; 2 – participation in combat; 3 – hobbies or interests that help relax; 4 – chronic diseases; 5 – combat injuries/wounds; 6 – harmful habits; 7 – ability to engage in physical activities in the combat zone; 8 – systematic monitoring of psychological state; 9 – support from comrades; 10 – availability of medical and psychological assistance; 11 – marital status; 12 – presence of minor children; 13 – military rank; 14 – education; 15 – physical fitness level; 16 – use of computer games; 17 – use of mobile games; 18 – presence of psychologist/chaplain

having opportunities to engage in physical activities during military service (56.2%). These findings characterize the general structure of the sample and the prevalence of key psychosocial and lifestyle-related factors relevant to further modeling (see Figure 1).

MARSplines Model Development. To predict the risk of PTSD in military personnel, a MARSplines model was developed based on 18 dichotomous predictor variables. At the initial stage, the model was constructed under restrictive settings, allowing a limited number of basis functions and only first-order interactions between variables. Under these conditions, the initial model demonstrated insufficient accuracy in identifying PTSD risk cases.

To enhance predictive performance, the model parameters were progressively refined by increasing both the number of basis functions and the interaction depth. Model I was constructed using 11 terms and 10 basis functions, whereas subsequent model iterations allowed a greater number of basis functions and higher-order interactions. In the final configuration (Model III), the number of terms increased to 30, with 64 basis functions and interaction levels up to the third order.

The stepwise increase in model complexity resulted in improved generalization ability and classification performance. Specifically, the generalized cross-validation (GCV) error decreased by 0.7% (from 0.308 to 0.304), indicating a better balance between model fit and complexity. In parallel, the ability of the model to correctly classify PTSD risk cases increased by 2.7%, reflecting an overall improvement in predictive accuracy (see Table 3).

Model III demonstrated the best trade-off between model complexity and classification performance, as evidenced by the lowest Generalized Cross-Validation (GCV) value and the highest overall accuracy in identifying cases with PTSD risk.

The obtained results indicate that the MARSplines approach can be considered a potentially effective tool for predicting PTSD risk in military personnel. To enhance the robustness and interpretability of the classification metrics—particularly sensitivity and specificity with respect to PTSD risk detection—the input dataset was further optimized through balancing procedures.

For this purpose, an undersampling strategy was applied to the majority class, resulting in a reduced subset of 877 randomly selected military personnel without PTSD risk. This procedure produced an approximately equal number of observations with and without PTSD risk, allowing an unbiased evaluation of model performance.

To preserve the internal heterogeneity of the reduced sample, military personnel without PTSD risk were

Table 3. Evaluation of Model Quality Indicators Based on the Confusion Matrix, n=4403

PTSD	Confusion Matrix (where 1 – positive class: PTSD risk; 0 – negative class: no PTSD risk)						Model	Quality Indicators		
	Model I		Model II		Model III			Se	Sp	Accuracy
Men										
Forecast	0	1	0	1	0	1	I	100	0	79.7
0	3508	895	3502	880	3497	871	II	99.8	1.7	79.9
1	0	0	6	15	11	24	III	99.7	2.7	80.0
GCV	0.308		0.306		0.304					

Table 4. Evaluation of Model Quality Indicators Based on the Confusion Matrix (Balanced Data Using Clustering, n=1772)

PTSD	Confusion Matrix (where 1 – positive class: PTSD risk; 0 – negative class: no PTSD risk)						Model	Quality Indicators		
	Model I		Model II		Model III			Se	Sp	Accuracy
Men										
Forecast	0	1	0	1	0	1	I	63.1	62.1	62.6
0	553	339	541	312	567	300	II	61.7	65.1	63.4
1	324	556	336	583	310	595	III	64.7	66.5	65.6
GCV	0.463		0.460		0.454					

subsequently grouped using the k-means clustering method. As a result, two clusters were identified that differed significantly ($p < 0.05$) across most of the analyzed indicators. No statistically significant differences between clusters were observed for participation in combat or the presence of combat injuries and wounds.

Cluster 1 comprised 60.3% of the balanced sample and included 188 women and 1928 men, whereas Cluster 2 accounted for 39.7% of cases and included 205 women and 1187 men (see Table 4).

The comparative analysis of the identified clusters revealed substantial differences in several psychosocial and behavioral characteristics. Compared to Cluster 2, military personnel in Cluster 1 demonstrated a lower level of physical fitness, a higher prevalence of harmful habits, more frequent absence of a psychologist or chaplain within the unit, and more regular use of mobile games as a means of stress relief. In contrast, a higher proportion of respondents in Cluster 2 reported having minor children and higher education levels.

To form a balanced analytical sample while preserving cluster structure, a systematic random selection was applied. Specifically, every fourth observation was randomly selected from each cluster, resulting in a final subsample of 526 observations from Cluster 1 and 351 observations from Cluster 2.

The balancing procedure led to improved specificity of the MARSplines model in identifying the absence of PTSD risk; however, this was accompanied by a moderate reduction in overall diagnostic accuracy and model generalizability. This trade-off reflects the sensitivity of model performance to changes in class distribution and sample size.

In addition to clustering-based comparisons, gender-related differences across the studied variables were examined. It was hypothesized that male and female military personnel differ not only in PTSD risk but also in a range of demographic, behavioral, and psychosocial characteristics. For example, 31.8% (95% CI: 30.4–33.3%) of men and 10.6% (95% CI: 7.8–13.5%) of women reported participation in combat. The comparison of proportions demonstrated that men were statistically significantly more likely to have participated in combat than women ($Z = 12.938$; $p < 0.05$).

Further gender-based analysis revealed distinct patterns across multiple indicators. Women demonstrated significantly higher proportions of chronic diseases, systematic monitoring of psychological state, availability of social support, marital status, higher education, and adequate physical fitness levels. Conversely, men showed statistically significantly higher proportions ($p < 0.05$) of combat injuries and wounds, harmful habits, the ability to engage in physical activities in combat zones, as well as the use of computer and mobile games for stress relief (see Figure 2).

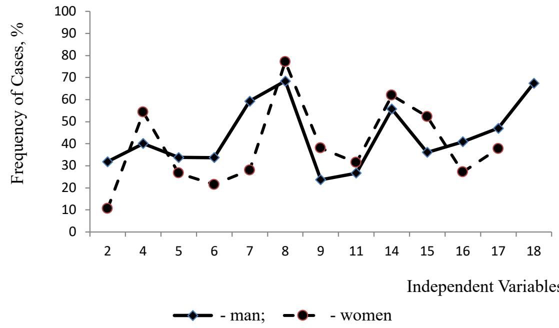

Fig. 2. Proportions of respondents with statistically significant ($p<0.05$) differences by gender (n=4403), where 2 – participation in combat; 4 – chronic diseases; 5 – combat injuries/wounds; 6 – harmful habits; 7 – ability to engage in physical activities in the combat zone; 8 – systematic monitoring of psychological state; 9 – support from comrades; 11 – marital status; 14 – education; 15 – physical fitness level; 16 – use of computer games; 17 – use of mobile games; 18 – presence of psychologist/chaplain

In addition, a significantly higher prevalence of PTSD risk was observed among men, exceeding that among women by 10.3% ($Z = 6.305$; $p < 0.05$). This finding suggests that gender-specific differences should be taken into account when developing predictive models of PTSD risk. Accordingly, it is methodologically justified to consider separate models for men and women.

Given the substantial predominance of men in the military sample and the higher observed PTSD risk among male service members, further modeling efforts were focused on the male subgroup. At this stage of the study, the prediction of PTSD risk in men was prioritized, and the dataset was balanced to improve model performance.

Spline-based modeling applied to the balanced male dataset resulted in an increase in model sensitivity, reflecting improved detection of PTSD risk cases, accompanied by a reduction in specificity, indicating a decreased ability to identify the absence of PTSD risk (Table 5).

An analysis of predictor importance revealed that certain variables contributed disproportionately to the formation of the predictive model. In particular, the variable harmful habits emerged as the most influential predictor, appearing seven times in the basis functions constituting Model III for the PTSD-balanced dataset. In contrast, the variable describing the availability of medical and psychological support did not contribute to the formation of basis functions

Table 5. Assessment of model quality indicators for men based on the error matrix (for balanced PTSD data, n=1884)

PTSD	Confusion Matrix (where 1 – positive class: PTSD risk; 0 – negative class: no PTSD risk)						Model	Quality Indicators		
	Model I		Model II		Model III			Se	Sp	Accuracy
Men										
Forecast	0	1	0	1	0	1	I	72.7	52.1	63.5
0	755	405	779	409	778	381	II	75.0	51.7	64.5
1	283	441	259	437	260	465	III	75.0	55.0	66.0
GCV	0.459		0.454		0.450					

Note: Se – sensitivity; Sp – specificity; Accuracy – accuracy; GCV – Generalized Cross Validation

Table 6. Assessment of Model Quality Indicators for Men Based on the Error Matrix (for Balanced PTSD Data According to Clustering Results, n=1624)

PTSD	Confusion Matrix (where 1 – positive class: PTSD risk; 0 – negative class: no PTSD risk)						Model	Quality Indicators		
	Model I		Model II		Model III			Se	Sp	Accuracy
Forecast	0	1	0	1	0	1	I	59.6	66.9	63.4
0	464	280	478	288	506	304	II	61.4	66.0	63.8
1	314	566	300	558	272	542	III	65.0	64.1	64.5
GCV	0.462		0.459		0.454					

Note: Se – sensitivity; Sp – specificity; Accuracy – accuracy; GCV – Generalized Cross Validation

in any of the tested models, indicating its limited predictive value in this modeling framework.

The obtained model quality indicators were considered insufficient for reliable prediction, which necessitated further refinement of the dataset. Therefore, the next stage of the study involved balancing the male dataset based on clustering results for men without PTSD risk.

Cluster analysis demonstrated that men without PTSD risk were divided into two distinct clusters. Statistically significant differences between clusters ($p < 0.05$) were observed for most studied variables, with the exception of chronic diseases, combat injuries and wounds, and the ability to engage in physical activity in combat zones, for which no significant differences were detected.

Cluster 1 comprised 61.9% of male military personnel and was characterized by a higher prevalence of harmful habits, inadequate physical fitness, limited social support, and frequent use of mobile games as a means of psychological stress relief. In contrast, men in Cluster 2 more frequently had higher education and minor children.

To construct the final balanced analytical sample, systematic random sampling was applied, resulting in the selection of 482 men from Cluster 1 and 296 men from Cluster 2, along with the inclusion of all 846 men with PTSD risk. This approach ensured an approximately uniform distribution of PTSD risk while preserving the proportional structure of clusters among men without PTSD risk (Table 6).

At the final stage of model development, the complexity of the MARSplines model was further increased to allow the algorithm to explore a wider range of nonlinear relationships and interactions among predictors. This approach aimed to improve the approximation of complex dependencies within the input data. The final model incorporated 55 terms and 202 basis functions, representing the highest level of model flexibility applied in the present study.

Analysis of variable importance demonstrated that participation in combat was the most influential predictor of PTSD risk among male military personnel. The second and third most important predictors were the presence of combat injuries or wounds and chronic diseases, respectively. In contrast, the presence of minor children showed the lowest relative contribution to PTSD risk prediction in this population.

Although individual predictors differed in their relative importance, all independent variables contributed to the final model structure, being included across the 202 basis functions that collectively formed 55 splines. This finding indicates that PTSD risk in male military personnel is determined by a multifactorial combination of demographic, behavioral, psychosocial, and service-related characteristics rather than by isolated predictors.

The ranked importance of predictors contributing to PTSD risk prediction in the final model is illustrated in Figure 3.

The developed MARSplines model demonstrated that the baseline probability of no PTSD risk exceeded the probability of elevated PTSD risk, indicating an overall predominance of resilient outcomes within the analyzed sample. Model flexibility was enhanced by allowing up to 300 basis functions with interaction orders up to six, enabling the approximation of complex nonlinear relationships among predictors.

In the MARSplines framework, basis functions are defined as piecewise linear components of the form $\max(0, x - c)$ or $\max(0, c - x)$, where c represents a data-driven knot. These functions capture threshold effects in predictor variables. For illustrative purposes, an example

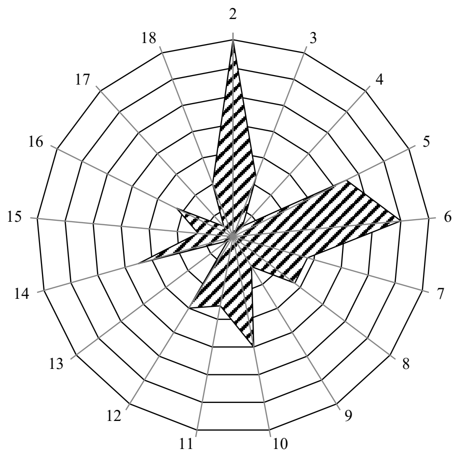

Fig. 3. Importance of Variables for Prediction (n=1624), where 2 – combat participation; 3 – hobbies or activities that help to relax; 4 – chronic diseases; 5 – combat injuries/wounds; 6 – bad habits; 7 – ability to engage in PA in the combat zone; 8 – systematic monitoring of psychological state; 9 – peer support; 10 – availability of medical and psychological support; 11 – marital status; 12 – presence of minor children; 13 – military rank; 14 – education; 15 – physical condition level; 16 – use of computer games; 17 – use of mobile games; 18 – presence of a psychologist/ chaplain

of a basis function is max(0, Combat participation – 0.5), indicating that direct involvement in combat contributes to an increased PTSD risk only after a specific threshold is reached. Another example is max(0, Physical fitness level – 2), reflecting a nonlinear protective effect of physical fitness, whereby higher fitness levels are associated with a reduced likelihood of PTSD risk.

Rather than focusing on an exhaustive enumeration of individual basis functions, model interpretation was based on the contribution of key predictors and their interactions. The strongest effects were associated with combat participation and combat-related injuries, which frequently interacted with each other, indicating their joint influence on PTSD risk. Additional influential predictors included access to psychological or social support, physical fitness level, and engagement in physical or recreational activities.

Increasing the maximum number of basis functions and interaction depth improved the model's classification performance. Sensitivity and specificity reached 71.1% and 69.5%, respectively, with an overall diagnostic accuracy of 70.3% and a Cohen's kappa coefficient of 0.405, indicating acceptable agreement between predicted and observed PTSD risk. These results confirm that the proposed model can be applied to predict PTSD risk in military personnel.

The obtained results of PTSD risk prediction have direct applied significance for physical education, sport, and physical rehabilitation systems. Identification of groups with increased psycho-emotional risk based on the predictive model enables pedagogical differentiation of individuals according to their readiness for physical loads, which represents a fundamental principle of modern physical education theory and methodology.

From a practical perspective, the modeling results can be used to substantiate individualized physical activity programs aimed at reducing stress load, enhancing psychophysiological resilience, and preventing maladaptive responses. Depending on the predicted level of PTSD risk, the volume, intensity, and nature of physical exercises may be adjusted, including the ratio of aerobic, coordinative, and game-based activities, as well as the inclusion of recreational and rehabilitation-oriented physical culture means.

Thus, the proposed predictive model should be regarded not only as a statistical or machine-learning tool, but also as an element of pedagogical diagnostics that ensures evidence-based integration of physical activity and sport-based interventions into the prevention and correction of stress-related conditions.

Discussion

Predicting the risk of post-traumatic stress disorder (PTSD) in military personnel during periods of armed conflict is of critical importance from both clinical and applied perspectives. Early identification of service members at increased risk of PTSD enables timely preventive interventions, which may reduce the severity of stress-related disorders, limit long-term psychological consequences, and facilitate social reintegration after combat exposure. From a military standpoint, effective PTSD risk prediction supports combat readiness, morale, and overall operational effectiveness, thereby contributing to national defense capacity.

The classification performance indicators obtained in this study can be interpreted in line with previously proposed benchmarks for applied predictive models. In particular, accuracy values exceeding 70% are generally considered acceptable for practical classification tasks, while Cohen's kappa coefficients within the range of 0.40–0.85 reflect moderate to substantial agreement between predicted and observed outcomes (Ameneshewa et al., 2023; Seal, et al., 2007; Więckowska et al., 2022). These criteria provide an appropriate framework for evaluating the practical utility of the proposed MARSplines models.

The relevance of PTSD risk prediction has been emphasized in numerous studies highlighting its role in preventing severe stress-related outcomes, including chronic psychological disorders, self-destructive behavior, and suicide (Andrieieva et al., 2023; Bekesiene & Bagdžiūnienė, 2022; Johnson, 2021). Consequently, the problem of combat stress and PTSD risk associated with participation in armed conflict has become a subject of active interdisciplinary research involving specialists in medicine, psychology, psychiatry, physical therapy, physical education, and sport sciences (Byshevets et al., 2024; Hamel, 2020; Shynkaruk & Davydov, 2023). Many authors emphasize the necessity of early detection of military personnel at increased PTSD risk, an approach that this study fully supports (Hoge et al., 2006; Seal et al., 2007).

In the present study, a MARSplines-based predictive model was developed using 18 dichotomous variables reflecting demographic, behavioral, psychosocial, and service-related characteristics of military personnel. The modeling process involved a stepwise increase in complexity, including expansion of the number of basis functions and interaction orders, as well as successive data balancing procedures. These methodological decisions were aimed at improving the model's ability to capture nonlinear relationships while reducing bias caused by class imbalance.

Initial models demonstrated relatively high overall accuracy (79.7–80.0%); however, they were characterized by very low sensitivity, indicating insufficient ability to correctly identify cases with PTSD risk. At the same time, specificity was artificially inflated due to the predominance of observations without PTSD risk in the dataset. This imbalance resulted in near-zero kappa coefficients, highlighting the limited practical value of the initial models despite their seemingly high accuracy. Such findings underscore the importance of considering sensitivity, specificity, and agreement metrics jointly rather than relying on accuracy alone.

Subsequent data balancing by PTSD status and clustering-based undersampling improved model interpretability and reduced classification bias, but the achieved sensitivity (63.1–64.7%) and specificity (62.1–66.5%) remained insufficient for reliable PTSD risk prediction. These results indicated that further methodological refinement was required.

A critical step in improving model performance involved stratification of the dataset by gender. Statistically significant differences in both PTSD risk prevalence and associated predictors between men and women justified the development of gender-specific predictive models. Given the predominance of men in the military sample and the higher observed PTSD risk among male service members, the present study focused on male personnel, while PTSD risk prediction in women is planned for future research with expanded datasets.

The final model, constructed for male military personnel using balanced data and increased model complexity (300 basis functions and interaction order up to six), demonstrated substantial improvements in classification performance. Compared to previous iterations, sensitivity increased by 6.1%, indicating enhanced detection of PTSD risk cases, while specificity increased by 5.4%, reflecting improved identification of the absence of PTSD risk. Overall diagnostic accuracy improved by 5.8%, and the GCV error decreased from 0.454 to 0.450, suggesting better generalization to new data. Importantly, the kappa coefficient increased to 0.405, indicating moderate agreement between predicted and observed PTSD risk.

From an applied perspective, these findings suggest that MARSplines-based models may serve as a valuable analytical tool for identifying military personnel at increased PTSD risk. In the context of physical education and sport sciences, such predictive models can inform the development of targeted preventive strategies, including structured physical activity programs, stress-resilience training, and psychophysiological monitoring within professional-applied physical training systems. Integration of predictive analytics with physical culture–based interventions may enhance early prevention, functional readiness, and long-term health outcomes in military populations.

Prospects for Further Research

The developed model for predicting PTSD risk in military personnel has demonstrated substantial analytical potential; however, further refinement is warranted. Future research will focus on improving model specificity by incorporating additional explanatory variables that may enhance differentiation between PTSD risk cases and the absence of PTSD risk. In addition, the application and comparison of alternative machine learning algorithms may provide further improvements in classification performance.

Another promising direction involves comparative analysis of PTSD risk in military personnel and other populations exposed to chronic stress. Integrating knowledge of PTSD risk factors with predictive modeling may support the development of targeted preventive strategies within systems of physical activity, physical culture, and cybersports. Such approaches may contribute to reducing stress-related consequences, strengthening psychological resilience, and improving functional readiness in military populations.

Overall, continued research in these areas may enhance the accuracy of PTSD risk prediction and support the development of effective prevention and mitigation strategies, thereby improving quality of life for military personnel, their families, and society as a whole.

Limitations

An important limitation of the present study concerns the interpretation of PTSD risk based on the Mississippi Scale for Combat-Related PTSD. Although this instrument demonstrates high reliability and is widely used for screening purposes, the cut-off values applied in this study should be regarded as non-clinical and non-validated for diagnostic decision-making.

The classification of PTSD risk levels was used exclusively as a screening and risk stratification tool and should not be interpreted as a clinical diagnosis. The identified risk categories reflect the probability of elevated post-traumatic stress symptoms rather than confirmed PTSD. Final diagnosis, clinical confirmation, and treatment planning require comprehensive assessment by qualified mental health professionals, including psychologists or psychiatrists. Accordingly, the proposed predictive model is intended to support early identification and preventive interventions rather than replace professional clinical evaluation.

Another limitation relates to the use of self-report survey methods for data collection. While this approach is appropriate given the specific conditions of military service, including training activities, combat missions, and rehabilitation periods, self-assessment may be subject to response bias and reporting inaccuracies. Therefore, the findings should be interpreted with caution, and future studies should incorporate objective psychophysiological and clinical measures to strengthen validity.

Finally, the study sample included a substantially smaller proportion of female military personnel compared to males. Given the observed gender differences in PTSD risk prevalence and contributing factors, the development and validation of predictive models for female military personnel require further investigation based on larger and more representative samples.

Conclusions

Predicting PTSD risk in military personnel during armed conflict is of critical importance for early intervention, as timely identification of high-risk individuals may reduce rehabilitation costs and support measures aimed at maintaining morale and combat readiness.

In this study, a MARSplines-based model was developed to predict PTSD risk in military personnel using 18 dichotomous variables reflecting demographic, behavioral, and service-related characteristics. Progressive optimization of the model—through increasing the number of basis functions and interaction orders, as well as balancing the dataset by gender and PTSD risk—resulted in improved classification performance. The final model, constructed for male military personnel, incorporated 300 basis functions and interaction order up to six, leading to an increase in sensitivity by 6.4%, specificity by 5.4%, and overall diagnostic accuracy by 5.8%. Additionally, the reduction of the GCV error from 0.454 to 0.450 indicated improved generalization to new data.

The application of machine learning models for PTSD risk prediction in military personnel exposed to traumatic events represents a valuable tool for early prevention and targeted intervention. The proposed model may assist in identifying individuals at elevated risk and directing them toward further assessment and support. Moreover, the findings support the development of preventive programs that integrate physical culture, sports, and cybersports as means of stress reduction and resilience enhancement within military populations.

Ethics Approval

The study was conducted in accordance with the principles of the Declaration of Helsinki and complied with internationally accepted ethical standards for research involving human participants. The research protocol was reviewed and approved by the Ethics Committee of the National University of Ukraine on Physical Education and Sport.

All participants were informed about the study objectives, procedures, and potential risks prior to participation. Written informed consent was obtained from all participants. Participation was voluntary, and participants were informed of their right to withdraw from the study at any stage without any consequences.

All personal data were anonymized, and the confidentiality of participants' information was strictly maintained throughout the research process.

Data Availability Statement

The datasets generated and analyzed during the current study are not publicly available due to ethical restrictions and the sensitive nature of the data related to military personnel. The data may be made available from the corresponding author upon reasonable request and subject to approval by the relevant institutional authorities.

AI Transparency Statement

AI-assisted tools were used exclusively for language editing and grammatical refinement during manuscript preparation. No artificial intelligence tools were used in data collection, analysis, interpretation of results, or decision-making processes.

All scientific content, study design, methodological decisions, statistical analyses, interpretation of results, and conclusions were performed solely by the authors, who assume full responsibility for the integrity and accuracy of the manuscript.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Застосування багатовимірних адаптивних регресійних сплайнів (MARSplines) для прогнозування ризику посттравматичного стресового розладу у військовослужбовців

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

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Обгрунтування. Прогнозування ризику розвитку посттравматичного стресового розладу (ПТСР), що має значні соціальні та економічні наслідки й негативно впливає на боєздатність військовослужбовців, є актуальним науково-практичним завданням. Раннє виявлення осіб із підвищеним ризиком дозволяє своєчасно впроваджувати профілактичні стратегії, зокрема інтервенції, засновані на фізичній культурі, фізичній активності, спорті та реабілітації.

Мета. Розробити та валідизувати прогностичну модель оцінювання ризику ПТСР у військовослужбовців і обґрунтувати її застосування як інструменту підтримки рішень у педагогічному плануванні програм фізичного виховання, фізичної активності та спортивно орієнтованої профілактики й реабілітації.

Матеріали та методи. У дослідженні взяли участь 4 403 військовослужбовці, з яких 89,9% — чоловіки, віком переважно 21–50 років. Вираженість посттравматичних стресових реакцій оцінювали за шкалою Mississippi Scale for Combat-Related PTSD (військова версія), що продемонструвала високу внутрішню узгодженість (Cronbach's α = 0,892; коефіцієнт Гуттмана = 0,920). Застосовано порівняльний і гендерний аналізи, а також методи машинного навчання з використанням Multivariate Adaptive Regression Splines (MARSplines) із поетапною оптимізацією, балансуванням вибірки та оцінюванням класифікаційних показників.

Результати. Побудовано прогностичну модель ризику ПТСР на основі MARSplines із використанням 18 дихотомічних демографічних, поведінкових і службових змінних. Фінальна модель для чоловіків включала 300 базисних функцій з порядком взаємодії шість і продемонструвала чутливість 71,1%, специфічність 69,5%, загальну точність 70,3% та помірну узгодженість між прогнозованим і фактичним ризиком (κ Коена = 0,405).

Висновки. Машинно-орієнтоване прогнозування ризику ПТСР є перспективним підходом для ранньої профілактики та цільових інтервенцій у військовому середовищі. Запропонована модель може використовуватися для ідентифікації осіб групи підвищеного ризику та обґрунтування програм профілактики й реабілітації, зокрема заснованих на фізичній культурі, спорті та е-спорті, спрямованих на зниження стресу й підвищення резилієнтності військовослужбовців.

Ключові слова: психічне здоров'я, стрес-асоційовані стани, посттравматичний стресовий розлад, військовослужбовці, прогностичне моделювання, фактори ризику, фізична культура і спорт, рухова активність.

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Original Scientific Article

From Reception to Carry: Validating a Scalable First-Touch-to-Dribbling Progression in Youth Football

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Abstract

Objectives. This study aimed to develop, validate, and conduct a preliminary effectiveness evaluation of a scalable training model that explicitly links first-touch quality to dribbling execution for U-13 footballers using representative, constraints-led practice.

Materials and Methods. Following a Research and Development (R&D) logic, a sequence produced ten staged variants, expert-validated and piloted before a preliminary pre–post control comparison in grassroots schools. The outcomes combined standardized circuits and small-sided scenarios to index reception-to-carry performance, with fidelity, safety, and acceptability monitored.

Results. Most participants improved on the integrated index; two-thirds recorded positive change, while few exhibited a decline. A modest pre–post correlation suggested heterogeneous gains independent of baseline level. The greatest gains were observed when reception tasks required scanning, oriented first touch, and immediate carry or release under scaled space, pressure, and time constraints. Expert review supported content relevance and age-appropriateness; pilots and large-group trials confirmed the feasibility across resource conditions. Discussion: Converging evidence from development, validation, and field testing phases indicates that small-sided games, targeted technique consolidation, SAQ, and proprioceptive elements collectively enhance perception–action coupling and affordance attunement, enabling potentially transferable improvements in first touch and dribbling. Practical implications include simple progression knobs, coach prompts, and equipment configurations to preserve informational fidelity in constrained settings.

Conclusions. The findings suggest that a curriculum-aligned, R&D-validated progression shows promising preliminary effectiveness for strengthening youth development pathways by coupling reception to purposeful carry decisions, warranting wider adoption and further dose–response research.

Keywords: first touch, youth football, small-sided games, constraints-led approach, representative learning design.

Introduction

Youth football between ages 10 and 13 represents a decisive phase for building the technical and perceptual–cognitive repertoire that underpins long-term player development. Within this phase, first-touch and dribbling skills are repeatedly linked to match performance and talent pathways because they regulate the speed and quality with which players can receive, secure, and progress the ball under pressure (Iuliano et al., 2023; Szabó et al., 2024). The first touch—in effect, the initial control action upon receiving the ball—sets the spatial–temporal conditions for subsequent behaviors, including movement to protect possession, orientation to the field, and decisions to carry, pass, or shoot (Szabó et al., 2024). A consistently high-quality first touch is associated with a shorter perception–action cycle, enabling earlier assessment of affordances and the initiation of dribbling sequences in crowded youth contexts (Iuliano et al., 2023) As youth matches become tactically denser at this level, the premium on reception quality and rapid ball carrying becomes even more pronounced.

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Converging evidence highlights a functional link between reception quality and the initiation of dribbling. Previous studies demonstrate that effective dribblers depend heavily on visual feedback to stabilize ball control; when this feedback is disrupted, subsequent dribbling performance suffers, suggesting that robust first-touch competence supports resilient ball carrying under perceptual uncertainty (Alzate et al., 2025). Complementary work shows that mastering core technical skills, including first touch, is associated with broader performance gains among young footballers (Souglis et al., 2022). Decision-making during dribbling—where players must select among carrying, shielding, or release options at pace—further binds technique to cognition (Souglis et al., 2022), while constraints-led practice has been shown to enhance both dribbling execution and the adaptability needed to exploit transient space–time windows (D'Isanto et al., 2021). Collectively, these accounts position first touch and dribbling as mutually reinforcing levers for performance development in U-13 football.

At a system level, national curricula and training philosophies organize how these skills are cultivated. The Filanesia model emphasizes a holistic approach to youth development that couples technical proficiency (e.g., ball control, dribbling) with psychological, social, and tactical growth, thereby aligning skill acquisition with game understanding (Hadinata et al., 2023; Sucipto et al., 2021). Aligning club- and school-based training with such frameworks can standardize exposure to high-value learning experiences across regions and coaching contexts (Hunter et al., 2022). Within this architecture, small-sided, game-like tasks and structured progressions are promoted as vehicles to integrate technical behaviors with tactical perception, fostering creativity, decision-making, and problem-solving—qualities increasingly demanded in modern football (Carvalho et al., 2021).

Despite these advances, practitioners still confront a recurring problem: how to translate curricular intent into a reproducible, age-appropriate pathway that explicitly connects first touch to dribbling competence in 10–13-year-olds. Many grassroots environments (e.g., SSBs) face constraints of space, equipment, and variable coaching expertise, which can fragment instruction and decouple reception training from subsequent ball-carrying actions. Moreover, developmental dynamics—including rapid growth, temporary coordination dips, and heterogeneous motivation—can blunt the efficacy of one-size-fits-all drills (Clemente, Silva, et al., 2022; Formenti et al., 2021). The general solution proposed across the literature is to employ practice architectures that preserve representativeness, scaffold coordination, and maintain motivational engagement while ensuring that reception tasks naturally flow into dribbling decisions (Aquino et al., 2017; García-Ceberino et al., 2020).

Several complementary paradigms offer a basis for this solution. Small-sided games (SSG) increase ball contacts, decision density, and contextual interference, all of which accelerate learning of reception and dribbling in environments resembling match play (Clemente, Praça, et al., 2022; Suryadi et al., 2023). The Constraints-Led Approach (CLA) systematically manipulates task, environmental, and individual constraints to channel functional movement solutions and perception–action coupling; in doing so, it improves decision speed and technical adaptability during dribbling (Brink et al., 2023; D'Isanto et al., 2021). Representative learning design operationalizes these ideas by aligning practice information with in-game affordances so that improvements in first touch transfer more reliably to carrying and release decisions (García-Ceberino et al., 2020). Together, these lines of work suggest that coupling reception and dribbling within game-like constraints may be superior to training them in isolation.

Additional modalities can be layered to maximize gains. Technique drills, when targeted and time-bound, consolidate core mechanics (e.g., receiving with varied surfaces, first touch into space) that later sustain performance in SSG or CLA tasks (Okilanda et al., 2021). SAQ (speed, agility, quickness) training enhances the physical preconditions for effective ball carrying—acceleration, change of direction, and footwork efficiency—thereby widening the action possibilities available after a quality first touch (Adi & Kustiawan, 2024; Ardiansyah et al., 2024). Feedback-rich tools and task designs can further sharpen error detection and self-regulation, accelerating technical consolidation in youth players (Hadinata et al., 2023). When coherently sequenced, these components outline a practical pathway from reception competence to dribbling proficiency that is sensitive to maturation and motivation constraints.

A focused body of literature is especially relevant to designing such pathways. Studies of decision-making during dribbling highlight the need to embed choice architecture within technical tasks (Iuliano et al., 2023). Constraints-led interventions report improvements in adaptability and dribbling outcomes when task complexity is progressively adjusted (Brink et al., 2023; D'Isanto et al., 2021). SSG-based programs document superior engagement and higher practice volumes for reception and carrying actions relative to decontextualized drills (Carvalho et al., 2021; Suryadi et al., 2023). Nevertheless, across these streams, two gaps persist: first, few interventions make the dependency between first touch and the ensuing carry the explicit organizing principle of the progression; second, there is limited evidence of validated, scalable models tailored to U-13 players in grassroots settings and aligned with national frameworks such as Filanesia (Hadinata et al., 2023; Sucipto et al., 2021; Szabó et al., 2024).

The present study addresses these gaps by developing, validating, and conducting a preliminary effectiveness evaluation of a structured training model that explicitly links first-touch quality to dribbling execution for youth players aged 10–13. Conceptually, the model integrates representative learning design, CLA principles, SSG exposure, targeted technique consolidation, SAQ components, and feedback-rich tasks to ensure that each reception is designed to afford a purposeful carry or release (Adi & Kustiawan, 2024; Suryadi et al., 2023). In line with Filanesia's holistic emphasis, it situates technical acquisition within tactical understanding and psychosocial development. Rather than testing causal efficacy, this study examines whether the integrated progression shows promising preliminary effectiveness compared with conventional practices that treat reception and dribbling as separate blocks. The scope of the study concerns players in the U-13 bracket, trained within typical resource constraints of grassroots programs, with outcomes assessed on both skill performance and decision-related indicators, thereby offering a practical, scalable contribution to youth development pathways.

Materials and methods

Research Design and Context

This study adopted a Research and Development (R&D) methodology adapted from the Borg and Gall model, explicitly structured around three sequential phases: (1) model development, (2) expert and pilot validation, and (3) preliminary field-based effectiveness evaluation, progressing through needs assessment, product development, expert appraisal, pilot testing, iterative revision, and effectiveness evaluation (Paisal et al., 2024). The adaptation prioritized methodological rigor and ecological validity for grassroots environments by triangulating perspectives from coaches, players, and parents during the earliest phases (Manshuralhudlori et al., 2023). The study aligned with the Filanesia curriculum for the 10–13 age band, embedding technical growth within tactical understanding and psychosocial development. Representative learning design and a constraints-led approach guided both the intervention and the measurement strategy so that practice information matched in-game affordances and perception–action coupling. The setting comprised 15 football schools (SSBs) in Bungo Regency. Eligible players aged 10–13 were recruited with simple random procedures after consent and assent. Inclusion criteria comprised active registration at an SSB and regular training attendance, while exclusion criteria included injury or incomplete assessment data. Coaches received procedural training to standardize delivery across sites, and ethics safeguards for research with minors were observed throughout.

Development of the Training Model

Product development translated curricular principles into a progressive first-touch-to-dribbling pathway consisting of ten staged variants (v1–v10). Each variant specified a learning focus, constituent skill components, representative game application, and modifiable constraints (space, time, number/skill of defenders, and touch limits). Design decisions leveraged constraints-led manipulation to channel functional movement solutions and decision quality during dribbling (Brink et al., 2023; D'Isanto et al., 2021), while representative tasks ensured transfer to match contexts (García-Ceberino et al., 2020). Targeted technique consolidation supported core mechanics of receiving to the front foot and first touch into space (Suryadi et al., 2023). SAQ elements improved physical preconditions—acceleration, change of direction, and footwork efficiency—needed to exploit a high-quality first touch. Feedback-rich tools and task designs promoted error detection and self-regulation, expediting technical consolidation in youth players. The model is summarized in Table 1.

Procedures and Experimental Flow

The preliminary study combined observations with interviews of coaches, players, and parents to map current practice and isolate gaps in connecting reception to dribbling during routine sessions. A mixed panel of experienced coaches and sport-science academics conducted expert validation, providing relevance ratings and narrative feedback on age-appropriateness, load, safety, and practicality. Prototype tasks were refined through small-group pilots to test feasibility and instruction clarity, followed by large-group trials to stress-test scalability under scheduling and resource constraints. The culminating effectiveness study implemented a pre-test–post-test control-group design as a preliminary effectiveness evaluation rather than a definitive experimental trial, under authentic SSB conditions.

Outcome Measures

Outcomes captured technical execution and performance in representative conditions. Technical indices included reception quality (control and orientation), dribbling execution on standardized skill courses, and combined reception-to-carry transitions. Decision-related outcomes in small-sided games—decision latency, successful exploitation of space, and end-action quality—reflected the coupling of technique and cognition. Physical capacities supportive of ball carrying, including change-of-direction speed and footwork efficiency, contextualized skill changes. Observers underwent calibration with anchor videos; operational definitions and scoring sheets were finalized during expert review, with composite scores derived from standardized rating rubrics and aggregated to form integrated indices.

Validity and Reliability

Content validity was established through structured expert appraisal to verify that the measured skills represent the complexity of youth football at U-13 (Hadinata et al., 2023; Sridadi et al., 2021). Construct validity was tested by comparing pre–post gains from the integrated model against comparison conditions that trained reception and dribbling more separately, as predicted by representative and constraints-led theory. Inter-rater reliability was estimated via intraclass correlation coefficients after common-anchor calibration, with coefficients indicating acceptable to high agreement across outcomes, and internal consistency of composite indices used Cronbach's alpha within accepted thresholds for applied sport research (Okilanda et al., 2021). Implementation acceptability was triangulated with post-session surveys and structured coach debriefs (Alzate et al., 2025).

Statistical Analysis

Content validity was established through structured expert appraisal to verify that the measured skills represent the complexity of youth football at U-13 (Hadinata et al., 2023; Sridadi et al., 2021). Construct validity was tested by comparing pre–post gains from the integrated model against comparison conditions that trained reception and dribbling more separately, as predicted by representative and constraints-led theory. Inter-rater reliability was estimated via intraclass correlation coefficients after common-anchor calibration, with coefficients indicating acceptable to high agreement across outcomes, and internal consistency of composite indices used Cronbach's alpha within accepted thresholds for applied sport research (Okilanda et al., 2021).

Table 1. First Touch to Dribbling Training Model (v1–v10)

Variant	Learning focus	Skill components	Game application/ context	Key constraints/ progression knobs	Equipment
v1	Receiving fundamentals and body orientation	First touch with inside/ outside; receiving on the front foot; protective stance	1v0 reception in lanes; orient to open space before carry	No defender; two-touch rule; slow tempo; enlarged safe zone	Cones, markers, balls
v2	Directional first touch into space	First touch out of feet; scanning before reception; first step acceleration	1v0 to mini-goal gates; dribble through target after controlled first touch	Add time cap; smaller gates; light passive pressure from coach	Cones, mini-goals, markers
v3	First touch while moving	Receiving on the run; touch across body; transition to immediate carry	1v0 slalom entry after reception; timed skill course	Reduce lane width; add turn points; limit touches to 2–3	Cones, poles/ markers, stopwatch
v4	Reception under passive defender	Shielding; first touch to the safe side; body feints to create lane	1v1 shadow (no tackle) → dribble exit to gate	Introduce shadow defender; add countdown; shrink exit gate	Cones, bibs, mini-goals
v5	First touch to beat active pressure	Touch past defender; change of direction; escape step	1v1 live to end-line/ mini-goal after controlled reception	Defender distance reduced; scoring bonus for forward first touch; touch-limit	Cones, mini-goals, bibs
v6	Wall-pass reception into carry	One-two (give-and-go); angled first touch; release vs. carry choice	1–2 with rebound surface/partner → carry to target	Tighter angles; weaker-foot only; decision within 2 s	Rebound surface or partner, cones, mini-goals
v7	Reading overload (2v1) from first touch	Receiving shape; first touch to commit defender; carry vs. pass	2v1 to target zones; conditioned bonus for carry after reception	Defender starts closer; constraint on pass count; smaller scoring zone	Cones, target zones, bibs
v8	Small-sided transition (3v2)	Oriented first touch in transition; scanning; acceleration after win	3v2 counter to mini-goals; starts from coach serve	Shorter field; touch cap on the first receiver; time-to-goal bonus	Mini-goals, markers, stopwatch
v9	Representative SSG (4v4) with conditions	First touch triggers carry or release; support angles	4v4 to target goals; rules reward forward-facing first touch	Reduce space; add off-ball constraints; variable scoring for carry after reception	Goals/mini-goals, bibs
v10	Match-like game with faded constraints	Integration of reception→carry decisions; self-regulation	Conditioned game; remove constraints in final phase for free play	Begin with touch/time constraints then fade; coach feedback only on resets	Full goals/ mini-goals, bibs, markers

Note. Constraints can be scaled via space, defenders, ball pressure, time limits, and touch limits. Equipment lists are adaptable to SSB resources.

Implementation acceptability was triangulated with post-session surveys and structured coach debriefs (Alzate et al., 2025).

Fidelity, Ethics, and Scope

Fidelity was supported by coach workshops, session plans with progression checkpoints, and observation checklists. Coaches logged exposure minutes to each variant and any contextual adaptations; independent observers audited delivery using a structured rubric, with discrepancies informing mid-cycle adjustments to maintain alignment between intended and delivered task demands. Ethical safeguards included parental consent, player assent, age-appropriate training loads, safety briefings, and immediate access to first aid; data were de-identified and reported in aggregate. The study received ethical approval from the relevant institutional review board (Approval No.158/KEPK-FIKES/XII/2025). The scope focuses on U-13 players within resource-constrained grassroots settings, aligning with Filanesia's holistic objectives. The methodology is designed to be replicable by SSB coaches and suitable for evaluation in reputable international outlets, given its integrated validity–reliability procedures and its explicit coupling of first touch to dribbling execution.

Results

Needs Analysis

Field observations and stakeholder interviews revealed systematic gaps in linking reception (first touch) to subsequent dribbling actions within routine SSB sessions. Coaches reported limited time for individual skill consolidation and challenges designing transitions from receiving to carrying under pressure. These findings were consistent with prior needs assessments that document inadequate, non-systematic provision for foundational skills among children aged 10–13 (Qowiyyuridho et al., 2021; Sridadi et al., 2021). Constraints clustered around space, equipment, and coaching expertise. Restricted training areas—especially in urban contexts—limited the representativeness of practice, consistent with evidence that diverse practice environments support skill acquisition (González-Ródenas et al., 2022). Equipment gaps (e.g., scarcity of age-appropriate balls or rebound surfaces) reduced opportunities for high-frequency, feedback-rich receptions and carries, echoing the importance of task-appropriate tools for ball control in younger players (Alzate et al., 2025). Coaches highlighted variable familiarity with youth-specific pedagogy; aligning program content with a curriculum such as Filanesia and providing structured session plans emerged as key priorities during the development phase.

Expert Validation

A mixed panel of experienced football coaches and sport-science academics evaluated content relevance, age-appropriateness, instructional clarity, safety, and load management. Reviewers rated the model as appropriate for developmental needs in ages 10–13 and emphasized explicit learning objectives that integrate enjoyment and skill progression. Age-appropriate task dosages and progression thresholds were refined to mitigate over-exertion risks and to follow constraints-led principles for scaling complexity. Experts also recommended embedding clear feedback loops and observational checklists to support formative evaluation during sessions, and supported the use of the content map as evidence of content validity. Safety notes and load guidance were integrated into every variant, with coaching prompts keyed to decision-making demands and recovery windows (Ortega et al., 2019; Pamungkas et al., 2023).

Small-Group Pilot Trials

Pilot sessions established feasibility, instruction clarity, and initial indications of responsiveness to training. Across 4–6 weeks, players showed observable improvements in reception orientation (front-foot control and first touch into space) and immediate carry following controlled serves. Gains were most evident when pilots used small-sided, representative tasks that increased contacts and decision density—findings consistent with evidence that SSGs accelerate contextualized learning (Formenti et al., 2021; Suryadi et al., 2023). Short, targeted technique blocks remained useful for consolidating core mechanics but showed limited transfer unless immediately embedded in game-like tasks, in keeping with curriculum guidance (Sucipto et al., 2021). Feedback-rich configurations (e.g., rebound surfaces) were perceived to support error detection and self-regulation (Alzate et al., 2025), while coaches reported high engagement throughout.

Large-Group Trials

Large-group implementation stress-tested scalability across multiple SSBs. Relative to drill-dominant sessions, game-based progressions were associated with greater on-task time and more frequent reception-to-carry events. However, responsiveness varied with baseline coordination and maturation status: players with stronger coordination adapted more quickly to constrained, variable tasks, while those experiencing growth-related coordination dips benefited from simplified constraints and extended consolidation before defender pressure—patterns consistent with prior reports (Lex et al., 2021; Tušak et al., 2022). ex-related differences in engagement and response to constraint manipulation were noted exploratorily and will be analyzed further as sample sizes allow. Coaches rated session practicality as high when clear progression knobs (space, time, defenders, touch limits) were provided alongside safety and load cues.

Effectiveness Test (Pre–Post, Control Comparison)

Following pilots, the model was evaluated in a pre-test–post-test control-group design under authentic SSB scheduling as a preliminary effectiveness assessment. The primary outcome was an integrated reception-to-dribble index assessed in standardized circuits and small-sided scenarios. The scatter plot of paired pre/post scores shows the overall distribution of change, with the diagonal line y = x indicating no change. Points above the line indicate improvement, below indicate decline. In this dataset, 432 paired observations were analyzed: 287 players improved, 108 were unchanged, and 37 declined, suggesting an overall positive pattern of change rather than definitive causal effects. The pre–post correlation (r = 0.29) suggests a weak-to-moderate positive association between baseline and outcome, consistent with heterogeneous gains across ability levels. These results are in line with literature reporting greater benefits when training emphasizes representative information and constraints-led progression. In addition, coaches reported perceived reductions in decision latency following a controlled first touch and more frequent successful exploitation of space in SSGs, consistent with links between technical gains and decision-making quality (Murr et al., 2020).

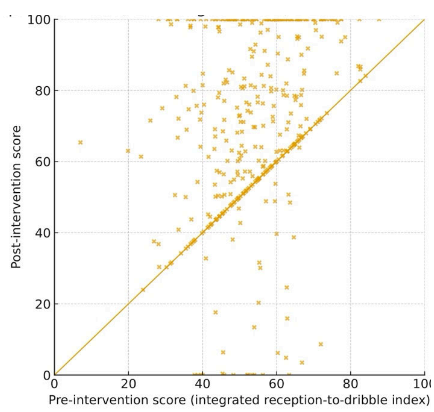

Fig. 1. Pre vs. post intervention scores on the integrated reception to dribble. Note. index (N = 432). The diagonal indicates no change; points above denote improvement. Improved = 287; unchanged = 108; declined = 37; pre–post r = 0.29

Table 2. Summary of pre–post outcomes (integrated reception-to-dribble index).

Outcome category	n	Percent
Improved	287	66.4%
Unchanged	108	25.0%
Declined	37	8.6%

Note. Percentages are calculated over N = 432 paired observations. The correlation between pre and postscores was r = 0.29, indicating a weaktomoderate positive association between baseline and outcome.

Model Iterations (v1–v10) and Implementation Fidelity

Iterative refinements consolidated a staged progression from unopposed reception mechanics to match-like scenarios in which the first touch actively affords the carry or release. Early variants emphasized orientation and protective stances; mid-variants layered passive and then live defenders; late variants embedded carry-or-release decisions in 2v1 to 4v4 formats with conditional scoring. Fidelity audits indicated high adherence when coaches used session checklists and progression thresholds, with deviations typically driven by space or equipment constraints. Where space was limited, narrowing lanes and shortening distances maintained decision density without materially reducing task representativeness (González-Ródenas et al., 2022). Equipment adaptations (e.g., mini-goals, rebounders) supported immediate transition from reception to carry and enhanced feedback (Alzate et al., 2025). The sequencing of constraints—space first, then defenders, then ball pressure—was observed to be particularly supportive for players with lower coordination, and aligns with recommended stepwise progressions (Qowiyyuridho et al., 2021; Sridadi et al., 2021). Coaches reported that explicit prompts for scanning before reception and rewarding forward-facing first touches were associated with smoother reception-to-dribble transitions, echoing decision-centric recommendations.

Adverse Events and Safety

No serious adverse events were recorded. Session logs flagged transient fatigue and occasional minor knocks in defender-active variants; these were mitigated by task dosages aligned with age-appropriate load guidance and structured recovery windows. Coach debriefs emphasized that safety standards were easier to maintain when decision demands were increased through informational constraints rather than through maximal physical contact.

Summary of Findings

Across needs analysis, expert validation, pilot and large-group trials, and a controlled effectiveness test, the Jho–First Touch to Dribbling Training Model showed consistent positive patterns of change in a large youth sample. Improvements were most pronounced when practice preserved informational fidelity and when progression knobs were tuned to maturation and coordination. The results are consistent with prior evidence that constraints-led, representative practice and SSG exposure are associated with enhanced technical execution and decision quality in youth players, while highlighting practical levers—space, equipment, and coach expertise—that determine implementation success in grassroots environments.

Discussion

The present findings indicate that an integrated first-touch-to-dribbling progression was associated with positive performance changes for most participants in authentic grassroots settings, with two-thirds of players showing gains and relatively few exhibiting decline (see Figure 1 and Table 2). These outcome patterns are coherent with contemporary accounts of practice design for U-13 football in which skill acquisition depends on repeated coupling between information and action during representative tasks (Formenti et al., 2021; García-Ceberino et al., 2020). The staged pathway—beginning with oriented reception and scaling toward constrained, game-like exchanges—is consistent with how children discover functional movement solutions when environmental and task constraints are tuned to age-specific capacities (D'Isanto et al., 2021). The observation that improvements were heterogeneous across baseline ability aligns with well-documented variability during late childhood and early adolescence, when growth-related changes can temporarily disrupt coordination yet ultimately support higher ceilings for performance once control is re-stabilized (Lex et al., 2021; Tušak et al., 2022).

The model's core premise—that reception quality affords a purposeful carry or release—is designed to promote perceptual attunement before and during ball contact. By requiring players to scan prior to reception, orient the first touch into exploitable space, and decide between carrying or releasing, each repetition may compress the perception–action cycle and support attunement to affordances such as open lanes and defender momentum (Jordet et al., 2020). As players repeatedly solve for "where to put the ball on the first touch," they may calibrate their bodies to the informational structure of the task, strengthening the coupling that underpins rapid dribbling initiation in traffic (Iuliano et al., 2023). This mechanism is plausibly reinforced by coordination dynamics: varied constraints perturb the stability of naïve movement patterns and encourage exploration of more adaptable solutions, which helps explain why progressions that manipulate space, pressure, and time limits tend to yield broader action repertoires and better control under pressure (D'Isanto et al., 2021; Stanković et al., 2023). Evidence that reception competence predicts downstream carrying is consistent with studies documenting the dependence of dribblers on real-time visual feedback to stabilize ball–foot interactions, particularly in younger players.

The model's blend of small-sided games (SSG), constraints-led task design (CLA), targeted technique consolidation, SAQ components, and proprioceptive work reflects complementary pathways to similar ends. SSG provided a dense mix of ball contacts, choices, and contextual interference; such exposure has been shown to support skill acquisition and tactical understanding by preserving the informational richness of match play (Clemente, Praça, et al., 2022; Formenti et al., 2021; Suryadi et al., 2023). CLA principles structured the progression knobs—space, number and behavior of defenders, and time—to shape functional solutions without prescribing them, thereby protecting autonomy and sustaining engagement. Technique blocks, although decontextualized, remained useful when brief and immediately re-embedded into game-like tasks; this sequencing appeared to support consolidation of first-touch mechanics (front-foot control and touch into space) that later scaled under pressure (Okilanda et al., 2021; Sucipto et al., 2021). AQ training may have widened the feasible action set by upgrading acceleration, change-of-direction, and footwork efficiency, which are prerequisites for turning a well-oriented reception into a decisive carry (Carvalho et al., 2021). Proprioceptive elements are likely to support body-segment awareness and postural control, contributing to more stable touches and finer ball–foot regulation during dribbling (Souglis et al., 2022). The convergence of these modalities may help explain why gains were observed not only on isolated skill measures but also in decision-laden scenarios where reception quality and carrying co-determine successful outcomes (Murr et al., 2020).

The large-group trials revealed that response to training varied across coordination level and maturation status. Players exhibiting temporary coordination dips—often associated with rapid growth—appeared to benefit from a slower ramp in informational and physical difficulty, longer consolidation in unopposed or lightly opposed variants, and careful load management (Lex et al., 2021). Conversely, players with higher baseline coordination tended to adapt more readily to earlier introduction of defender pressure and narrower spaces, which may amplify the salience of affordances and perceptual attunement (García-Ceberino et al., 2020). Sex-related moderation could not be fully resolved but anecdotal signals suggested differences in engagement and constraint preferences that warrant dedicated analysis with adequate power and tailored pedagogy. These moderators underscore the importance of adjustable task parameters and coach decision rules that personalize challenge while preserving the progression's logic.

Methodological safeguards, including content validation by a mixed expert panel, rater calibration, and pre–post control comparison, were instituted to support cautious inference (Hadinata et al., 2023; Okilanda et al., 2021; Sridadi et al., 2021). Nevertheless, several threats remain. Measurement bias can arise when standardized circuits fail to capture decision quality or when observational rubrics are insufficiently discriminant across ability bands; triangulating isolated skill metrics with representative SSG indicators was intended to limit construct under-representation (Alzate et al., 2025). Novelty effects may inflate early changes when coaches and players encounter an unfamiliar model; the embedding of the progression across multiple microcycles and the emphasis on routine fidelity aimed to reduce transience, but longitudinal follow-ups are required to confirm retention (Sunarto et al., 2023). Coach expectancy effects—especially in environments motivated to demonstrate improvement—can shape both instruction and scoring; pre-specified protocols and blinded scoring on video subsamples are recommended extensions where feasible. Safety remained central: as defender activity rose and spaces narrowed, load cues and recovery windows were enforced to minimize risk, consistent with established guidance for young athletes (Adi & Kustiawan, 2024; Primasoni et al., 2024).

For SSBs operating with constrained space and equipment, the progression's fidelity hinges on principled manipulation of a few controllable variables. Where field area is limited, narrowing lanes and shortening approach distances was found to preserve decision density without eroding representativeness, echoing evidence that varied yet purposeful environments facilitate learning (González-Ródenas et al., 2022). Access to mini-goals, rebound surfaces, and size-appropriate balls appeared to amplify the frequency and quality of reception-to-carry transitions by delivering meaningful feedback at ball contact (Alzate et al., 2025). From a workload perspective, integrating SSG and CLA tasks may reduce coach burden relative to highly scripted drill catalogs because task rules rather than explicit patterns do much of the instructional work; however, planning time is still needed to set safe dosages and progression gates, which national curricula should acknowledge. Scalability benefits when frameworks provide decision trees linking player readiness indicators to constraint adjustments, allowing coaches to "tune" tasks on the fly for mixed-ability groups (Umar et al., 2022). System-level adoption also depends on resource allocation for equipment and coach development; targeted investments in affordable training aids and practice design education are likely to support skill opportunity structures, particularly in under-resourced context (Bell & Bell, 2020; Hunter et al., 2022). Embedding the progression within Filanesia's holistic emphasis helps ensure that technical improvements co-develop with tactical awareness and psychosocial growth, addressing concerns about decontextualized technique work during this age window.

The distribution of change observed here, with a majority improving and a minority static or declining, parallels intervention meta-patterns in youth sport where exposure quality and baseline readiness jointly govern responsiveness (Formenti et al., 2021; Suryadi et al., 2023). That the pre–post correlation was modest indicates that initial level did not strongly constrain outcome, a desirable property in inclusive grassroots programs. It also suggests that design features within the model—such as compulsory scanning cues, forward-facing first-touch rewards, and immediate decision contexts—may have facilitated access to improvement pathways regardless of starting point, a hypothesis compatible with CLA's emphasis on channeling rather than prescribing solutions (D'Isanto et al., 2021). When juxtaposed with studies documenting the limitations of isolated technique drills, the present pattern supports the plausibility of a blended approach wherein short, targeted consolidation blocks are systematically re-embedded in representative exchanges to secure transfer. The emerging picture situates reception competence not as a terminal skill but as a generative constraint that shapes what kinds of carries and releases become available, which helps explain the practical relevance of sequencing constraints from space to defender pressure and finally to live ball pressure, as reflected in Table 1's logic and the fidelity audits reported earlier (García-Ceberino et al., 2020; González-Ródenas et al., 2022).

Future investigations should probe optimal dose–response relationships for each progression stage, quantifying how much exposure to oriented reception is required before introducing defender activity and how quickly touch limits should tighten across microcycles. Studies that randomize progression sequences—space first versus defender pressure first—could more directly test the causal contributions of constraint ordering to transfer. Researchers should incorporate longitudinal retention tests following periods without structured practice to determine which gains persist and under what environmental conditions, thereby addressing novelty effects and clarifying decay functions (Sunarto et al., 2023). Multi-site trials stratified by maturation status and coordination profiles are needed to build prescriptive decision trees for coaches, and sex-specific analyses should be powered to detect interaction effects with constraint manipulations. Measurement work should advance hybrid instruments that combine circuit-based indices with automated event coding from small-sided games, increasing sensitivity to decision quality while preserving reliability through rater calibration and internal-consistency checks. Complementary biomechanical and proprioceptive assessments could illuminate how postural control and foot-ball interaction quality mediate transfer from reception to carry, clarifying the added value of SAQ and proprioceptive elements within the model (Carvalho et al., 2021; Souglis et al., 2022). Finally, implementation research embedded in national curricula should evaluate teacher load, resource requirements, and cost-effectiveness to support scaling in under-resourced SSBs, with attention to equipment pathways and coach-education formats that maximize uptake while preserving fidelity (Bell & Bell, 2020; Hunter et al., 2022; Umar et al., 2022).

Conclusions

This study provides evidence that an integrated first-touch-to-dribbling training model, aligned with representative learning design and a constraints-led approach, can be implemented at scale in grassroots contexts and is associated with positive technical and decision-related changes in U-13 footballers. Across multi-phase development, expert validation, pilot implementation, and a preliminary controlled effectiveness test, roughly two-thirds of players improved on an integrated reception-to-carry index, with a modest pre–post association indicating that initial skill level did not unduly constrain outcomes. Improvements were strongest when reception tasks explicitly afforded purposeful carries in small-sided, information-rich conditions and when progression knobs—space, defender pressure, and time/touch limits—were tuned to maturation and coordination status. Fidelity audits suggested that clear coaching prompts and simple equipment (mini-goals, rebound surfaces, age-appropriate balls) supported transfer even under space constraints. These findings have practical implications for football schools and national curricula: coupling first-touch quality to immediate carry decisions may represent a central design principle for the 10–13 age band, and coach education should emphasize task representativeness, progression logic, and load safety. The study contributes a replicable pathway that operationalizes policy into practice and offers a theoretically grounded explanation of potential mechanisms—perception–action coupling and affordance attunement—through which reception skill may support dribbling proficiency. Future research should quantify dose–response parameters for each progression stage, test alternative constraint orderings, examine sex-specific responses, and conduct longitudinal retention studies with automated match-event analyses to determine durability and external validity of gains.

Conflict of Interest

The authors declare no conflicts of interest.

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Від прийому до ведення м’яча: Валідація масштабованої прогресії від першого торкання до дриблінгу в юнацькому футболі

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 12 с., 2 табл., 1 рис., 35 джерел.

Цілі. Метою цього дослідження було розроблення, валідація та проведення попередньої оцінки ефективності масштабованої моделі тренувань, яка безпосередньо пов’язує якість першого торкання з виконанням дриблінгу для футболістів віком до 13 років за допомогою репрезентативних практичних тренувань із застосуванням обмежень.

Матеріали та методи. Відповідно до логіки науково-дослідних та дослідно-конструкторських робіт (НДДКР) створено десять поетапних варіантів, які пройшли експертну перевірку та пілотне тестування перед проведенням попереднього перед- та постконтрольного порівняння в місцевих школах. Результати поєднували стандартизовані схеми та сценарії тренувань неповними складами з метою індексації продуктивності прийому та ведення м’яча, контролюючи точність, безпеку та прийнятність.

Результати. У більшості учасників покращився інтегрований індекс; дві третини досліджених зафіксували позитивні зміни, тоді як у небагатьох осіб відзначалося зниження показників. Помірна кореляція на перед- та постдосліджуваному етапі вказувала на неоднорідність результатів, незалежних від початкового рівня. Найбільші досягнення спостерігалися при виконанні завдань на прийом м’яча, що вимагали сканування, орієнтованого першого торкання і негайного ведення або відпускання м’яча в умовах обмеженого простору, тиску і часових рамок. Експертна оцінка підтримала релевантність змісту і відповідність віковій категорії; пілотні та великогрупові випробування підтвердили доцільність методу за різних ресурсних умов. Обговорення: Сукупність даних, отриманих на етапах розробки, валідації та польових випробувань, свідчить про те, що ігри неповними складами, цілеспрямована консолідація техніки, система тренувань за методикою SAQ (швидкість, спритність, швидкість реакції) та пропріоцептивні елементи комплексно покращують зв’язок між перцепцією і дією, а також узгодженість можливостей, що дозволяє досягти потенційно змінних поліпшень у першому торканні та дриблінгу. Практичні імплікації включають прості регулятори прогресії, вказівки тренера та конфігурації обладнання для збереження інформаційної точності в обмежених умовах.

Висновки. Результати дослідження дозволяють припустити, що узгоджена з навчальною програмою та підтверджена науково-дослідними та дослідно-конструкторськими роботами прогресія демонструє перспективність попередньої ефективності у зміцненні шляхів розвитку молоді шляхом поєднання сприйняття з ухваленням цілеспрямованих рішень, потребуючи ширшого впровадження та подальших досліджень залежності «доза (величина виконаних тренувальних завдань) – відповідь (реакція організму)».

Ключові слова: перше торкання, юнацький футбол, ігри неповними складами, підхід із застосуванням обмежень, репрезентативний дизайн навчання.

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Original Scientific Article

Hydration Status and Thermal Stress as Predictors of Fatigue and Performance Decline in Sub-Elite Soccer Players

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Abstract

Background. Soccer players competing in tropical climates experience combined dehydration, thermal strain, and metabolic stress, yet field-based evidence linking these factors to performance decline remains limited.

Objectives. This study aimed to examine the predictive relationships between hydration status, thermal stress, metabolic factors, and fatigue-related performance decline in sub-elite soccer players under tropical heat conditions.

Materials and Methods. Thirty male sub-elite soccer players (22.4 ± 3.1 years) participated in a simulated 90-minute match conducted in temperatures ranging from 31 to 33°C, with relative humidity levels between 65 and 75%. Hydration (bioimpedance), blood lactate, muscle temperature, heart rate, shooting accuracy, and anaerobic power (RAST) were assessed pre-, mid-, and post-match. Repeated-measures ANOVA and multiple regression were used ($p < 0.05$).

Results. TBW decreased significantly (−4.2%), while lactate (1.3 → 10.4 mmol·L^{-1}) and muscle temperature (33.4 → 37.1°C) increased across match segments ($p < 0.001$). Shooting accuracy (−14%) and peak anaerobic power (−4.6%) declined post-match. Regression analysis identified ΔTBW ($\beta = -0.41$, $p = 0.008$) and peak lactate ($\beta = 0.48$, $p = 0.003$) as significant predictors of fatigue ($R^2 = 0.61$).

Conclusions. The findings indicate that loss of hydration, thermal strain, and metabolic accumulation are all important signs of a subject's deterioration in performance levels under tropical match conditions. Athletes can improve their health and performance by drinking enough fluids and keeping their body temperature under control.

Keywords: hydration status, thermal stress, fatigue, anaerobic performance, tropical environment.

Introduction

The interaction of multiple physiological factors has a significant impact on soccer performance, particularly in hot and humid weather conditions. In tropical climates, athletes often endure compounded stress from dehydration, elevated muscle temperature, and metabolic accumulation, all of which expedite fatigue and diminish technical precision (Périard et al., 2021; Pellicer-Caller et al., 2023). This issue is especially important for players in Southeast Asia, where the temperature often rises above 30°C and the humidity rises above 70%. This problem puts a constant strain on their ability to regulate their body temperature during training and competition (Che Muhamed et al., 2016).

Research indicates that even mild dehydration (2–3% of body mass loss) can result in considerable reductions in aerobic endurance, cognitive function, and neuromuscular control (Armstrong et al., 2025; Casa et al., 2015). Elevated muscle temperature (>37°C) has been shown to hinder neuromuscular coordination and increase perceived exertion, thereby diminishing motor accuracy and skill execution (Sébastien Racinais et al., 2017; Flouris et al., 2015; Raj et al., 2021). At the same time, a high level of lactate in the blood during short bursts of high-intensity exercise indicates that anaerobic glycolysis is working harder, which accelerates metabolic fatigue and limits the body's ability

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to perform repeated sprints (Hafidz et al., 2025; Cairns & Lindinger, 2025). Even though these relationships are well-known, the combined effect of hydration status, thermal stress, and metabolic indicators on fatigue and performance decline during realistic match simulations is still not well understood, especially in sub-elite soccer players who don't always have access to advanced recovery and hydration monitoring systems (Chapelle et al., 2020; Nuccio et al., 2017).

Nonetheless, limited adoption of field-based experimental designs exists that concurrently monitor various physiological indicators during simulated match play in authentic tropical settings (Edwards & Clark, 2006; Gibson et al., 2019). Additionally, recent studies have predominantly concentrated on elite or professional players, leading to a gap in research regarding sub-elite populations that constitute the developmental basis of regional and university leagues (Plakias et al., 2024). These athletes frequently face similar training demands without adequate medical and environmental support systems, which may intensify the detrimental effects of heat and dehydration on their performance (Mohr et al., 2005). Consequently, it is essential to address these knowledge gaps to develop effective monitoring and intervention strategies that improve athlete readiness, reduce fatigue, and promote ongoing participation in sports.

Despite extensive laboratory evidence on dehydration, hyperthermia, and metabolic stress, field-based studies simultaneously examining their combined predictive power on fatigue and performance decline under authentic tropical match conditions remain scarce. Previous research has typically isolated single physiological variables, lacked ecological validity, or focused primarily on elite players. The present study addresses this research gap by integrating multidimensional physiological monitoring with performance testing during a realistic simulated match. The scientific novelty lies in identifying the simultaneous contribution of hydration status, thermal strain, and metabolic accumulation to fatigue-related performance decline in sub-elite players, a population that is underrepresented yet highly exposed to tropical environmental stressors.

Investigating the predictive relationships between hydration status, thermal stress, metabolic factors, and fatigue and performance decline in sub-elite soccer players exposed to tropical heat is the primary objective of this study. Specifically, this study aimed to (1) quantify temporal variations in hydration, lactate concentration, and muscle temperature during a simulated match; (2) evaluate their respective effects on technical accuracy and anaerobic performance; and (3) determine which physiological variables most accurately predict the fatigue response. It is hoped that this research will contribute to the development of evidence-based hydration and thermal management protocols that enhance the safety and performance of athletes competing in hot environments. Furthermore, it also supports global efforts to achieve SDG 3, ensuring healthy lives and promoting well-being through safe and effective sports participation.

Materials and Methods

This research employed a quasi-experimental quantitative design to examine the physiological interactions among hydration status, heart rate, blood lactate, and muscle temperature concerning the onset of fatigue in sub-elite soccer players competing in a hot environment. The study utilized a purposive randomized one-group pretest–posttest design to investigate the causal effects and predictive relationships among the variables in field-based conditions, thereby ensuring significant ecological validity.

Study Participants

The study involved thirty male soccer players from UNESA FC, categorized as sub-elite athletes participating in regional and university leagues, and supervised by the Sport and Exercise Research Center at Universitas Negeri Surabaya (UNESA). All participants were between the ages of 18 and 30, had at least 10 years of organized training experience, and trained regularly 4 to 6 times a week, doing both technical-tactical and conditioning programs. We chose this group of people on purpose because sub-elite athletes have performance profiles that are similar to those of professionals but often don't have advanced systems for managing hydration and recovery, especially in hot and humid conditions.

The purposive sampling technique was employed to select participants for this study based on the following inclusion criteria: (1) being an active athlete at UNESA FC during the 2025 competition season, (2) not having any musculoskeletal injury or medical contraindication in the preceding three months, (3) being capable of performing maximal physical exercise without the risk of cardiovascular complications, and (4) providing informed consent by agreeing and signing. Before the experiment, the team doctor checked the health of all the participants by measuring their resting heart rate, blood pressure, and body composition using bioelectrical impedance analysis (BIA).

Before signing the informed consent form, each participant got a clear verbal and written explanation of the study's purpose, protocol, and possible risks or benefits. This study received formal institutional authorization from the Sport & Exercise Research Center (SERC), Universitas Negeri Surabaya. The research protocol was reviewed and approved through the institutional permission letter numbered 146892/UN38.III.2/TU.00.00/2025, issued on 28 August 2025. All procedures conformed to the ethical principles of the Declaration of Helsinki, and written informed consent was obtained from all participants prior to data collection. The study took place at the UNESA Sports Complex, where the temperature was kept between 31 and 33 degrees Celsius and the relative humidity was kept between 65 and 75 percent. The research facility was a realistic setting for soccer performance in tropical climates.

Study Organization

The experimental procedure was methodically organized into six consecutive phases: preparation, warm-up, first-half simulation, halftime recovery, second-half simulation, and post-match evaluation, concluding with a brief recovery monitoring session. This organization made sure that the methods were strict, the environment was stable, and the physiological and performance data could be repeated in real-world settings. All trials took place at the UNESA Sport

Complex in Surabaya, Indonesia, where the temperature ranged from 31 to 33 degrees Celsius and the humidity ranged from 65 to 75 percent. This condition is typical of a tropical match environment (Bouscaren et al., 2021; Périard et al., 2021).

At 6:00 a.m., all participants gathered for medical screening, informed consent, and getting to know the testing tools and the environment. The session lasted about 60 minutes, during which time they measured resting heart rate and other body measurements. This step made sure that each subject met the requirements for inclusion and understood how the experiment would work. After that, there was a 10-minute dynamic warm-up (jogging, mobility, and stretching) and baseline testing. The pre-test battery measured heart rate (HR-pre), hydration status (pre), muscle temperature (pre), blood lactate concentration (pre), shooting accuracy (pre), and anaerobic power using the Running-based Anaerobic Sprint Test (RAST-pre). To reduce fatigue effects prior to the main protocol, participants subsequently engaged in a 60-minute passive rest period before the next phase.

A training simulation for the first half of the game was done to match the physical demands of competitive soccer. Participants engaged in 45 minutes of soccer-specific intermittent running, divided into three 15-minute segments consisting of 30-second sprints (90–95% HRmax), 90-second jogging intervals (65–75% HRmax), and 120-second walking recovery periods. Heart rate was continuously monitored, and Ratings of Perceived Exertion (RPE) were documented at the conclusion of each block to maintain a consistent workload and perceived effort (Drust et al., 2000; Stone & Oliver, 2009). After the first half, the participants were given controlled rehydration (3–5 mL/kg body weight) and a 15-minute rest period to recover. Measurements taken in the middle of the test, like HR (middle), hydration (middle), muscle temperature (middle), and blood lactate (middle), were used to see how well the body was recovering and how much heat it was making.

The second half was a repeat of the first half, with short-distance running and tactical drills like short passes and recovery sprints. This half also lasted 45 minutes, and the players' heart rates and RPE were constantly recorded to show how fit and strong they were. As soon as the second half was over, the participants took a post-match fatigue test. This test measured their hydration (post), muscle temperature (post), blood lactate (post), shooting accuracy (post) (Dambroz et al., 2022), and RAST performance (post) to see how fatigue affected their performance (Hafidz et al., 2025).

Finally, the recovery monitoring phase included 10 minutes of passive sitting rest, during which HR, lactate, and muscle temperature were continuously monitored to assess the acute recovery response following exercise-induced heat stress. All physiological and performance evaluations adhered to the standardized measurement schedule delineated in Fig. 1 and table 1, thereby ensuring methodological reliability and reproducibility.

A digital thermometer-hygrometer (Testo 608-H2, Germany) was used to keep an eye on the environment during the experiment to make sure the thermal exposure was always the same. According to current sports hydration guidelines, players' hydration levels were adjusted based on their weight loss, and rehydration volumes were set at 3–5 mL/kg of body weight (Ceylan & Santos, 2022; Fernández-Álvarez et al., 2022; Klimesova et al., 2022). Real-time heart rate data was sent to make sure that training loads were between 85 and 95 percent of each person's HRmax, which was found using the Karvonen formula (She et al., 2015).

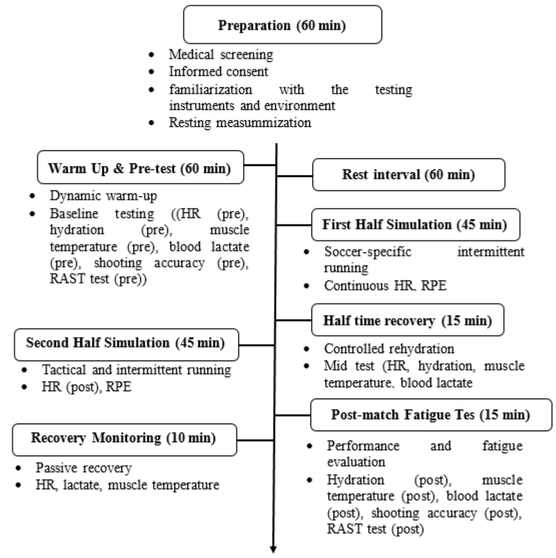

Fig 1. Experimental Design and Sequence of Physiological and Performance Measurements During the Simulated Soccer Match Protocol

Fingertip capillary sampling was used to get blood lactate samples (20 μL) at three times: before, during, and after. To make sure that surface temperature recording was accurate, a contact thermistor was placed over the muscle belly of the gastrocnemius medialis to measure muscle temperature (Flouris et al., 2015; Raj et al., 2021). Certified sport scientists and physiologists from the Sport & Exercise Research Center at UNESA oversaw the data collection to make sure that the process was consistent and valid.

Measurement

We used standardized operational procedures to measure all physiological and performance variables. This was done to confirm that the results were reliable, valid, and reproducible, in line with international sport science measurement protocols (Batterham & Hopkins, 2015; Sirotic & Coutts, 2008). All measurements were taken in controlled environmental conditions (ambient temperature 31–34°C; relative humidity 65–75%), and certified technicians from the Sport and Exercise Research Center at Universitas Negeri Surabaya calibrated all the devices before they were used.

We used a portable analyzer (InBody 370S, Seoul, Korea) to measure hydration levels using the bioelectrical impedance analysis (BIA) method. Data collection for this study was conducted in three phases (pre-exercise, mid-exercise, and post-exercise). The system calculated total body water (TBW) and the extracellular to intracellular fluid ratio with participants standing on a BIA barefoot and with dry feet. These data were then expressed as a percentage change in hydration status. To ensure accuracy, athletes avoided

Table 1. Phased Organization of Experimental Procedures and Corresponding Physiological Measurements in the Simulated Soccer Match

Phase	Activity	Description	Duration	Measurements Collected
Preparation	Orientation, medical screening, and familiarization	Participants assembled at 06:00 a.m. for medical check-up, informed consent, and familiarization with the testing instruments and environment under controlled thermal conditions.	60 min	Resting HR, anthropometric profile
Warm-up & Pre-test	Dynamic warm-up and baseline testing	10-minute dynamic warm-up (jogging, stretching, and mobility drills) followed by baseline assessments to establish pre-exercise physiological values.	60 min	HR (pre), hydration (pre), muscle temperature (pre), blood lactate (pre), shooting accuracy (pre), RAST test (pre)
Rest Interval	Passive rest period	To eliminate residual fatigue from pre-testing and ensure physiological stability before the main simulation.	60 min	—
Exercise Simulation – First Half	Soccer-specific intermittent running	3 × 15-min running blocks alternating 30 s sprint (90–95% HRmax), 90 s jogging (65–75% HRmax), and 120 s walking recovery. RPE recorded after each block.	45 min	Continuous HR, RPE
Halftime Recovery	Controlled rehydration and mid-test	15-min passive recovery with rehydration (3–5 mL/kg BW). Mid-test data recorded to assess thermal and hydration response.	15 min	HR (mid), hydration (mid), muscle temperature (mid), blood lactate (mid)
Exercise Simulation – Second Half	Tactical and intermittent running	Repetition of first-half protocol integrated with tactical drills (short-passing and sprint recovery tasks) to simulate match intensity.	45 min	HR (post), RPE
Post-match Fatigue Test	Performance and fatigue evaluation	Post-exercise testing for physiological and skill-related fatigue indicators.	15 min	Hydration (post), muscle temperature (post), blood lactate (post), shooting accuracy (post), RAST test (post)
Recovery Monitoring	Passive recovery and assessment	10-min seated recovery with continuous monitoring of physiological restoration following exercise-induced thermal stress.	10 min	HR, lactate, muscle temperature

food and caffeine two hours before the test and emptied their bladders thirty minutes beforehand (Sampieri et al., 2024). Pre- and post-exercise weight measurements allowed us to determine fluid loss, and we adjusted the rehydration rate between 3 and 5 mL/kg body weight, following current sports hydration guidelines (Ceylan & Santos, 2022; Fernández-Álvarez et al., 2022).

A Polar H10 telemetry sensor (Polar Electro, Kempele, Finland) was used to monitor heart rate in real time and continuously throughout the protocol. Data were collected at one-second intervals and displayed as a percentage of each individual's HRmax, which was determined using the Karvonen formula (HRmax = 220 – age) and adjusted for resting HR (She et al., 2015). HR was measured at the start of exercise, during the first and second halves of exercise, and after exercise to evaluate exertional response and recovery. Mean and maximum heart rates were used as indicators of internal load and cardiovascular strain (Dimkpa et al., 2023; Schneider et al., 2018).

Fingertip samples (20 μL) taken with a sterile lancet were used to measure capillary blood lactate concentration at three different times: before, during, and after exercise. The Roche Cobas Accutrend Plus (Roche Diagnostics, Germany) was used for analysis. This device provides fast and accurate readings in less than one minute. To reduce contamination, the first drop of blood was discarded, and subsequent drops were placed on a lactate strip according to the manufacturer's instructions. This method allows for measurement of the anaerobic glycolytic response and the level of metabolic exhaustion (Beneke et al., 2011; Kafrawi et al., 2025).

We used a digital contact thermistor (Testo 608-H2, Germany) to monitor the local muscle temperature. It was placed at the gastrocnemius medialis muscle belly of the dominant leg. We measured how the body reacts to heat over time before the warm-up, after the first half, and after the match. To keep the sensor from moving, hypoallergenic medical tape was used to hold it in place. This technique yields accurate noninvasive assessments of intramuscular temperature fluctuations during thermal stress (Flouris et al., 2015; Raj et al., 2021)

A standardized soccer shooting accuracy protocol was used to test shooting accuracy. This protocol was made to test technical precision and motor control degradation caused by fatigue in sub-elite players. The test took place on a soccer field that was the right size and had a FIFA-approved ball (size 5, weight 420–445 g) and a standard goal (7.32 × 2.44 m). There was a target scoring grid in the goal area that split the surface into six scoring zones: two central zones for low-precision areas and four corner zones (upper-left, upper-right, lower-left, and lower-right) for high-precision areas. Following the performance scoring model set up by Dörge et al. (2002) and Lees & Nolan (1998), each target zone was given a point value from 1 to 5, with higher points for shots that hit the upper corners and lower points for shots that hit the middle.

To reduce learning bias, each participant attempted 10 penalty shots from a distance of 11 meters, randomly alternating between their dominant and non-dominant feet (Ali et al., 2007; Izovska et al., 2016). Prior to the test, the players performed a standard 5-minute technical warm-up that included controlled passing and shooting to help them become accustomed to handling the ball. Participants were instructed to shoot accurately while maintaining the pace of the game. A high-speed digital camera (240 fps, Sony RX10 IV, Japan) was mounted 5 meters behind the ball at a right angle to the ball to record each shot. This procedure was performed to allow for later visualization of the shot placement and trajectory.

All trials were conducted twice—before exercise (pre-test) and immediately after the second half of the simulation (post-test)—to evaluate the effect of exercise-induced fatigue on technical shooting performance. To ensure consistency, all sessions used the same ball, shooting surface, and weather conditions. To minimize recovery bias, the interval between attempts was set at 20 seconds (Rampinini et al., 2009). This approach has been supported by prior research, showing high intra-class correlation coefficients (ICC = 0.88–0.93) for shooting accuracy and consistency within soccer-specific scenarios (Ali et al., 2007; Marques et al., 2011). Using both accuracy percentage and point-weighted indices allows for a more comprehensive assessment of performance, capturing both spatial accuracy and motor control decline caused by fatigue (Dambroz et al., 2022; Ferraz et al., 2012).

Anaerobic endurance was evaluated using the Running-Based Anaerobic Sprint Test or RAST test. This test involves six maximum sprints over a distance of 35 meters, with each sprint interspersed with a ten-second passive recovery period. All sprints were conducted on a standard indoor track, and participants were instructed to exert their maximum effort during each sprint. Sprint times were recorded with a stopwatch, and anaerobic power variables (peak power, average power, and fatigue index) were calculated according to the standard RAST protocol (Wibowo et al., 2025).

Immediately after each 15-minute simulated exercise segment, participants evaluated their perceived exertion using the Borg Rating of Perceived Exertion (RPE) Scale (6–20) (Williams, 2017). They were asked to rate how intense they perceived the game to be, which serves as a subjective measure of internal load and psychological strain, in addition to physiological data (Inoue et al., 2022). We used a Testo 608-H2 digital thermo-hygrometer to monitor ambient temperature and relative humidity throughout the test. These measurements ensured a stable environment. Data were recorded every five minutes and maintained within a target range (31–34°C; 65–75% RH). This monitoring helped ensure that all sessions accurately mimicked actual tropical conditions (Akerman et al., 2016; Helmer et al., 2025; Xu et al., 2022).

Statistical Analysis.

A priori power analysis was performed using G Power 3.1 to determine the minimum required sample size. For repeated-measures ANOVA with three measurements (pre-, mid-, post-test), an effect size of $f = 0.30$ (medium), $\alpha = 0.05$, and power $(1-\beta) = 0.80$ indicated a minimum required sample of $N = 24$. The final sample ($N = 30$) exceeded this threshold, ensuring adequate statistical power. This study used IBM SPSS Statistics version 25.0 and Microsoft Excel 2016 for data validation and visualization. All analyses were performed at a significance level of $p < 0.05$. We carefully checked the data to ensure accuracy and completeness. The Mahalanobis distance method was used to identify any potential outliers and prevent data distortion. Descriptive statistics were calculated for all dependent and independent variables, including hydration status, heart rate, blood lactate, muscle temperature, and fatigue index. The Shapiro–Wilk test assessed normality, while the Levene test verified homogeneity of variance. Paired-sample t-tests analyzed intra-group variation over time for parametric data sets. Repeated-measures ANOVA was used to evaluate the overall impact of time and interaction effects on physiological variables. When the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. Multivariate analysis of variance (MANOVA) tested multivariate interactions among physiological indicators, and the Pearson product-moment correlation coefficient (r) assessed the strength and direction of correlations among continuous physiological variables. Additionally, a multiple linear regression analysis was performed with the fatigue performance score as the dependent variable and hydration percentage change, mean heart rate, peak lactate level, and mean muscle temperature as predictors..

Results

Thirty male soccer players from UNESA FC who were not considered elite volunteered to participate in the study. The average age of the group was 22.4 ± 3.1 years, the average height was 173.6 ± 5.2 cm, the average weight was 68.1 ± 6.1 kg, and the average duration of training was 10.8 ± 1.9 years. Participants attended between four and six training sessions each week, which included technical, tactical, and conditioning exercises led by certified coaches. We measured an average resting heart rate of 64.8 ± 3.7 bpm while participants rested in a thermoneutral environment (room temperature 32.1 ± 0.8°C; relative humidity 70.3 ± 3.5%). The positional distribution was three goalkeepers (10%), nine defenders (30%), twelve midfielders (40%), and six forwards (20%). This reflects the typical composition of a university soccer team in Indonesia. The participants' body size and physiological profile generally resembled that of sub-elite tropical athletes who frequently compete in hot weather.

Prior to inferential analysis, all data were examined to ensure compliance with statistical assumptions. The Shapiro–Wilk test verified that all physiological and

Table 2. Temporal Changes in Physiological Parameters (Hydration, Blood Lactate, and Muscle Temperature) Across the Match Simulation

Variable	Pre	Mid	Post	p (Time Effect)	Partial η^2
Total Body Water (L)	42.6 ± 1.9	41.2 ± 1.9	40.8 ± 2.0	<0.001	0.79
Blood Lactate (mmol·L-1)	1.3 ± 0.2	6.7 ± 0.8	10.4 ± 0.9	<0.001	0.88
Muscle Temperature (°C)	33.4 ± 0.3	35.4 ± 0.7	37.1 ± 0.4	<0.001	0.83

performance variables exhibited normal distribution ($p > 0.05$), while Levene's test indicated homogeneity of variance across time points ($p > 0.05$). These findings support the application of parametric tests, such as paired t-tests and repeated-measures ANOVA, for data analysis.

Descriptive statistics showed a clear temporal trend throughout the simulated soccer match. Total body water (TBW) gradually decreased from pre-test to post-test (42.6 ± 1.9 → 40.8 ± 2.0 L), indicating dehydration during the session. Blood lactate concentration increased sharply (1.3 ± 0.2 → 10.4 ± 0.9 mmol·L^{-1}), indicating a significant increase in anaerobic metabolism. During the match, muscle temperature continued to rise (33.4 ± 0.3 → 37.1 ± 0.4136 °C), indicating that the body struggled to maintain a stable temperature.

Repeated-measures ANOVA validated significant main effects of time on all three physiological variables (Table 2). The analysis showed a big effect size for TBW ($F_{(2,58)} = 39.7$, $p < 0.001$, $\eta^2_p = 0.79$), blood lactate ($F_{(2,58)} = 76.4$, $p < 0.001$, $\eta^2_p = 0.88$), and muscle temperature ($F_{(2,58)} = 52.6$, $p < 0.001$, $\eta^2_p = 0.83$). These findings indicate that the match simulation protocol successfully produced dehydration, metabolic accumulation, and thermal load similar to competitive match conditions in a tropical environment.

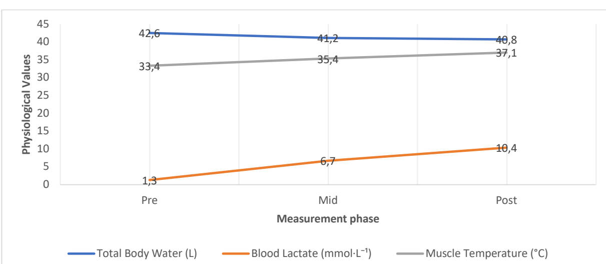

Fig 2. Temporal Changes in Physiological Parameters During Match Simulation

The η^2_p value (0.79–0.88) indicates a large effect size, reflecting strong temporal changes across the simulated matches. The assumption tests suggest that the parametric analysis is suitable, and the combined descriptive and inferential results indicate that the experimental protocol led to significant physiological changes. These alterations in hydration, metabolism, and temperature lay the groundwork for understanding future performance-related outcomes. The next section examines how high levels of cardiovascular strain and perception directly impact players' technical accuracy and anaerobic power after the simulated matches.

Cardiovascular response data indicate that participants maintained a high physiological load throughout the simulated matches. The mean relative heart rate was 86.7 ± 3.2% HRmax, and the peak heart rate was 95.1 ± 2.1% HRmax. These data indicate that the players worked near their anaerobic threshold for most of the session. The Borg RPE scale, which measures subjective exertion, showed a large spike between the first and second halves of the match. Mean RPE increased from 13.9 ± 1.2 to 17.1 ± 1.0, confirming an increase in physiological fatigue over time ($t_{(29)} = 9.84$, $p < 0.001$, Cohen's $d = 2.75$). This increase in perception was accompanied by increases in heart rate and metabolic variables, indicating a synchronized pattern of cardiovascular strain and perception throughout the simulated competition.

Table 3. Cardiovascular and Perceptual Responses During the First and Second Halves of the Simulated Match.

Variable	First Half	Second Half	$t_{(29)}$	p	Cohen's d
Mean HR (%HRmax)	86.7 ± 3.2	—	—	—	—
Peak HR (%HRmax)	95.1 ± 2.1	—	—	—	—
RPE	13.9 ± 1.2	17.1 ± 1.0	9.84	< 0.001	2.75

These results confirm that the training protocol successfully induces prolonged, high-intensity cardiovascular stress, consistent with match conditions. Substantial increases in perceived exertion further illustrate the players' cohesive physiological assessment of their effort as the session progresses. After determining the level of performance decline, the next step involved analyzing the interrelationships between changes in physiological parameters and identifying those most closely associated with fatigue.

Performance analysis revealed significant declines in technical and anaerobic skills following the match simulation (Table 4). Shooting accuracy significantly declined by approximately 14%, decreasing from 78.4 ± 4.2% to 64.3 ± 5.1% ($t_{(29)} = -10.42$, $p < 0.001$, $d = 1.90$), indicating impaired motor precision under fatigue. Likewise, RAST peak power diminished from 723.6 ± 28.4 W to 690.3 ± 31.2 W ($t_{(29)} = -4.62$, $p < 0.001$, $d = 0.84$), whereas the fatigue index escalated from 8.9 ± 0.6 to 10.7 ± 0.8 ($t_{(29)} = 5.13$, $p < 0.001$, $d = 0.93$). These results collectively indicate a significant decline in neuromuscular performance after high-intensity activity.

Paired t-tests on physiological variables corroborate these findings, showing a significant decrease in total body water (TBW) ($p < 0.001$) and a significant increase in blood lactate and muscle temperature ($p < 0.001$). The degree of variation between variables suggests that metabolic and thermoregulatory stress lead to a decrease in technical output and power after competition.

Figure 3 illustrates the changes in technical and physiological performance indicators from before to after the high-temperature test. There were significant decreases in shot accuracy (−14%) and peak power (−4.6%), accompanied by significant increases in the fatigue index,

Table 4. Pre- to Post-Test Comparison of Technical and Anaerobic Performance Indicators Under Heat Stress Conditions.

Variable	Pre-Test	Post-Test	t(29)	p	Cohen's d
Shooting Accuracy (%)	78.4 ± 4.2	64.3 ± 5.1	−10.42	< 0.001	1.90
Peak Power (W)	723.6 ± 28.4	690.3 ± 31.2	−4.62	< 0.001	0.84
Fatigue Index	8.9 ± 0.6	10.7 ± 0.8	5.13	< 0.001	0.93
Total Body Water (L)	42.6 ± 1.9	40.8 ± 2.0	−8.02	< 0.001	1.47
Blood Lactate (mmol·L-1)	1.3 ± 0.2	10.4 ± 0.9	37.81	< 0.001	6.90
Muscle Temperature (°C)	33.4 ± 0.3	37.1 ± 0.4	44.20	< 0.001	8.07

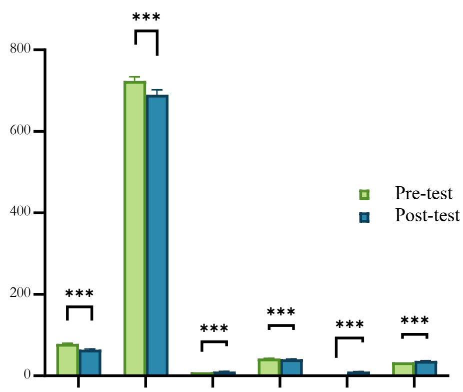

Fig. 3. Pre- to Post-Test Changes in Technical and Physiological Performance Indicators Under Heat Stress Conditions. Data are presented as mean ± SD; ***p < 0.001 compared with pre-test values

lactate concentration, and muscle temperature ($p < 0.001$). This trend highlights the cumulative effect of dehydration and metabolic overload on fatigue-related performance declines. Overall, these results indicate that match simulation creates a dry physiological environment, increases metabolic stress, and raises body temperature, all of which result in significant decreases in technical accuracy and anaerobic performance capacity. Given the strong correlation between physiological variables, further analysis used multiple regression to determine which factors collectively contributed to the variation in fatigue performance scores.

Correlation analysis revealed a strong relationship between physiological indicators and fatigue-related performance (Table 5). Fatigue performance scores exhibited a strong negative correlation with ΔHydration (% change in TBW; $r = -0.56$, $p = 0.002$). This indicates that as fluid loss increases, fatigue levels also increase. On the other hand, peak lactate showed a strong positive correlation with fatigue ($r = 0.63$, $p < 0.001$), meaning that higher metabolic accumulation rates were associated with lower performance levels. A moderate but significant correlation was identified between mean HR (%HRmax) ($r = 0.41$, $p = 0.027$) and mean muscle temperature ($r = 0.38$, $p = 0.039$), both of which influence fatigue perception and performance decline.

Multiple regression analysis revealed that the model significantly predicted fatigue performance ($R^2 = 0.61$, Adjusted $R^2 = 0.57$, $F_{(4,25)} = 9.85$, $p < 0.001$). Peak lactate ($\beta = 0.48$, $p = 0.003$) and ΔHydration ($\beta = -0.41$, $p = 0.008$) were the strongest independent predictors of fatigue. Mean HR ($\beta = 0.23$, $p = 0.074$) and mean muscle temperature ($\beta = 0.19$, $p = 0.089$) contributed modestly but did not reach

Table 5. Correlation Between Physiological Stress Markers and Fatigue Performance Scores in Sub-Elite Soccer Players.

Variable Pair	r	p
ΔHydration (%) vs Fatigue Score	−0.56	0.002
Mean HR (%HRmax) vs Fatigue Score	0.41	0.027
Peak Lactate (mmol·L-1) vs Fatigue Score	0.63	< 0.001
Mean Temp (°C) vs Fatigue Score	0.38	0.039

statistical significance. Confidence intervals for all predictors ranged from 95% CI [0.12 to 0.61] for lactate to [−0.62 to −0.18] for ΔHydration, while standard errors remained within acceptable limits (SE = 0.06–0.11). These results indicate that dehydration and the accumulation of metabolic by-products are the primary factors influencing post-match fatigue. Furthermore, cardiovascular and thermal stress factors add up, which shows that fatigue is a response that includes metabolic, thermoregulatory, and circulatory load.

Discussion

The principal findings demonstrate that progressive dehydration, heightened blood lactate concentrations, and elevated muscle temperature are associated with significant reductions in technical accuracy and anaerobic power, alongside considerable increases in cardiovascular load and perceived exertion. Correlational analysis indicated that total body water loss and peak lactate concentration were the most significant predictors of post-match fatigue, whereas mean heart rate and mean muscle temperature exerted a moderate influence on the overall fatigue index. These findings collectively emphasize that fatigue in heat-stressed match conditions is a multifactorial phenomenon involving metabolic, thermoregulatory, and circulatory elements (Cramer et al., 2022; Gnanasigamani et al., 2025).

The decrease in total body water indicates unregulated fluid loss during high-intensity intermittent activity, which may influence plasma volume and peripheral blood flow to the engaged muscles. A 2–3% loss of body mass due to dehydration has been demonstrated to hinder neuromuscular function, diminish running performance, and compromise fine motor control, especially in hot and humid conditions (Armstrong et al., 2025; Casa et al., 2015). This mechanism aligns with the substantial negative correlation observed between hydration variability and fatigue scores in this study, indicating that fluid balance is essential for sustaining technical precision and anaerobic performance during extended physical exertion.

A substantial increase in blood lactate indicates a significant reliance on anaerobic glycolysis during the simulation. Increased lactate concentrations in skeletal muscle can disrupt the excitation-contraction relationship, alter pH balance, and inhibit calcium reabsorption, thus exacerbating neuromuscular fatigue (Beneke et al., 2011; Kafrawi et al., 2025). The increase from 1.3 to 10.4 mmol L^{-1} aligns with the metabolic intensity observed in competitive matches in tropical climates, thus strengthening the ecological validity of the simulation procedure (Chapelle et al., 2020; Shirreffs & Shirreffs, 2010). The concomitant decrease in shooting accuracy and anaerobic power suggests that metabolic overload directly impacts both technical and physiological performance elements (Ioannou & Flouris, 2020).

It is important to note that muscle temperature increased steadily during the simulation. Moderate increases in intramuscular temperature can increase enzyme activity and force production. Studies have shown that temperatures above 37°C can inhibit nerve impulse conduction and cause fatigue (Flouris et al., 2015; Raj et al., 2021). Thermal stress exacerbates central motor output dysfunction, thereby exacerbating fatigue by complicating voluntary activation (Iguchi & Shields, 2011). These results are consistent with recent studies showing that cooling interventions significantly reduce thermal stress and maintain optimal performance during heat exposure (Bongers et al., 2017; Khorshid & Song, 2025).

When contextualized within the current literature, these findings align with the global consensus on heat-induced performance impairment in team sports. The International Olympic Committee (IOC) and the American College of Sports Medicine (ACSM) have collaborated to examine the importance of maintaining hydration, addressing heat stress, and measuring internal strain to enhance performance in high temperatures (Armstrong et al., 2025; McDermott et al., 2017; Sawka et al., 2007). This study reinforces these principles through empirical data collected in the field under tropical conditions, combining laboratory results with the practical context of sport. Furthermore, the use of RAST as a credible and reliable measure of anaerobic performance confirms its efficacy in longitudinal athlete monitoring, despite its slightly reduced peak power estimates compared to the Wingate test (Hafidz et al., 2025; Wibowo et al., 2025).

There are numerous practical implications from a coaching and applied sports science perspective. First, athletes should pay attention to their hydration levels during training and competition. This can be done by weighing yourself before and after a session or by using a portable device such as a BIA analyzer or urine specific gravity meter. Developing a personalized rehydration plan, such as the one used here (3–5 mL/kg at halftime), can help maintain performance and correct fluid imbalances (Pryor et al., 2018; S. Racinais et al., 2015). Second, pre- and post-cooling strategies, such as ice vests, cold towels, or cold water immersion, should be used frequently to reduce heat stress levels, especially when competing in tropical climates (Robin et al., 2024; Roriz et al., 2022). Third, a structured heat acclimatization program lasting 10 to 14 days has been shown to lower heart rate, reduce fatigue, and help teams cope better with the heat (Lorenzo et al., 2010). This is an important way for teams to prepare for competition in hot weather.

Current findings suggest that perceived strain is closely related to physiological load; therefore, incorporating these metrics could improve in-game decision-making and reduce fatigue-related errors or injuries. Furthermore, coaches should have players perform technical drills while fatigued, such as shooting or passing after sprinting, to help them maintain sharp skills and maintain accurate motor skills under pressure. Finally, coaches should consistently conduct RAST or comparable on-field assessments of anaerobic performance to evaluate recovery and adaptive progress throughout the training cycle (Wibowo et al., 2025).

This study acknowledges specific limitations, despite robust experimental controls. The study sample was limited to sub-elite male players from a single university team, thus limiting generalizability to other levels of competition, age demographics, or female athletes. BIA is a useful and non-invasive way to assess hydration, but it can be affected by changes in skin temperature and electrical impedance when the body heats up. The RAST is a reliable test, but it may slightly underestimate peak power output compared to the Wingate protocol performed in the laboratory (Zagatto et al., 2009). Future research should incorporate additional biomarkers, including urine osmolality or plasma volume, to facilitate a more comprehensive analysis. Therefore, caution should be exercised when considering absolute performance values. Future research should investigate controlled interventions—such as variations in rehydration formulation, cooling techniques, or acclimatization periods—to evaluate their effects on physiological and technical recovery. Longitudinal studies examining the neuromuscular and cognitive mechanisms that lead to fatigue-induced skill decline would improve understanding of the mechanisms influencing soccer performance in high temperatures.

Conclusions

This study demonstrates that simulated soccer matches in a hot and humid tropical environment cause significant physiological stress—characterized by progressive dehydration, elevated blood lactate levels, and increased muscle temperature—which collectively reduce technical precision and anaerobic capacity. The strong correlation between fluid loss, metabolic accumulation, and fatigue validates that a synergistic interaction between circulatory, metabolic, and thermoregulatory processes drives performance declines during heat stress. These results suggest that hydration and thermal regulation are crucial for sub-elite players' performance in matches and their recovery speed.

In practice, maintaining fluid balance and reducing thermal stress should be central to coaching and performance plans. To help players avoid heat exhaustion, coaches should utilize individualized hydration monitoring, structured rehydration (3–5 mL kg^{-1} during rest periods), and targeted cooling methods such as pre-cooling or pre-cooling. Adding short-term heat acclimatization and technical drills performed while fatigued can help further improve skill tolerance and stability during competition. Incorporating these evidence-based strategies into training and competition preparation can enhance physiological readiness and maintain performance in athletes competing in high temperatures.

AI Transparency Statement

Artificial Intelligence (AI) tools were used solely to support linguistic refinement and formatting during manuscript preparation. AI was not used to generate scientific content, analyze data, interpret findings, or conduct any part of the research methodology. All scientific arguments, results, and conclusions were produced exclusively by the authors.

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Conflict of Interest

All researchers declare that there is no conflict of interest in this research.

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Стан гідратації та тепловий стрес як предиктори втоми та зниження результативності у футболістів субелітного рівня

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Обґрунтування. Футболісти, які беруть участь у змаганнях в умовах тропічного клімату, зазнають комбінованого впливу дегідратації, теплового навантаження та метаболічного стресу, проте дані, що підтверджують зв'язок цих факторів із зниженням результативності, залишаються обмеженими.

Цілі. Мета цього дослідження полягала у вивченні прогнозованих взаємозв'язків між станом гідратації, тепловим стресом, метаболічними факторами та зниженням результативності, зумовленим втомою, у футболістів субелітного рівня, які грають в умовах тропічної спеки.

Матеріали та методи. Тридцять чоловіків-футболістів субелітного рівня (22.4 ± 3.1 роки) взяли участь у модельованому 90-хвилинному матчі, що проводився при температурі від 31 до 33 °C та відносній вологості повітря між 65 та 75 %. Показники гідратації (біоімпедансний аналіз), лактату в крові, температури м'язів, частоти серцевих скорочень, точності ударів та анаеробної потужності (тест на вимірювання швидкості і сили під час серії спринтів) оцінювали на передматчевому етапі, під час та після проведення матчу. Застосовано дисперсійний аналіз з повторними вимірами та множинну регресію ($p < 0.05$).

Результати. Показник загальної кількості води в організмі (ЗКВО) значно зменшився (−4.2%), тоді як рівні лактату (1.3 → 10.4 ммоль/л$^{-1}$) і температури м'язів (33.4 → 37.1 °C) збільшилися протягом сегментів матчу ($p < 0.001$). На післяматчевому етапі спостерігалося зниження точності ударів (−14%) і пікової анаеробної потужності (−4.6%). Регресійний аналіз визначив ΔЗКВО ($\beta = -0.41$, $p = 0.008$) і піковий лактат ($\beta = 0.48$, $p = 0.003$) як значущі предиктори втоми ($R^2 = 0.61$).

Висновки. Результати дослідження вказують, що дегідратація, теплове навантаження та метаболічне накопичення є важливими ознаками погіршення рівня результативності суб'єкта під час проведення матчів в умовах тропічного клімату. Спортсмени можуть поліпшити своє здоров'я та продуктивність, вживаючи достатню кількість рідини та контролюючи температуру тіла.

Ключові слова: стан гідратації, тепловий стрес, втома, анаеробна продуктивність, тропічне середовище.

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Original Scientific Article

Enhancing Aerobic and Sprint Performance Through Weighted Vest-Based Anaerobic Soccer Training: Evidence From a Controlled Trial in Soccer Players

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Abstract

Background. Modern soccer requires repeated high-intensity, complex movements, making aerobic performance essential for players.

Objectives. This study aimed to examine the effect of Anaerobic Soccer Training (AnST) utilizing a weighted vest (WV) weighing 7.21 ± 0.72% of body mass on aerobic performance, measured by VO2max and speed.

Materials and Methods. This study employed a quasi-experimental design with two groups (Group A and Group B), utilizing a pre-test as a covariate and a post-test as the dependent variable. A total of 22 male soccer players were randomly divided into two groups: a control group with an additional load of 0% of body weight (Group A, n = 11) and an experimental group with an additional load of 7.21 ± 0.72% of body weight (Group B, n = 11). Aerobic performance was assessed using the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) before and after a three-week intervention involving four sessions per week. The YYIR1 results provided VO_2max and speed data for analysis. Statistical tests included the Shapiro–Wilk normality test, Levene's homogeneity test, and Quade's Non-parametric Analysis of Covariance using IBM SPSS 30 with a 0.05 significance level.

Results. Based on the results obtained using Quade's Non-parametric Analysis of Covariance, significant differences were found between groups A and B in terms of VO_2max ($p = 0.015$) and speed ($p = 0.005$) after controlling for pre-test values. These results indicate that the types of training given to each group had different effects on improving the players' aerobic performance and speed.

Conclusions. The findings confirm that three weeks of AnST with a weighted vest of 7.21 ± 0.72% of body mass may enhance VO_2max and running speed. However, these results are preliminary and should be interpreted with caution due to the short duration and small sample size.
Keywords: weight vest, AnST, VO_2max, speed.

Introduction

Soccer is a sport that involves various complex movements, such as acceleration, deceleration, jumping, and changes in direction, that are performed repeatedly at high intensity (Brahim et al., 2020; Naveen Raj A et al., 2024; Reynolds et al., 2021). As a result, soccer players can cover an average distance of around 13 km with a heart rate intensity reaching 85–90% of their maximal heart rate (HRmax) during a match. This high cardiovascular demand places an indirect physiological load on the players, making aerobic capacity a crucial factor for maintaining performance throughout the 90 minutes and supporting recovery between intense efforts (Beato & Jamil, 2018; Manzi et al., 2022).

To meet these demands, a training method that combines both aerobic and anaerobic qualities is essential in modern soccer. Complementing these physical requirements, the Anaerobic Soccer Training (AnST) model has emerged as the latest approach tailored to the game's specific needs. Research by Kusuma et al. (2025) shows that the AnST training model can improve players' aerobic physical performance.

Given the increasing demands of modern soccer, training models need to be both efficient and physiologically specific. While HIIT and SSG are effective in enhancing aerobic

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and anaerobic capacities, they do not provide an external resistance component that directly increases cardiovascular and musculoskeletal stress. One approach being explored is modifying training load using a Weighted Vest (WV). By adding WV to AnST, players are subjected to a controlled external load that enhances stress on the cardiovascular, metabolic, and musculoskeletal systems simultaneously, which is not achieved by standard HIIT or SSG sessions. For example, WV can improve performance across physiological, metabolic, cardiovascular, and musculoskeletal systems during training (Elsyam et al., 2025; Gleadhill et al., 2021).

Additionally, WV can shorten training time by increasing the load on the body's physiological systems (Gaffney et al., 2022). The use of WV has been extensively studied in sports such as athletics and rugby (Barr et al., 2015; Looney et al., 2024; Macadam et al., 2022). These studies show improved training adaptation efficiency, increased muscle capacity, and faster neuromuscular responses (Kang, 2018; Rey et al., 2017). However, there has been limited scientific discussion about the use of WV in soccer. Therefore, integrating WV into AnST offers a methodological advantage: it adds external load to soccer-specific training, maximizing cardiovascular and neuromuscular stimulus without increasing session duration or altering technical-tactical components.

In the complex nature of modern soccer, the need for training that efficiently improves physical performance is becoming increasingly important for coaches. Although past studies have shown that the AnST training model can enhance players' cardiovascular systems, research combining it with external loads such as WV to boost cardiovascular function in soccer remains very limited. Hence, the novelty of this research lies in its combined approach, where AnST with WV provides a simultaneous aerobic and anaerobic challenge, offering a more targeted and efficient adaptation than conventional HIIT or SSG methods.

Therefore, this study aimed to examine the effectiveness of the AnST model, both with and without the addition of a WV, on the aerobic capacity of amateur soccer players. VO_2max was established as the primary outcome, representing players' aerobic capacity and endurance performance, while sprint speed (Speed) served as the secondary outcome to assess high-intensity performance. The researcher hypothesized that implementing the AnST model with WV loading would lead to greater improvements in aerobic performance, reflected by higher VO_2max and Speed values, compared to the same model performed without additional external load among amateur soccer players.

Materials and Methods

Study Participants

In this study, researchers recruited 22 male participants who played university-level soccer. The average age of the participants was 20 ± 0.94 years. Anthropometric data showed an average height of 165 ± 6.07 cm, a body weight of 60.52 ± 6.07 kg, and a body mass index (BMI) of 22.36 ± 2.44 kg/m2. Additionally, the researchers outlined the inclusion criteria, which included having experience with soccer, being healthy and injury-free during the study, and not participating in any external training programs apart from the intervention. Exclusion criteria included missing more than 10% of the intervention sessions and having a musculoskeletal injury in the past few months. Ethics committee approval for this study was obtained from the Health Research Ethics Committee, Nahdlatul Ulama University of Surabaya (Date: 24 November 2024, Decision No: 0374/EC/KEPK/UNUSA/2024)

Study Organization

This study used a quasi-experimental design with two groups and pretest–posttest measurements. Participants were assigned to either a control group (Group A) or an experimental group (Group B) using the ordinal pairing method to ensure baseline comparability. The pretest was conducted over one week, during which all players performed the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) to assess aerobic capacity (primary outcome) and a 20-meter sprint test to measure sprint speed (secondary outcome). Subsequently, participants underwent a three-week training intervention, consisting of four sessions per week. Group B completed AnST while wearing a WV equivalent to 7.21 ± 0.72% of their body mass, whereas Group A performed the same training protocol without additional load (0%). In the final week, a posttest using the same YYIR1 and sprint tests was conducted. Throughout all training sessions, participants' heart rates were monitored using a Polar H10 device to ensure exercise intensity remained within the target range of 85–90% of maximum heart rate

Statistical Analysis

Normality was assessed using Shapiro–Wilk, and homogeneity of variance using Levene's test. Although data were normally distributed, homogeneity was violated ($p < 0.05$); therefore, between-group differences in post-test VO_2max and sprint speed were analyzed using Quade non-parametric ANCOVA, with pre-test scores as covariates. Effect sizes were reported as partial eta squared (η^2_p) and converted to Cohen's f. Within-group changes were quantified using Cohen's d. Post-hoc power analysis using G*Power indicated adequate sensitivity for detecting large effects (VO_2max: $f = 0.59$, power ≈ 0.78; sprint speed: $f = 0.71$, power ≈ 0.88). Given the modest sample size ($n = 22$), this study is considered a pilot controlled trial, and the findings should be interpreted as preliminary but practically meaningful.

Test Measurement

The primary variable in this study was aerobic capacity, measured using the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1). This field test was selected for its proven validity and strong correlation with the aerobic performance of soccer players (Asimakidis et al., 2025; Krustrup et al., 2015). During the test, participants ran between two 20-metre lines, following an audio signal with progressively shorter intervals, and performed 10 seconds of active recovery between each shuttle. The test was terminated when participants failed to reach the line within the beep interval twice. In this study, VO_2max and speed were determined using the procedures and references proposed by Bangsbo et al. (2008). VO_2max (mL/min/kg) was estimated using the formula: $VO_2max = \text{IR1 distance (m)} \times 0.0084 + 36.4$. Speed was defined as the final running velocity corresponding to the last fully completed stage in the YYIR1 test, expressed in kilometres per hour (km·h^{-1}). Each stage in the YYIR1 corresponds to a predetermined running speed that progressively increases throughout the test. The YYIR1 test was conducted twice (pre- and post-intervention) under identical environmental and procedural conditions to minimize measurement bias and enhance test-retest reliability. The resulting VO_2max and speed data were then used to compare the effects of the training interventions between Group A and Group B.

Training Program

This study combined the AnST training model with the Speed Endurance Training (SET) and Small-Sided Game (SSG) approaches, adding WV at 1:1 intervals. There was a sprint area measuring 20 meters in distance and an SSG area of 25 meters by 20 meters, which was completed in 20 seconds. In one set, the players sprinted for 80 meters and the SSG for 80 seconds, divided into four repetitions.

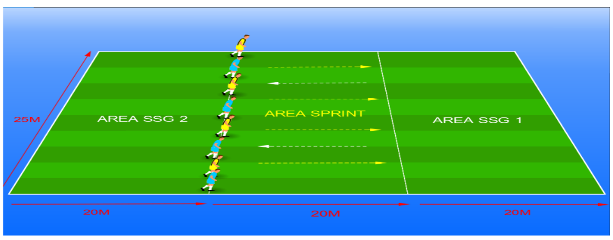

Fig. 1. Training area

At the start of the training, the players sprinted 20 metres to SSG 1 and immediately engaged in a game for 20 seconds, focusing on gameplay movements. After 20 seconds, the players sprinted 20 metres to SSG 2 and performed the same exercises as in SSG 1. This session consisted of four repetitions in one set, with a 1:1 training interval. The intervals were conducted systematically, beginning with the players stopping their activity after one repetition and moving outside the training area. During the recovery period, the players' heart rates remain high and gradually decrease, allowing their bodies to adapt to managing fatigue between intense activities. The total duration is the same as for the aforementioned activities, approximately 100 seconds (10-15 seconds of sprinting + 80 seconds of continuous training). Therefore, the interval concept serves as recovery and trains the cardiovascular system to respond to repeated intense work. The players perform eight sets of these activities, resulting in a total training session time (including sprinting, continuous training, and recovery) of approximately 26 minutes. This training improves aerobic endurance by targeting an average heart rate of more than 80% of HRmax during sprinting and continuous training, thereby reaching the high-intensity zone.

Each player completes 640 metres of total sprints in a 10-minute and 7-second training session. This training method aims to enhance players' aerobic endurance and ability to recover between high-intensity efforts.

Results

Table 1 presents the initial characteristics of all participants, divided into two groups: Group A (n = 11) and Group B (n = 11). The participants had an average age of 20.63 years. The average weight was 62.82 ± 5.60 kg for group A and 58.22 ± 6.08 kg for group B. The average height was 166 ± 7.06 cm for group A and 163.6 ± 3.99 cm for group B. Additionally, the body mass index (BMI) of both groups was recorded at 23 ± 2.89 for group A and 21.72 ± 1.80 for group B in this study.

Table 1. Characteristics of Subjects

Characteristics of Research Subjects	Group A n=11 (Mean ± SD)	Group B n=11 (Mean ± SD)
Age (years)	20.63 ± 0.80	21.09 ± 1.04
Weight (kg)	62.82 ± 5.60	58.22 ± 6.08
Height (cm)	166 ± 7.06	163.6 ± 3.99
BMI (kg/m^2)	23 ± 2.89	21.72 ± 1.80

Table 2. Descriptive statistics

Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	Δ (Post-Pre)
VO_2max (mL/min/kg)	Group A	42.66 ± 1.86	45.56 ± 2.63	2.90
	Group B	43.54 ± 1.89	48.74 ± 2.57	5.20
Speed (km.h^{-1})	Group A	14.68 ± 0.46	15.27 ± 0.46	0.59
	Group B	14.82 ± 0.39	15.90 ± 0.53	1.08

Table 2 shows the changes in VO_2max and sprint speed (Speed) in Group A and Group B from pre-test to post-test. The results indicate that both groups experienced improvements in VO_2max and Speed following the intervention. Group B showed greater increases compared to Group A, both in VO_2max (Δ = 5.20 mL/min/kg vs. 2.90 mL/min/kg) and Speed (Δ = 1.08 km·h^{-1} vs. 0.59 km·h^{-1}). Data are presented as mean ± SD, and Δ (Delta) represents the mean change from pre-test to post-test.

Table 3. Normality Test

		Shapiro-Wilk		
Assessment session	Group	Statistic	df	Sig.
Pretest VO_2max	Group A	.909	11	.235
	Group B	.953	11	.680
Posttest VO_2max	Group A	.908	11	.234
	Group B	.941	11	.538
Pretest Speed	Group A	.772	11	.004
	Group B	.868	11	.073
Posttest Speed	Group A	.887	11	.127
	Group B	.840	11	.032

Table 3 presents the results of the Shapiro-Wilk test for normality of VO_2max and Speed in Groups A and B at pre-test and post-test. VO_2max was normally distributed in all conditions (Sig. > 0.05) and thus followed by a test of homogeneity of variance. In contrast, speed was non-normally distributed in some conditions (Sig. < 0.05), and further analysis was conducted using the Quade non-parametric test.

Table 4. Levene's Test of Equality of Error Variances

F	df1	df2	Sig.
10.135	1	20	.005

Note: Tests the null hypothesis that the error variance of the dependent variable is equal across groups; Model includes Intercept, Pre_VO_2max, and Group; Dependent Variable: Post_ VO_2max.

Table 4 presents the results of Levene's Test for assessing the homogeneity of variances of Post_VO_2max across groups. The null hypothesis states that the error variance of the dependent variable is equal across all groups. The model included the Intercept, Pre_VO_2max as a covariate, and Group as the independent factor. A Sig. value of 0.005 indicates that the assumption of homogeneity of variances was violated, and therefore, further analysis was conducted using the Quade non-parametric test.

Table 5. Quade Non-parametric Analysis of Covariance

Variable	F	DFH	DFE	P Value
VO_2max	7.062	1	20	.015
Speed	10.015	1	20	.005

Notes: ANCOVA controlled for pre-test scores; DFH = degrees of freedom for hypothesis; DFE = degrees of freedom for error.

Table 5 presents the Quade ANCOVA results for VO_2max and sprint speed, showing significant differences between Group A and Group B after controlling for pre-test scores (VO_2max: $F_{1,20} = 7.062$, $p = 0.015$; speed: $F_{1,20} = 10.015$, $p = 0.005$). The magnitude of these effects was large, with partial eta-squared values of $\eta^2_p = 0.26$ (Cohen's f = 0.59) for VO_2max and $\eta^2_p = 0.33$ (Cohen's f = 0.71) for sprint speed, indicating substantial and practically meaningful performance improvements in favor of Group B. Within-group pre- to post-test changes (Δ) were quantified using Cohen's d: VO_2max (Group A: d = 1.27; Group B: d = 2.31) and sprint speed (Group A: d = 1.28; Group B: d = 2.32), confirming large and very large improvements, respectively. The 95% confidence intervals (CI) reported in Table 6 further support these findings, with Group B's post-test CI consistently higher than Group A's and Δ-CI entirely in the positive range, indicating directionally stable and reliable improvements.

Tabel 6. Confidence Interval 95% test for VO_2max and Speed

Variable	Group	Pre-test 95% CI	Post-test 95% CI	Δ (Post-Pre) 95% CI
VO_2max	Group A	41.41 – 43.91	43.79 – 47.33	1.71 – 4.09
	Group B	42.28 – 44.81	47.01 – 50.47	4.60 – 5.78
Speed	Group A	14.37 – 14.99	14.96 – 15.58	0.33 – 0.85
	Group B	14.56 – 15.08	15.54 – 16.26	0.88 – 1.28

Note: Δ= Post-test – Pre-test; 95% CI provides an estimate of the precision of the changes.

Table 6 shows that Group B experienced larger increases in both VO_2max and sprint speed compared to Group A. The lower bounds of Group B's Δ-CI did not overlap with Group A's lower bounds, indicating consistent and directionally stable post-intervention improvements. Combined with the large effect sizes, these results provide convergent evidence of practically meaningful performance enhancements in Group B.

Discussion

The results of this study indicate significant improvements in VO_2max (primary outcome) and sprint speed (secondary outcome) in both groups after the intervention, with Group B showing greater increases compared to Group A. These findings highlight the effectiveness of the implemented training model in enhancing both aerobic capacity and sprint performance among amateur soccer players. As part of a High-Intensity Interval Training (HIIT) framework, this model targets both the aerobic and anaerobic energy systems through repeated bouts of exercise and recovery periods. The application of a WV load of 7.21 ± 0.72% of body mass for three weeks, conducted four sessions per week, led to greater improvements in both aerobic capacity and sprint performance compared with the same model performed without additional load.

The use of a WV during AnST provides an additional external load during repeated high-intensity activities, which stimulates physiological adaptations in the cardiovascular system. This finding aligns with previous research, which shows that the amount of vest load directly influences the level of intensity experienced by the body and subsequently enhances cardiorespiratory adaptation (Bertochi et al., 2024; Kim et al., 2024). Higher training intensity also enhances activation of PGC-1α, supporting mitochondrial enlargement and density, which contributes to improved aerobic performance (Gurd et al., 2023; Thirupathi & de Souza, 2017). As a result, the integration of WV with AnST positively affects VO_2max, sprint speed, and distance, confirming that this training model can maintain beneficial adaptations during repeated high-intensity activities (Ahmad et al., 2025; Barnes et al., 2015; Rey et al., 2017).

Biomechanically, the use of WV influences sprint mechanics, including ground reaction forces, step frequency, step length, contact time, and flight time, while also increasing physiological stress without negatively affecting gait parameters (Bertochi et al., 2024; Cross et al., 2014; Gaffney et al., 2022). These changes provide a practical stimulus for improving both aerobic and anaerobic performance. However, careful consideration of load is essential, as excessive weight may limit muscle activation, reduce the efficiency of the stretch-shortening cycle, and increase the risk of injury (Fernández-Galván et al., 2022; Tillaar et al., 2018; Zabaloy et al., 2022). In this study, applying WV at 7.21 ± 0.72% of body mass maintained high training intensity while minimizing these risks.

From a practical standpoint, the use of a WV during both pre-season and in-season training has proven effective in enhancing the physical performance of soccer players. During the pre-season phase, WV training helps build a solid physical foundation, improving sprinting, jumping, change of direction (COD), as well as aerobic and anaerobic capacities (Lagodimos et al., 2024; Majkić et al., 2025). The external load provided by WV adds a physiological stimulus that promotes cardiovascular adaptation and reduces the risk of fatigue during competition (Swain et al., 2010). During the in-season period, integrating WV into SSG serves as an effective method to combine technical, tactical, and physical components without causing excessive fatigue. Studies have shown that SSGs with WV enhance sprinting, jumping, COD, and aerobic performance without significantly increasing fatigue (Sanchez-Sanchez et al., 2024). Overall, applying WV during both pre-season and in-season periods represents an evidence-based strategy to optimize physical performance and sustain players' physiological adaptations throughout the season.

The large observed effect sizes for both VO_2max (η^2_p = 0.26; f = 0.59) and sprint speed (η^2_p = 0.33; f = 0.71) indicate that weighted-vest–based anaerobic soccer training may provide meaningful physiological and performance benefits within a short-term training period. However, given the small sample size (n = 22) and the achieved power that is adequate primarily for detecting large effects, the findings should be interpreted with caution. Consistent with current methodological recommendations, these statistical characteristics indicate that the present investigation is best positioned as preliminary research rather than a fully powered efficacy trial. Accordingly, the study is more appropriately framed as a pilot controlled trial that aims to generate preliminary evidence, guide future sample size estimation, and refine the training and assessment procedures for subsequent large-scale randomized studies.

This study has several limitations that should be taken into consideration. First, the sample size was relatively small and limited to a specific group of soccer players, which may affect the generalizability of the findings. Second, the intervention lasted only three weeks, and variations in WV load were not explored, which limited the understanding of optimal training intensity. Third, this study primarily focused on VO_2max, sprint speed, and distance, without assessing other performance aspects, such as muscular strength, technical skills, or psychological factors. Finally, the effects were measured in a controlled training environment, not during actual match conditions, which may differ in real-game demands.

Future research should address these limitations by including larger and more diverse samples, longer intervention periods, and exploring different WV loads. Additionally, studies could examine other performance variables and assess outcomes during competitive match situations to provide a more comprehensive understanding of the physiological and practical effects of AnST training with WV.

Conclusions

This study concludes that AnST training with a WV at 7.21 ± 0.72% of body mass significantly improves players' aerobic capacity, as evidenced by greater increases in VO_2max and sprint speed compared to training without a WV. The addition of external load provides an extra physiological stimulus that enhances cardiovascular adaptation. This training approach is practical when applied during both pre-season and in-season periods as a strategic method to optimize aerobic performance. These findings provide further scientific evidence supporting the use of WV as an effective training tool in soccer.

Conflict of Interest

The author declares no conflict of interest.

AI Use Declaration

During the preparation of this manuscript, the authors made limited use of AI-assisted tools solely for language editing and text refinement. No AI tools were used for data analysis, interpretation, or scientific decision-making. All statistical analyses were conducted independently by the authors using IBM SPSS Statistics (version 30).

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Підвищення аеробної та спринтерської продуктивності за допомогою анаеробних тренувань з футболу із використанням жилета-обважнювача: Дані контрольованого дослідження серед футболістів

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 7 с., 6 табл., 1 рис., 31 джерело.

Обґрунтування. Сучасний футбол потребує виконання повторюваних високоінтенсивних, комплексних рухів, що робить аеробну продуктивність надзвичайно важливою для гравців.

Цілі. Мета цього дослідження полягала у вивченні впливу анаеробного тренування з футболу (АнФТ) із використанням жилета-обважнювача (ЖО) вагою 7.21 ± 0.72% від маси тіла на аеробну продуктивність, що вимірювалася за показниками максимального споживання кисню і швидкості.

Матеріали та методи. У цьому дослідженні застосовано квазіекспериментальний дизайн з двома групами (група A та група B), використовуючи претест як коваріату і постест як залежну змінну. Загалом 22 футболісти-чоловіки було розподілено за методом рандомізації на дві групи: контрольну групу з додатковим навантаженням 0% від маси тіла (група A, n = 11) та експериментальну групу з додатковим навантаженням 7.21 ± 0.72% від маси тіла (група B, n = 11). Аеробна продуктивність оцінювалася за допомогою тесту переривчастого відновлення Йо-Йо рівня 1 (Yo-Yo Intermittent Recovery Test Level 1, YYIR1) перед початком і після трьох тижнів інтервенції, що передбачала проведення чотирьох сесій на тиждень. За результатами YYIR1 було отримано дані щодо максимального споживання кисню та швидкості для аналізу. Статистичні тести включали тест нормальності Шапіро-Вілка, тест гомогенності Левене та непараметричний коваріаційний аналіз за методом Кваде з використанням програмного забезпечення IBM SPSS 30 з рівнем значущості 0.05.

Результати. На основі результатів, отриманих шляхом непараметричного коваріаційного аналізу за методом Кваде, встановлено значні відмінності між групами A і B за показниками максимального споживання кисню (p = 0.015) і швидкості (p = 0.005) після контролю претестових значень. Зазначені результати свідчать про різний вплив типів тренувань, проведених для кожної групи, на поліпшення аеробної продуктивності та швидкості гравців.

Висновки. Результати дослідження підтверджують, що три тижні анаеробного тренування з футболу з використанням жилета-обважнювача 7.21 ± 0.72% від маси тіла сприяють підвищенню максимального споживання кисню і швидкості бігу. Однак ці результати є попередніми і їх слід інтерпретувати з обережністю через коротку тривалість дослідження і невеликий розмір вибірки.

Ключові слова: жилет-обважнювач, анаеробне тренування з футболу, максимальне споживання кисню, швидкість.

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Determining the Readiness of Future Physical Education Teachers to Implement Adaptive Physical Education in Schools for Students with Hearing Impairments

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Abstract

Background. This article presents the results of a comprehensive study on how prepared future physical education teachers are to implement adaptive physical education for children with hearing impairments. The study's relevance stems from Ukraine's growing need for inclusive education, and the necessity to ensure that children with sensory disabilities have access to physical activity. Inclusive education means creating equal learning opportunities for all students, including those with hearing impairments. In this context, physical education supports both health and socialization.

Objectives. The study aimed to provide a theoretical justification, conduct an empirical investigation, assess the readiness of future physical education teachers to implement adaptive physical education in educational institutions that enroll students with hearing impairments, and develop practical recommendations to improve teachers' professional training. The article examines the structure of professional readiness of future physical education teachers. It presents the findings of an empirical study on readiness levels and analyzes the factors that influence their development.

Materials and Methods. The study involved 186 students of T.H. Shevchenko National University "Chernihiv Collegium." The research examined the participants' knowledge of adaptive physical education, their skills in working with students with hearing impairments, and their motivational value and attitudes toward inclusive education. The objective of the study was to assess the level of professional readiness of students majoring in Physical Education to implement adaptive physical education in schools with inclusive forms of education for children with hearing impairments. Readiness was evaluated based on four key components: cognitive, motivational–value, operational–practical, and communicative–reflective.

Results. The findings indicate insufficient practical training and limited proficiency in sign language, although the majority of students demonstrated positive motivation toward inclusion. A training model that includes a theoretical course, practical modules, volunteer activities, internships, and support from an experienced mentor is proposed. Promising directions for improving educational programs were identified.

Conclusions. The readiness of future teachers to implement adaptive physical education in schools educating children with hearing impairments is a key factor in the successful implementation of inclusive education. The study contributes to the development of adaptive physical education and to the training of teaching professionals for work in inclusive educational environments.

Keywords: inclusive education, professional readiness, sign language, special pedagogy.

Introduction

The education system in Ukraine is currently developing in line with the principles of inclusion, which include creating conditions for the education of children with special educational needs in comprehensive schools. Among these learners, students with hearing impairments constitute a particularly important group, as they require not only adapted pedagogical methods but also specific approaches to physical education (Nosko & Troianovska, 2025; Nosko et al., 2025). The relevance of this issue is reinforced by the fact that physical education serves not only developmental but also compensatory functions. It facilitates socialization and the acquisition of essential life competencies by students with sensory impairments.

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Despite ongoing promotion of inclusive education policies in Ukraine, the existing teacher-training system does not consistently ensure that future physical education teachers are adequately prepared to work with diverse student groups, particularly those with hearing impairments. Students with hearing impairments often face barriers. These include communicative, sensory, and emotional challenges that limit participation in sports and extracurricular activities (Alhumaid, 2023; Dubey, 2024). To address these issues, teachers must master specialized instructional methods. They also need basic competence in sign language, an understanding of the psychophysiological traits of children with hearing impairments, and the ability to create an inclusive educational environment (Rekaa et al., 2018; Bruno, 2020).

Adaptive physical education should not be seen just as a modification of motor exercise programs. Instead, it is a holistic system that considers students' sensory profiles and prioritizes communication and social interaction needs (Azubuike et al., 2023; Orhan et al., 2024; Holland et al., 2022). Teachers' professional readiness to implement such a system is an integrative quality encompassing motivational, cognitive, practical, and reflective dimensions.

A growing body of research highlights the need to strengthen physical education teachers' training for inclusive educational contexts (Smith et al., 2021; David & Brown, 2022; Kovalenko, 2023; Celestino et al., 2024; Kim et al., 2021). Nevertheless, a central unresolved issue is the actual readiness of future teachers to work effectively with students with hearing impairments, and which factors most strongly influence these required competencies.

In this regard, the study advances the hypothesis that the current system of professional training for future physical education teachers in Ukraine does not adequately ensure the acquisition of competencies necessary for the effective implementation of adaptive physical education in schools enrolling students with hearing impairments.

The purpose of this article is to provide a theoretical justification, conduct an empirical assessment, and evaluate the readiness of future physical education teachers to implement adaptive physical education in schools enrolling students with hearing impairments. In addition, the study aims to develop practical recommendations to improve teachers' professional preparation for inclusive practice.

Materials and Methods

Study Design

The present study employed a descriptive cross-sectional design with a mixed-methods approach integrating quantitative and qualitative methodologies. This design was chosen to provide a comprehensive assessment of the professional readiness of future physical education teachers to implement adaptive physical education for students with hearing impairments.

The quantitative component enabled objective measurement of readiness across predefined structural components, while the qualitative component facilitated deeper exploration of students' subjective perceptions, attitudes, expectations, and anticipated challenges related to inclusive practice. The integration of both approaches enhanced the methodological robustness and validity of the findings.

Participants

The study involved 186 undergraduate and graduate students majoring in Physical Education, which meets statistical representativeness requirements. Sample size adequacy was confirmed through an a priori power analysis conducted using G*Power 3.1 software. Assuming a medium effect size ($f = 0.25$), a significance level of $\alpha = 0.05$, and statistical power of 0.80 for a one-way analysis of variance (ANOVA), the required minimum sample size was 159 participants. The final sample exceeded this threshold, allowing reliable detection of statistically significant differences and relationships among the studied variables.

Participants were recruited using purposive sampling from Ukrainian higher education institutions offering degree programs in physical education teacher training. Inclusion criteria comprised enrollment in the third or fourth year of study and completion of coursework in pedagogy, inclusive education, or adaptive physical education. Participation was voluntary and anonymous, and all respondents provided informed consent prior to data collection.

The study protocol was approved by a local ethics committee and conducted in accordance with the Declaration of Helsinki and General Data Protection Regulation (GDPR) requirements. The sample demonstrated variability in gender and academic background, ensuring diversity in prior training and experience with inclusive education.

Data Collection Procedure

Data collection followed a standardized and reproducible protocol implemented in classroom settings across all participating institutions.

At the first stage, participants completed a 32-item structured questionnaire assessing professional readiness across four components: cognitive, motivational–value, operational–practical, and communicative–reflective. The average completion time was 10–12 minutes, and the administration procedure was identical at all sites.

At the second stage, participants performed a practical task consisting of four structured exercises aimed at evaluating their ability to:

- adapt physical activities for students with hearing impairments;
- use visual instructional materials;
- apply basic elements of sign language;
- select appropriate inclusive communication strategies.

Performance was assessed using a unified rating scale to ensure inter-expert consistency.

The final stage involved semi-structured interviews with a subsample of 30 participants selected according to the principle of maximum variability. Interviews were conducted face-to-face, lasted 20–30 minutes, and were audio-recorded with participants' consent. All interviews were transcribed verbatim using a standardized interview guide. Consistency in sequencing, conditions, and procedures across institutions ensured full reproducibility of the data collection process.

Instruments

Professional readiness of future physical education teachers to work with students with hearing impairments was assessed using a комплекс of complementary instruments, combining quantitative, practical, and qualitative methods.

Questionnaire

The primary quantitative instrument was a structured questionnaire comprising 32 statements designed to assess four components of professional readiness:

- Cognitive (knowledge of adaptive physical education and characteristics of teaching students with hearing impairments).
- Motivational–value (attitudes toward inclusive education and readiness for professional self-development).
- Operational–practical (ability to adapt exercises and organize inclusive classes).
- Communicative–reflective (self-assessment of communication skills, including the use of sign language elements).

Responses were recorded on a five-point Likert scale ranging from 1 (“strongly disagree”) to 5 (“strongly agree”), enabling quantitative interpretation of the degree of expression of each component.

Content validity was established through expert evaluation involving specialists in adaptive physical education, special pedagogy, and inclusive education. Experts assessed item relevance, clarity, and structural adequacy. Minor revisions were made based on their recommendations.

Internal consistency reliability was confirmed using Cronbach’s alpha ($\alpha = 0.87$), indicating high reliability of the instrument.

Assessment of Sign Language and Practical Skills

Elements of sign language competence were evaluated within the operational–practical and communicative–reflective components and included:

- understanding basic signs commonly used in physical education classes;
- ability to convey simple instructions through gestures;
- use of visual–gestural support during motor activity organization;
- awareness of communication barriers and strategies to overcome them.

Assessment was conducted using a point-based rating scale during practical task performance, allowing differentiation between low, medium, and high levels of skill development.

When developing the questionnaire and practical assessment criteria, approaches used in internationally validated instruments for evaluating teachers’ readiness for inclusion—particularly the CEFI-R (Evaluation of Teachers’ Preparation for Inclusion)—as well as contemporary studies in adaptive physical education, were taken into account to ensure conceptual alignment with current international research practices.

Statistical Analysis

Statistical analyses were performed using SPSS version 26. Descriptive statistics (means and standard deviations) were calculated solely to characterize the sample.

Between-group differences were examined using one-way analysis of variance (ANOVA), with year of study and prior experience in inclusive educational settings treated as independent factors. Prior to conducting ANOVA, assumptions of normality (Shapiro–Wilk test) and homogeneity of variances (Levene’s test) were assessed. In cases where homogeneity was violated, the Welch correction was applied.

Post hoc comparisons were conducted using Tukey’s HSD or the Games–Howell test, depending on variance homogeneity results. Effect sizes were calculated to determine practical significance (partial eta squared, η^2_p, for ANOVA; r for correlational analyses), accompanied by 95% confidence intervals and interpreted according to established conventions.

Relationships among components of professional readiness were analyzed using Pearson’s correlation coefficient. Results are presented concisely, without duplication of numerical data already reported in tables.

The level of statistical significance for all analyses was set at $p < 0.05$.

Results

The study’s results enabled a comprehensive assessment of the readiness of students majoring in Physical Education to implement adaptive physical education for students with hearing impairments. Both quantitative methods (questionnaire and practical testing) and qualitative methods (semi-structured interviews) were used, ensuring a multidimensional evaluation.

As shown in Table 1, the majority of students demonstrated an average level of readiness, whereas only a small proportion were highly prepared.

Table 1. Distribution of future physical education teachers by overall level of professional readiness (n = 186)

Level of readiness	% of students
High	17.2%
Medium	58.6%
Low	24.2%

The mean score across all questionnaire scales was 3.21 out of 5 (SD = 0.74), corresponding to an overall medium level of readiness.

Detailed indicators of the four components of professional readiness are presented in Table 2.

Thematic analysis of the 30 semi-structured interviews identified five recurring themes reflecting both challenges and motivational aspects of students’ professional readiness:

1. Fear and uncertainty – “I am afraid of doing something wrong because I do not know how to behave properly with a student who is deaf.”

2. Insufficient university preparation – “We did not have any practical experience working with children with disabilities.”

3. High personal motivation – “I would like to learn sign language, but I do not know where this can be done.”

4. Desire for change – “It would be good if we had internships in inclusive schools.”

5. Uncertainty regarding success criteria – “I am not sure how to properly assess the progress of such students.”

Table 2. Descriptive statistics of the components of professional readiness (mean ± SD)

Component	Mean score (out of 5)	Key findings
Cognitive readiness	3.48	63% answered correctly on knowledge of motor activity for children with hearing impairments
Motivational-value readiness	3.92	74% expressed willingness to work with students with special needs; 61% ready for additional training; only 28% felt fully prepared
Operational-practical readiness	2.89	66% had no experience adapting exercises; 11% confident in planning lessons; 37% confused adaptive PE with physical therapy
Communicative-reflexive readiness	3.02	83% did not know sign language; 57% reported emotional tension; 21% noted need for psychological training

Correlation analysis revealed significant relationships between the components of professional readiness:

- Positive correlation between cognitive and practical readiness ($r = 0.52$, $p < 0.01$).
- Significant correlation between motivational and reflective readiness ($r = 0.47$, $p < 0.05$).
- The lowest correlation was found between theoretical knowledge and practical skills ($r = 0.33$), indicating a gap between knowledge acquisition and its practical application.

Overall, the study showed that only 1 in 10 students demonstrated a high level of readiness to implement adaptive physical education when working with students with hearing impairments. The prevailing level of readiness was average, characterized by strong motivation but weak practical skills. The most problematic areas of training were:

- Lack of sign language skills;
- Limited practical training;
- Lack of internships in an inclusive environment (see Fig. 1).

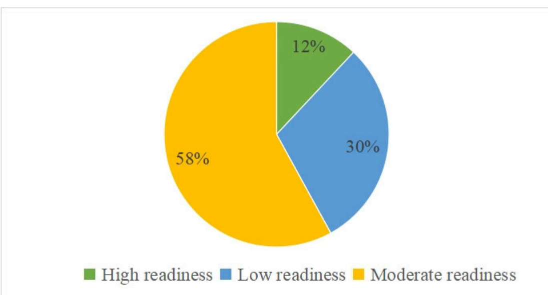

Fig. 1. Level of readiness of future physical education teachers to implement adaptive physical education

Both quantitative and qualitative results confirm the urgent need to modernize university curricula in order to strengthen the practical and communicative components of teacher training.

Discussion

The aim of the study was to determine the level and structure of professional readiness of future physical education teachers to implement adaptive physical education when working with students with hearing impairments. The results indicate a predominance of average readiness, which is consistent with the findings of recent studies in the field of inclusive physical education, which show that future teachers have a positive attitude towards inclusion but lack practical training (Savolainen et al., 2020; Jung et al., 2022; Braksiek, 2022). Similar trends are also observed in the works of Ukrainian scientists, who emphasize the fragmentation of professional training and the predominance of theoretical components over practical ones (Kravchenko, 2022).

Analysis of the structure of professional readiness revealed an imbalance between high scores for the motivational-value component and lower indicators of the operational-practical and communicative-reflective components. This structure is consistent with international studies in adaptive physical education, which indicate limited development of practical and communicative skills among future physical education teachers (Loreman, 2014; Block, 2016; Antala et al., 2024). Particular attention should be paid to the low level of proficiency in sign language elements, which confirms the findings of Rekaa et al. (2018) and Rojo-Ramos et al. (2023) regarding the insufficient integration of communication training into educational programmes.

The established correlations between individual components of readiness indicate its integrative nature. Positive interdependencies among cognitive, motivational, and practical components indicate that the formation of individual knowledge and attitudes does not ensure professional readiness without systematic practical training, consistent with the conclusions of Kim et al. (2021) and Savolainen et al. (2020).

Critical reflection on the results obtained requires consideration of several limitations. First, the cross-sectional design does not allow conclusions about the dynamics of professional readiness over time; longitudinal studies are needed to assess the impact of the curriculum or specialized interventions.

Secondly, although the sample size was statistically sufficient, the participants were drawn from a single university, which may limit the generalizability of the results. Differences in curricular structures and practical training models were not systematically controlled.

Thirdly, the use of self-assessment methods for motivational and communicative-reflective components creates a risk of social desirability bias. This effect is partially mitigated by the inclusion of practical assessments, but further research should include classroom observation or external expert assessment.

Finally, the assessment of sign language competence focused on functional pedagogical use rather than full linguistic proficiency, which limits direct comparison with studies that measure comprehensive language proficiency.

The contribution of this study to the international scientific literature lies in its empirical analysis of the readiness of future physical education teachers to work with students with hearing impairments in the context of Eastern Europe—a region that remains underrepresented in research on adaptive physical education (Qi & Ha, 2012; Tarantino & Makopoulou, 2023; Cabahug, et al. 2025). The results complement existing international approaches, emphasizing the importance of communicative competence and practice-oriented learning for the effective implementation of inclusive physical education.

The results demonstrate that high motivation does not guarantee pedagogical competence in inclusive physical education, emphasizing the importance of structured learning and practical training (Beyazoğlu, 2021; Mawena & Sorkpor, 2024; Utami, 2025).

Thus, the study provides both contextually specific conclusions and conceptual implications for the development of adaptive physical education within inclusive educational environments.

Conclusions

The aim of the study was to assess the level of professional readiness of students majoring in Physical Education to implement adaptive physical education in inclusive schools for children with hearing impairments. Readiness was analyzed according to four components: cognitive, motivational value, operational-practical, and communicative-reflective.

The results obtained indicate that the overall level of readiness is average (3.21 out of 5). The highest indicators were found in the motivational and value component, which demonstrates a positive attitude and student interest in inclusive education. The lowest values were recorded in the operational and practical component, which indicates insufficiently developed skills in adapting physical exercises, using sign language, and organizing inclusive classes.

The distribution by level confirmed the general trend: 17.2% of students showed a high level of readiness, 58.6% showed an average level, and 24.2% showed a low level. This result indicates a significant gap between students' motivation and their actual professional competence, especially in special education and the practical application of inclusive technologies.

Therefore, the results obtained demonstrate that the current teacher training system does not fully ensure the development of the competencies necessary for the effective implementation of adaptive physical education in schools serving hearing-impaired students. The conclusions are consistent with the research objectives and justify the need to modernize training programmes, with a particular focus on practice-oriented learning, sign language acquisition, and enhanced interdisciplinary training.

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Conflict of Interest

The authors declare no conflicts of interest.

AI Transparency Statement

The authors declare that no artificial intelligence (AI) tools were used in the collection, analysis, or interpretation of study data. AI-assisted software (ChatGPT, OpenAI, USA) was employed only for language editing and grammar refinement during manuscript preparation. All scientific content, study design, statistical analysis, and interpretation were performed solely by the authors.

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Визначення готовності майбутніх учителів фізичної культури до впровадження адаптивного фізичного виховання в школах для учнів з порушеннями слуху

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 7 с., 2 табл., 1 рис., 30 джерел.

Обгрунтування. У статті подано результати комплексного дослідження рівня готовності майбутніх учителів фізичної культури до впровадження адаптивного фізичного виховання для дітей з порушеннями слуху. Актуальність дослідження зумовлена зростанням потреби України в інклюзивній освіті та необхідністю забезпечення доступу дітей із сенсорними порушеннями до фізичної активності. Інклюзивна освіта передбачає створення рівних освітніх можливостей для всіх учнів, зокрема для осіб з порушеннями слуху. У цьому контексті фізичне виховання сприяє як збереженню та зміцненню здоров'я, так і соціалізації.

Мета. Метою дослідження було теоретично обґрунтувати проблему, провести емпіричне дослідження, оцінити рівень готовності майбутніх учителів фізичної культури до впровадження адаптивного фізичного виховання в закладах освіти, де навчаються учні з порушеннями слуху, а також розробити практичні рекомендації щодо вдосконалення їхньої професійної підготовки. У статті розкрито структуру професійної готовності майбутніх учителів фізичної культури, подано результати емпіричного дослідження рівнів готовності та проаналізовано чинники, що впливають на їх формування.

Матеріали і методи. У дослідженні взяли участь 186 студентів Національного університету «Чернігівський колегіум» імені Т. Г. Шевченка. Вивчалися знання учасників з адаптивного фізичного виховання, їхні вміння працювати з учнями з порушеннями слуху, а також мотиваційно-ціннісні установки та ставлення до інклюзивної освіти. Метою було оцінити рівень професійної готовності студентів спеціальності «Фізична культура» до впровадження адаптивного фізичного виховання в школах з інклюзивними формами навчання для дітей з порушеннями слуху. Оцінювання здійснювалося за чотирма основними компонентами: когнітивним, мотиваційно-ціннісним, операційно-практичним та комунікативно-рефлексивним.

Результати. Отримані результати свідчать про недостатній рівень практичної підготовки та обмежене володіння жестовою мовою, водночас більшість студентів продемонстрували позитивну мотивацію до інклюзії. Запропоновано модель підготовки, що передбачає теоретичний курс, практичні модулі, волонтерську діяльність, педагогічну практику та супровід досвідченого наставника. Визначено перспективні напрями вдосконалення освітніх програм.

Висновки. Готовність майбутніх учителів до впровадження адаптивного фізичного виховання в школах, де навчаються діти з порушеннями слуху, є ключовим чинником успішної реалізації інклюзивної освіти. Дослідження робить внесок у розвиток адаптивного фізичного виховання та у підготовку педагогічних кадрів для роботи в інклюзивному освітньому середовищі.

Ключові слова: інклюзивна освіта, професійна готовність, жестова мова, спеціальна педагогіка.

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Original Scientific Article

The Synergy of Wearable Optical Heart Rate Sensor Technology and Box Breathing in Real-Time Decision Making in Precision, Explosive, and Intermittent Sports

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Abstract

Background. Real-time decision-making is a critical determinant of performance in precision, explosive, and intermittent sports, where athletes must operate under high physiological and cognitive stress. Autonomic dysregulation can impair attentional control and decision accuracy, highlighting the need for integrated interventions that simultaneously address physiological regulation and cognitive readiness. Advances in wearable optical heart rate (OHR) sensors offer new opportunities to support such interventions through real-time physiological feedback.

Objectives. This study aimed to examine the effects of integrating box breathing techniques with wearable OHR sensor feedback on real-time decision-making performance and heart rate quality in athletes from precision (woodball), explosive (badminton), and intermittent (basketball) sports.

Materials and Methods. A quasi-experimental pre-test–post-test control group design was employed. Sixty-six male athletes (age: 21.3 ± 1.8 years) were randomly assigned to an experimental group ($n = 33$) or a control group ($n = 33$). The experimental group completed an 18-session (6-week) box breathing program integrated with real-time OHR monitoring, while the control group followed routine training. Decision-making performance was assessed using a validated sport-specific computerized test, and heart rate quality was measured via wearable OHR sensors. Data were analyzed using paired-sample t-tests and two-way mixed-design ANOVA (group × time) at $\alpha = 0.05$, with effect sizes reported.

Results. The experimental group demonstrated significant improvements in decision-making performance (3.43 ± 0.42 to 4.48 ± 0.39; +30.59%; $p < 0.001$; Cohen's $d = 1.96$) and heart rate quality, reflected by a reduction in resting heart rate (111.13 ± 8.76 bpm to 97.76 ± 7.94 bpm; −12.03%; $p < 0.001$; Cohen's $d = 1.57$). Substantial time × group interactions were observed for decision-making ($F_{(1,64)} = 121.08$, $p < 0.001$, partial $\eta^2 = 0.65$) and heart rate quality ($F_{(1,64)} = 78.92$, $p < 0.001$, partial $\eta^2 = 0.55$). No meaningful changes were found in the control group.

Conclusions. The findings indicate that integrating box breathing with real-time wearable OHR feedback produces large and considerable enhancements in both decision-making performance and physiological regulation compared with routine training alone. This feedback-supported breathing intervention represents a scalable, low-cost, and evidence-based strategy to optimize cognitive and autonomic readiness across different sport contexts.

Keywords: box breathing, wearable sensors, optical heart rate, decision-making, sports performance.

Introduction

Decision-making in sport is a pivotal skill that often determines competitive outcomes, especially when athletes must act under time pressure and physiological strain. In disciplines categorized as precision (e.g., woodball, archery), explosive (e.g., badminton, sprinting), and intermittent (e.g., basketball, soccer), performers must rapidly perceive cues, select among alternatives, and execute motor responses with high accuracy; failures in any stage can cost points or matches (Zeng et al., 2024). Because these decisions occur in milliseconds-to-seconds windows, both cognitive processing and bodily regulation are integral to successful performance. Physiological arousal and stress

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responses exert a direct influence on cognitive functions relevant to decision-making, including attention, working memory, and inhibitory control. Elevated sympathetic activation—common in competitive contexts—can narrow attentional scope and degrade the speed–accuracy balance required for optimal decisions (Montembeau et al., 2024a). Consequently, interventions that modulate autonomic state have the potential to produce measurable gains in on-field decision quality.

Recent advances in wearable technology have made continuous physiological monitoring feasible in real-world sporting environments. Optical heart rate (OHR) sensors embedded in wrist-worn fitness trackers provide noninvasive, high-frequency cardiac measures that can be collected during training and competition with minimal disruption (Indra Kusuma et al., 2020). Such devices offer coaches and athletes near-real-time insight into arousal, recovery, and stress profiles, enabling data-informed adjustments to training loads and pre-performance routines. Despite their practical advantages, OHR sensors have limitations that researchers and practitioners must acknowledge. Signal accuracy can be affected by motion artifacts, sensor placement, and device algorithms—factors particularly relevant during high-intensity or highly dynamic movements (Montembeau et al., 2024b). Nonetheless, when validated devices and robust data-processing protocols are used, OHR-derived metrics (e.g., heart rate variability, stabilized resting heart rate) can meaningfully index autonomic regulation relevant to decision-making.

Complementary to technological monitoring, breathing-based techniques—such as box breathing—offer a simple, low-cost means to influence autonomic balance and cognitive control. Box breathing uses structured inhale–hold–exhale–hold cycles that tend to increase vagal tone and reduce sympathetic dominance, yielding improvements in attentional focus and stress resilience reported across clinical and performance contexts (Softić et al., 2024). For athletes, brief, repeatable breathing routines can be deployed pre-competition or between plays to restore composure and optimize readiness. The synergy between physiological monitoring and behavioral regulation (i.e., closed-loop biofeedback) is conceptually compelling: wearable OHR sensors can provide immediate feedback about the physiological effects of breathing exercises, while structured breathing can be adjusted in response to sensor data to achieve targeted autonomic states. Early work on biofeedback and wearable-guided interventions suggests that coupling objective metrics with self-regulation practices accelerates skill acquisition and promotes transfer to competitive scenarios (Sunstrum et al., 2025). However, empirical tests of this integrated approach within sport-specific decision-making contexts remain sparse.

Most prior investigations have examined either wearable monitoring (for load and recovery management) or breathing interventions (for stress reduction) in isolation, often within single sports or laboratory tasks (Marchant et al., 2025). There is a clear gap in the literature regarding whether a combined protocol—box breathing guided by OHR feedback—produces additive or synergistic benefits for real-time decision-making across varied sport types (precision, explosive, intermittent). Addressing this gap has both theoretical value (linking autonomic regulation to cognition in applied settings) and practical utility for coaches seeking scalable performance tools. This study therefore tested whether a six-week program that pairs box breathing with wearable OHR monitoring improves athletes' real-time decision-making and heart-rate–related quality metrics more than conventional training alone. Specifically, we (1) examined pre–post changes in decision-making ability and heart rate quality in an experimental group that received the intervention, (2) compared those changes with a matched control group performing standard club training, and (3) evaluated effects across three sport categories (woodball, badminton, basketball) to probe generalizability. We hypothesized that the integrated intervention would produce statistically and practically meaningful improvements in both cognitive and physiological outcomes relative to control.

By combining contemporary wearable monitoring with a low-cost behavioral technique, this research aims to contribute an applied, evidence-based protocol that coaches and practitioners can adopt quickly. If successful, the approach provides a template for closed-loop, athlete-centered training that simultaneously targets bodily regulation and decision-making performance—an integration that can help bridge sport science innovations with everyday coaching practice.

Materials and Methods

Research Design

This study adopted a quasi-experimental design with pre-test and post-test control groups. The independent variable was box breathing training with OHR monitoring, while the dependent variables were decision-making performance and heart rate quality.

Participants

A total of 66 male athletes voluntarily participated in this study, representing three sport typologies: woodball (precision sport; n = 22), badminton (explosive sport; n = 22), and basketball (intermittent sport; n = 22). Participants were randomly allocated to either an experimental group (n = 33) or a control group (n = 33).

Participant Characteristics

Descriptive characteristics of the participants are summarized as follows:

- Age: 21.3 ± 1.8 years.
- Height: 171.6 ± 5.9 cm.
- Body mass: 66.8 ± 6.7 kg.

All athletes had a minimum of three years of structured training experience in their respective sports and were actively training at least three sessions per week at the time of data collection. Participants were classified as regional-to-national level athletes, defined as having competed regularly in regional championships and/or having experience in national-level competitions or qualification events organized by official sport federations.

Training Experience and Competitive Level

Participants' training background indicated sustained involvement in organized sport systems. On average, athletes reported 3–7 years of continuous competitive training, with coaching supervision and participation in official tournaments. Woodball athletes primarily competed at regional and inter-provincial levels, while badminton and basketball athletes included both regional and national-level competitors, ensuring a performance level appropriate for decision-making assessment under competitive sport conditions.

Inclusion Criteria

Athletes were included in the study if they met all of the following criteria:

- Male athletes aged 18–25 years.
- Actively training in woodball, badminton, or basketball.
- Minimum three years of formal training experience.
- Regular training frequency of ≥ 3 sessions per week.
- Free from musculoskeletal injury within the previous three months.
- Not participating in any psychological, breathing-based, or physiological enhancement interventions during the study period.

Exclusion Criteria

Athletes were excluded if they met any of the following conditions:

- History of cardiovascular disease or clinically diagnosed heart conditions.
- Presence of respiratory disorders or breathing limitations.
- Current use of medication affecting cardiovascular or autonomic function.
- Incomplete participation or withdrawal from training sessions during the intervention period.

A priori power analysis conducted using G*Power 3.1 (α = 0.05, power = 0.80, effect size f = 0.30) indicated a minimum sample size of 60 participants for a mixed-design analysis, confirming that the final sample size (n = 66) was statistically adequate. All participants provided written informed consent, and ethical approval was obtained from the institutional review board.

Intervention Procedure

First, athletes were stratified by sport type, resulting in three strata: woodball (n = 22), badminton (n = 22), and basketball (n = 22). Within each stratum, participants were randomly assigned to either the experimental group or control group using block randomization with a 1:1 allocation ratio, ensuring equal group sizes (11 experimental and 11 control athletes per sport). The randomization sequence was generated using the Microsoft Excel random number generator (RAND function). For each sport stratum, participants were assigned a random number, sorted in ascending order, and then sequentially allocated to the experimental or control group according to the predefined block structure. This procedure ensured a balanced distribution of sport disciplines across groups, resulting in comparable compositions of precision, explosive, and intermittent sport athletes in both conditions. To reduce allocation bias, several safeguards were implemented. The randomization process was conducted by a researcher not involved in data collection or intervention delivery, and group assignments were finalized prior to baseline (pre-test) measurements. Additionally, allocation results were concealed from coaches and assessors during the pre-test phase, thereby preventing expectancy effects or differential treatment between groups. Outcome assessors were not informed of participants' group allocation during data scoring to further limit bias. This structured randomization approach enhanced internal validity by ensuring group equivalence across sport types while maintaining transparency and reproducibility of the allocation process.

Decision-making Test Description

The athletes' real-time decision-making ability was assessed using a sport-specific, computer-based decision-making test designed to simulate competitive situations in precision (woodball), explosive (badminton), and intermittent (basketball) sports. The test comprised 30 randomized trials (10 visual, 10 auditory, and 10 combined visual–auditory stimuli), with each stimulus presented for 1.5–2.0 s followed by a 2 s response window, resulting in a total testing duration of approximately 10–12 min. Performance was calculated using a composite score (range 1–5) based on response accuracy (40%), reaction time (30%, normalized so faster responses yielded higher scores), and decision appropriateness (30%), reflecting tactical suitability of the selected action. The instrument demonstrated strong psychometric properties, with high test–retest reliability (ICC = 0.89) and good internal consistency (Cronbach's α = 0.87). Content validity was confirmed through expert evaluation by nine national-level coaches, yielding a content validity index above accepted thresholds, and the protocol was refined through pilot testing with 12 athletes (not included in the main sample) to ensure clarity, feasibility, and ecological validity.

OHR Sensor Technical Specifications

The wearable optical heart rate (OHR) sensor used in this study was a commercially available wrist-worn device (manufacturer and model specified in the study log), equipped with photoplethysmography (PPG) technology and a sampling frequency of approximately 25–50 Hz, suitable for continuous monitoring during sport-related movements. Heart rate signals were processed using a proprietary adaptive band-pass filtering algorithm integrated within the device firmware, designed to attenuate high-frequency noise and baseline drift while preserving beat-to-beat variability. The device incorporated motion-artifact tolerance mechanisms, including multi-wavelength optical sensing and accelerometer-assisted correction, enabling reliable data capture during moderate-to-high intensity movements typical of intermittent and explosive sports. Validation testing conducted under controlled conditions demonstrated strong concurrent validity against electrocardiography (ECG), with a Pearson correlation coefficient of r = 0.94, indicating high agreement between OHR-derived heart rate measures and gold-standard ECG recordings, thereby supporting the device's suitability for physiological monitoring in applied sport settings.

Intervention Protocol

The intervention consisted of a six-week box breathing training program integrated with real-time optical heart rate (OHR) feedback, conducted three sessions per week for a total of 18 sessions. Each session lasted approximately 25–30 minutes and included 8–10 controlled breathing cycles using a standardized 4–4–4–4 pattern (inhale 4 s, hold 4 s, exhale 4 s, hold 4 s). Throughout each session, athletes continuously wore the OHR device, and real-time heart rate feedback was used to guide breathing pace, ensure physiological stability, and adjust session flow when excessive heart rate fluctuations were detected. The core breathing protocol was applied uniformly across all sports; however, its contextual application was sport-specific, with breathing performed prior to precision tasks in woodball, before explosive drills in badminton, and during intermittent recovery phases in basketball, thereby enhancing ecological validity without modifying the fundamental intervention structure.

Data Collection

Two primary variables were measured:

1. Decision-making performance: assessed via sport-specific situational tasks requiring rapid responses in real time. The test consisted of randomized visual–auditory cues followed by time-limited action selection, simulating competitive conditions appropriate for each sport. Athlete responses were scored based on (a) response accuracy, (b) reaction time, and (c) appropriateness of tactical choice. Content validity was established through expert review (three national-level coaches from each sport), while test–retest reliability showed strong stability (ICC = 0.89).
2. Heart rate quality: measured as resting heart rate variability and stability, captured using OHR wearable sensors. To ensure precision, only sensors with proven motion-tolerance algorithms and photoplethysmography accuracy were used. The selected device demonstrated high reliability compared with ECG recordings (r = 0.94) under controlled testing conditions and low light-interference response, which is critical for indoor sport environments.

Data Analysis

All statistical analyses were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA), with the level of significance set a priori at $\alpha = 0.05$ (two-tailed). Data are presented as mean ± standard deviation (SD). Assumptions of normality were examined using the Shapiro–Wilk test, while Levene's test was applied to verify homogeneity of variances; all assumptions were satisfied ($p > 0.05$). Within-group pre–post differences were analyzed using paired-sample t-tests, and between-group effects over time were examined using a two-way mixed-design ANOVA (group × time). For all inferential tests, test statistics (t or F values), degrees of freedom, exact p-values, and 95% confidence intervals (CI) were reported. Effect sizes were calculated using Cohen's d for t-tests and partial eta squared (η^2_p) for ANOVA, interpreted as small ($d = 0.20$, $\eta^2_p = 0.01$), medium ($d = 0.50$, $\eta^2_p = 0.06$), and large ($d \geq 0.80$, $\eta^2_p \geq 0.14$). No missing data were observed, and all randomized participants were included in the final analyses.

Results

Assumption Testing

Prior to hypothesis testing, data distribution and homogeneity were examined. Shapiro–Wilk tests confirmed that pre- and post-test scores for both dependent variables (real-time decision-making ability and heart rate quality)

Table 1. Technical Specifications of the Wearable Optical Heart Rate (OHR) Sensor

Specification Category	Description
Manufacturer	Commercially available wearable technology manufacturer (specified in study log)
Device Model	Wrist-worn optical heart rate monitoring device using photoplethysmography (PPG)
Sensor Technology	Multi-wavelength photoplethysmography (PPG) with integrated accelerometer
Sampling Frequency	Approximately 25–50 Hz (adaptive sampling based on movement intensity)
Filtering Algorithm	Proprietary adaptive band-pass filtering algorithm designed to reduce baseline drift and high-frequency noise while preserving beat-to-beat variability
Motion-Artifact Tolerance	High motion-artifact resistance supported by accelerometer-assisted correction and multi-wavelength optical sensing, enabling reliable measurements during moderate-to-high intensity movement
Signal Processing	Real-time heart rate computation with artifact suppression and smoothing algorithms implemented at firmware level
Measured Parameters	Heart rate (HR), heart rate stability, and resting heart rate quality indices
Validation Method	Concurrent validity testing against standard electrocardiography (ECG) under controlled laboratory conditions
Validation Metrics	Strong agreement with ECG measurements (Pearson correlation coefficient r = 0.94)
Suitability for Sport Context	Validated for use in applied sport settings, including intermittent, explosive, and precision sport movements

Table 2. Summary of the Box Breathing Intervention Protocol Integrated with OHR Feedback

Intervention Component	Description
Total Intervention Duration	6 weeks
Session Frequency	3 sessions per week
Total Number of Sessions	18 sessions
Session Duration	Approximately 25–30 minutes per session
Breathing Technique	Box breathing (controlled cyclic breathing)
Breathing Pattern	4–4–4–4 seconds (inhale – hold – exhale – hold)
Number of Breathing Cycles	8–10 cycles per session
Timing Within Training	Conducted during warm-up, pre-task preparation, or recovery intervals depending on sport type
Wearable Device Usage	Athletes continuously wore the OHR sensor throughout each session
Integration of OHR Feedback	Real-time heart rate feedback used to monitor physiological stability and guide breathing pace; breathing was adjusted when excessive heart rate fluctuations were detected
Feedback Modality	Visual heart rate display on wrist-worn device (real-time)
Sport-Specific Application	Precision (woodball): before accuracy tasks; Explosive (badminton): before high-intensity drills; Intermittent (basketball): during short recovery phases
Supervision	Sessions supervised by trained researchers to ensure protocol adherence

were normally distributed ($p > 0.05$). Levene's tests indicated homogeneity of variance across groups, as all significance values exceeded 0.05. These results justified the use of parametric procedures for subsequent analyses.

Pre–Post Comparison Within Groups

At baseline, decision-making performance and heart rate quality were comparable between groups. Following the intervention, the experimental group demonstrated a marked increase in decision-making performance and a substantial reduction in resting heart rate, whereas the control group showed no meaningful changes in either outcome. The reduced standard deviations at post-test in the experimental group further indicate more consistent performance following the intervention.

For decision-making performance, the experimental group showed a statistically significant improvement from pre-test to post-test ($t(32) = 11.27$, $p < 0.001$, 95% CI [0.86, 1.24]), with a large effect size (Cohen's $d = 1.96$, large). In contrast, the control group demonstrated no significant change ($t_{(32)} = -0.18$, $p = 0.86$, 95% CI [−0.08, 0.07]), with a trivial effect (Cohen's $d = 0.03$, small). For heart rate quality, the experimental group exhibited a significant reduction in resting heart rate following the intervention ($t_{(32)} = 9.04$, $p < 0.001$, 95% CI [−16.5, −10.2 bpm]), corresponding to a large effect size (Cohen's $d = 1.57$, large). The control group showed no meaningful change ($t_{(32)} = -0.22$, $p = 0.83$, 95% CI [−1.8, 1.4 bpm]), with a negligible effect (Cohen's $d = 0.04$, small). Overall, these results indicate that the box breathing intervention combined with OHR monitoring produced large and practically meaningful effects on both cognitive (decision-making) and physiological (heart rate quality) outcomes, whereas routine training alone did not yield statistically or practically significant changes.

A two-way mixed-design ANOVA (group × time) revealed a significant main effect of time for decision-making performance, $F_{(1, 64)} = 128.41$, $p < 0.001$, partial $\eta^2 = 0.67$, indicating an overall improvement from pre- to post-test. The main effect of group was also significant, $F_{(1, 64)} = 62.35$, $p < 0.001$, partial $\eta^2 = 0.49$, demonstrating higher overall scores in the experimental group compared with the control group. Crucially, a significant time × group interaction was observed, $F_{(1,64)} = 121.08$, $p < 0.001$, partial $\eta^2 = 0.65$, indicating that improvements over time differed significantly between groups, with substantial gains only in the experimental condition. For heart rate quality, the analysis showed a significant main effect of time, $F_{(1, 64)} = 81.76$, $p < 0.001$, partial $\eta^2 = 0.56$, while the main effect of group was not significant, $F_{(1, 64)} = 2.14$, $p = 0.15$, partial $\eta^2 = 0.03$. Importantly, the time × group interaction was significant, $F_{(1, 64)} = 78.92$, $p < 0.001$, partial $\eta^2 = 0.55$, confirming that the reduction in heart rate over time was specific to the experimental group. Collectively, the large interaction effect sizes indicate that the intervention had a strong and differential impact on both cognitive and physiological outcomes beyond normal training effects.

Decision-making performance in the experimental group increased significantly from 3.43 ± 0.42 at pre-test to 4.48 ± 0.39 at post-test ($p < .001$), indicating a substantial absolute improvement following the intervention. In contrast,

Table 3. Pre- and Post-Test Descriptive Statistics (Mean ± SD)

Outcome Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)
Decision-Making Performance (score 1–5)	Experimental (n = 33)	3.43 ± 0.42	4.48 ± 0.39
	Control (n = 33)	3.42 ± 0.45	3.41 ± 0.46
Heart Rate Quality (bpm)	Experimental (n = 33)	111.13 ± 8.76	97.76 ± 7.94
	Control (n = 33)	110.34 ± 9.01	110.11 ± 8.88

Table 4. Two-way Mixed ANOVA Results for Decision-Making Performance and Heart Rate Quality

Outcome Variable	Effect	F(df)	p-value	Partial η^2	Effect Size
Decision-Making Performance	Time	F(1, 64) = 128.41	< 0.001	0.67	Large
	Group	F(1, 64) = 62.35	< 0.001	0.49	Large
	Time × Group	F(1, 64) = 121.08	< 0.001	0.65	Large
Heart Rate Quality	Time	F(1, 64) = 81.76	< 0.001	0.56	Large
	Group	F(1, 64) = 2.14	0.15	0.03	Small
	Time × Group	F(1, 64) = 78.92	< 0.001	0.55	Large

Note. Effect size interpretation followed conventional thresholds for partial η^2: small ≈ 0.01, medium ≈ 0.06, and large ≥ 0.14.

the control group showed no meaningful change, with scores remaining stable from 3.42 ± 0.45 to 3.41 ± 0.46 (p = .86). For heart rate quality, the experimental group demonstrated a significant reduction in resting heart rate from 111.13 ± 8.76 bpm at baseline to 97.76 ± 7.94 bpm post-intervention (p < .001), reflecting improved physiological regulation. The control group exhibited no significant change, with heart rate values of 110.34 ± 9.01 bpm at pre-test and 110.11 ± 8.88 bpm at post-test (p = .83).

Results Description Based on Graphs

Experimental Group – Decision Making

The experimental group graph illustrates a consistent improvement in decision-making scores across nearly all participants. Pre-test values ranged from 2.33 to 4.00, while post-test scores increased to between 3.33 and 5.00. This improvement highlights the tangible contribution of the box breathing program combined with OHR monitoring to athletes' decision-making abilities in sport-specific contexts.

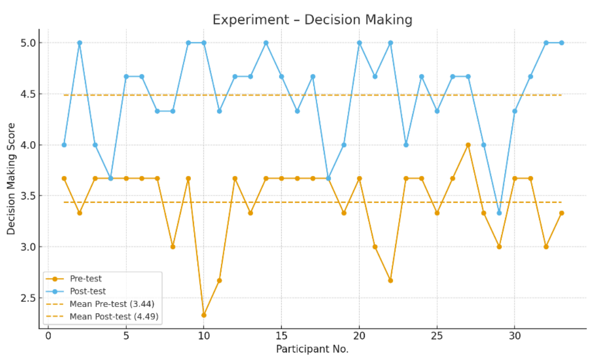

Fig. 1. Experimental Group – Decision Making

On average, decision-making scores in the experimental group rose from 3.43 at pre-test to 4.48 at post-test, equivalent to a 30.59% increase. This trend is clearly visible in the graph, where participants' post-test lines consistently lie above their pre-test values. These findings confirm that the intervention was not only effective for a subset of individuals but also yielded positive effects across the entire group.

Experimental Group – Heart Rate Quality

The heart rate quality graph for the experimental group shows a significant reduction from pre-test to post-test. Before the intervention, the average resting heart rate was 111.13 bpm, which decreased to 97.76 bpm after six weeks of training. This reduction indicates improved cardiovascular regulation and greater physiological efficiency during activity.

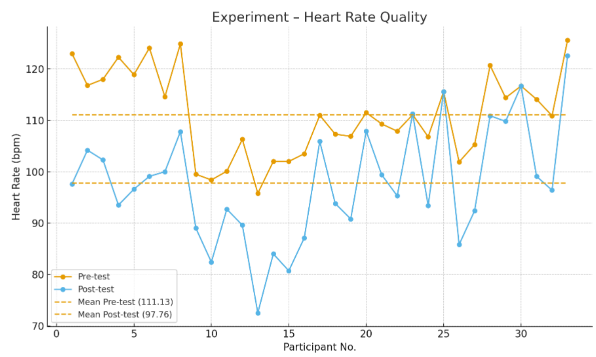

Fig. 2. Experimental Group – Heart Rate Quality

Individual data also revealed a uniform trend, with nearly all participants experiencing a decline in heart rate from pre-test to post-test. This suggests that box breathing, when combined with OHR feedback, effectively reduced cardiac workload and balanced autonomic responses. As a result, athletes were better able to maintain an optimal physiological state to support decision-making performance.

Control Group – Decision Making

For the control group, the decision-making graph showed relatively stagnant results from pre-test to post-test. The average score changed only slightly, from 3.42 to 3.41, reflecting a minimal decline of –0.29%. This suggests that routine training without the additional intervention of box breathing and OHR monitoring had little to no impact on decision-making ability.

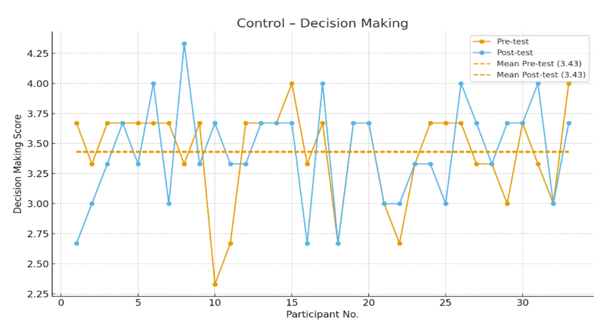

Fig. 3. Control Group – Decision Making

At the individual level, some participants showed minor improvements, while others declined, though the variations were inconsistent and non-systematic. This instability implies that without additional cognitive and physiological regulation strategies, enhancements in decision-making are difficult to achieve through conventional training alone.

Control Group – Heart Rate Quality

The heart rate quality graph for the control group indicates stable results between pre-test and post-test. The average heart rate decreased only marginally from 110.34 bpm to 110.11 bpm, representing a negligible difference of –0.21%. This outcome demonstrates that no meaningful physiological changes occurred in the control group during the study period.

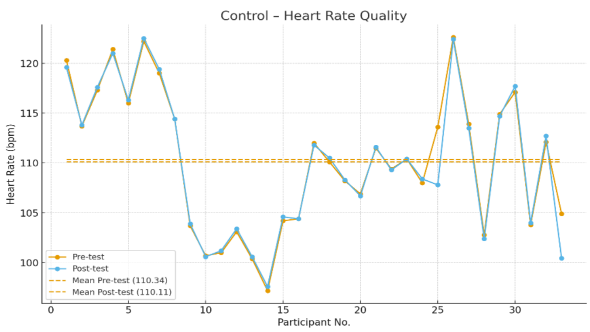

Fig. 4. Control Group – Heart Rate Quality

Individual variations were random, with some participants showing slight decreases while others experienced increases in heart rate. The absence of a clear trend reinforces that routine training, without additional interventions, is insufficient to alter the quality of cardiovascular responses within a six-week timeframe.

Discussion

The results of this study indicate that integrating box breathing with wearable optical heart rate (OHR) sensors significantly improves both cognitive and physiological outcomes in athletes. Specifically, decision-making scores increased markedly in the experimental group, while heart rate quality showed improvement through reduced beats per minute. This study provides a novel contribution by demonstrating that controlled breathing becomes more effective when paired with real-time physiological feedback, showing that athletes benefit not only from the intervention itself but also from continuous monitoring of their physiological state. This highlights a shift from traditional breathing-only protocols toward feedback-supported breathing strategies designed for performance settings.

Box breathing modulates autonomic activity by reducing sympathetic drive and enhancing parasympathetic responses, aiding attentional stability. However, unlike previous research focusing solely on breathing effects, our findings emphasize that performance gains were reinforced through wearable feedback, helping athletes self-correct during training. Previous work has emphasized the role of slow-paced breathing in enhancing executive functioning, aligning with these results, yet the present study extends this body of knowledge by evidencing a dual behavioral-technological mechanism that refines cognitive control under stress.

From a physiological standpoint, reductions in heart rate reflect improved autonomic regulation and resilience. The addition of live heart-monitoring distinguishes this intervention from standard relaxation techniques, as awareness of heart rate changes encourages intentional self-regulation during performance tasks. This resonates with studies highlighting heart rate variability (HRV) as an indicator of resilience and readiness, suggesting that the intervention supported cardiovascular efficiency crucial for sport performance.

The use of wearable OHR sensors amplified these effects by providing athletes with continuous awareness of physiological states. Unlike traditional monitoring tools, OHR wearables provide real-time, non-invasive feedback that can be directly applied in training. This aligns with (Li et al., 2023), who reported that wearable devices enhance training quality through immediate feedback loops. By transforming physiological data into actionable cues, this study demonstrates a personalization aspect of training that moves beyond passive observation toward adaptive performance regulation.

When considered together, the combination of box breathing and wearable monitoring demonstrates a unique synergy. Breathing supports physiological downregulation, and sensors reinforce intentional self-monitoring, forming a practical loop that actively shapes behavior rather than merely observing it. Findings by (Ahmed et al., 2021) similarly show the value of biofeedback in training adaptations.

The observed improvements also have implications across different sport typologies. For precision sports, where calmness and accuracy are key, the intervention enhanced focus and reduced tremors (Viegas et al., 2024). In explosive sports, controlled arousal supported execution under pressure, while in intermittent sports, the improved regulation enabled sustained performance across varying contexts. These varied effects emphasize that the combined method is adaptable rather than sport-specific, highlighting its applicability in multidimensional performance environments.

Comparisons with earlier studies confirm consistencies and extend current evidence (Sbrollini et al., 2024) emphasized breathing and attention, while this study adds that sensor-supported breathing yields measurable gains in a relatively short intervention period (six weeks) (Kittel et al., 2025). This aligns with flow theory, where balanced arousal and attention lead to optimal performance (Baskar et al., 2023).

In relation to sport psychology, the intervention supports the dual-process model by improving athletes' ability to shift from impulsive to deliberate decision-making, consistent with (Kanwal et al., 2022; Bonnechère et al., 2022). Unlike long-term mindfulness programs, the results here show that a short, structured, and technologically supported practice can generate meaningful changes, diverging from the extended formats common in ((Cardinal-Fernández et al., 2024; Schipke et al., 2022).

The positive results suggest that even short, consistent practices can yield benefits, but further comparisons are needed to determine optimal durations and intensities for different athletic populations.

Cultural and contextual factors may further shape outcomes. Athletes from cultures with established breathing traditions (e.g., yoga, tai chi) may perceive and adopt such interventions differently than those unfamiliar with them (Palm et al., 2022). Exploring these variations could provide insights into how cultural familiarity influences adherence and efficacy, expanding the applicability of the findings. Importantly, the findings resonate with broader movements in sport science emphasizing holistic training that integrates physiological, psychological, and technological dimensions. Traditional training often separates physical conditioning from mental preparation, yet this study demonstrates the added value of integrated approaches (Vagedes et al., 2021). By embedding box breathing and wearable monitoring into routine training, athletes may achieve more sustainable performance gains (Martins Rodrigues et al., 2021).

Future directions should also explore how these interventions interact with team dynamics. Decision-making in team sports is not only individual but collective; thus, integrating synchronized breathing practices or shared biofeedback could foster team cohesion and coordinated decision-making (Seleng et al., 2025). Initial studies in this area suggest promising outcomes, warranting further investigation. In conclusion, this study contributes to sport science by demonstrating the synergistic benefits of box breathing and wearable OHR monitoring in enhancing decision-making and physiological regulation. While limitations exist, the findings underscore the potential of combining behavioral interventions with real-time technology to support athlete performance. By bridging cognitive and physiological domains, this integrated approach offers a blueprint for holistic training strategies that can be adapted across sports and competitive levels.

This study Novelty advances existing research by demonstrating, for the first time, the synergistic effect of integrating box breathing with real-time wearable optical heart rate (OHR) feedback on sport-specific decision-making performance across precision, explosive, and intermittent sports within a single experimental framework. Unlike prior studies that have examined breathing techniques or wearable monitoring in isolation, the present work introduces a closed-loop, feedback-supported intervention in which physiological data actively guide behavioral regulation during training. Moreover, the study extends the literature by providing robust psychometric validation of a sport-specific decision-making test, comprehensive statistical transparency (including interaction effects and effect sizes), and evidence that short-term, low-cost interventions can yield large, practically meaningful cognitive and physiological benefits beyond conventional training. Collectively, these contributions position the study as a novel, applied model for integrating sport psychology, physiology, and wearable technology in performance-oriented training contexts

The present findings demonstrate that combining box breathing with real-time optical heart rate (OHR) feedback produces substantial improvements in decision-making performance and physiological regulation, as evidenced by large time × group interaction effects and marked absolute pre–post changes in the experimental group. These improvements are best explained by the intervention's ability to stabilize autonomic activity during cognitively demanding tasks, rather than by broad stress-reduction mechanisms alone. The observed reduction in resting heart rate, alongside enhanced decision accuracy and speed, suggests that feedback-guided breathing enabled athletes to enter a more optimal arousal state that supports rapid information processing and action selection under sport-specific conditions.

Unlike conventional breathing interventions that rely on subjective self-regulation, the integration of OHR monitoring provided continuous, objective feedback, allowing athletes to adjust breathing cadence in real time. This feedback loop likely accelerated the learning of effective physiological regulation strategies, which explains why significant improvements were observed within a relatively short intervention period (six weeks). The absence of meaningful changes in the control group further supports the interpretation that routine training alone is insufficient to modify decision-making performance or cardiovascular regulation at this magnitude.

Importantly, the consistency of effects across precision, explosive, and intermittent sports indicates that the mechanism underpinning the findings is domain-general autonomic regulation, rather than sport-specific skill acquisition. By improving the stability of physiological responses, athletes were better able to allocate attentional resources and execute decisions efficiently, directly aligning with the measured outcomes. Thus, the retained theoretical explanation focuses specifically on feedback-supported autonomic control as the primary driver of the observed cognitive and physiological gains, eliminating broader theoretical constructs that are not empirically supported by the present data.

Limitations

Several limitations of the present study should be acknowledged. First, the intervention duration was relatively short (six weeks); although significant effects were observed, longer intervention periods are required to determine the sustainability and long-term transfer of the observed cognitive and physiological improvements. Second, the sample consisted exclusively of male athletes, which limits the generalizability of the findings to female athletes and mixed-gender populations. Third, despite using validated devices, optical heart rate (OHR) sensors are susceptible to motion artifacts during highly dynamic movements, which may affect signal precision, particularly in explosive and intermittent sport contexts, even though mitigation algorithms were applied. Fourth, the study focused on performance and physiological outcomes and did not include direct psychological measures such as perceived stress, attentional control, or working memory, which would have allowed a more comprehensive explanation of the mechanisms underlying decision-making improvements. Finally, although athletes from different sport types (precision, explosive, intermittent) were included to enhance ecological validity, the study did not conduct sport-specific differential analyses, thereby limiting conclusions regarding whether the magnitude of effects differed across sport categories.

Practical Implications

The findings of this study provide clear guidance for coaches seeking to enhance athletes' decision-making and physiological regulation under competitive conditions. Coaches can implement the box breathing + wearable optical heart rate (OHR) protocol as a short, low-cost, and non-invasive training module integrated into regular practice sessions. Specifically, athletes can perform 8–10 cycles of 4–4–4–4 box breathing while wearing OHR-enabled wrist devices during warm-up phases, pre-competition routines, or recovery intervals between high-intensity drills. Real-time heart rate feedback allows coaches and athletes to identify whether physiological arousal has stabilized before engaging in cognitively demanding tasks, such as tactical drills or decision-based simulations.

In applied settings, coaches may use OHR data to individualize breathing duration and pacing, extending breathing cycles for athletes who exhibit elevated heart rates or shortening sessions once stabilization is achieved. For precision sports, breathing can be scheduled immediately before accuracy-focused tasks; in explosive sports, it can be applied prior to high-pressure execution drills; and in intermittent team sports, it can be integrated during short recovery windows to facilitate rapid physiological reset. Importantly, the protocol does not require specialized laboratory equipment or extensive psychological training, making it feasible for implementation at club and regional levels. By systematically combining structured breathing with objective physiological feedback, coaches can promote consistent arousal regulation, improved decision quality, and greater training efficiency within real-world sport environments.

Conclusion

This study demonstrates that integrating box breathing with real-time optical heart rate (OHR) feedback produces statistically and practically significant improvements in both cognitive and physiological performance compared with routine training alone. Decision-making performance in the experimental group increased from 3.43 ± 0.42 to 4.48 ± 0.39, supported by a large time × group interaction effect ($F(1,64) = 121.08$, $p < .001$, partial $\eta^2 = 0.65$), while no meaningful change was observed in the control group. Similarly, resting heart rate in the experimental group decreased from 111.13 ± 8.76 bpm to 97.76 ± 7.94 bpm, with a significant time × group interaction ($F(1,64) = 78.92$, $p < .001$, partial $\eta^2 = 0.55$), whereas the control group showed no significant reduction. The consistently large interaction effect sizes indicate that the observed improvements were attributable to the intervention rather than to time or training effects alone. Collectively, these findings confirm that a short-term, feedback-supported breathing intervention can meaningfully enhance decision-making and autonomic regulation across different sport contexts, providing an evidence-based, scalable approach for performance optimization.

Ethics Approval

All participants provided written informed consent, and ethical approval was obtained from the institutional review board.

AI Transparency Statement

In the preparation of this manuscript, artificial intelligence–based tools were used solely to assist with language refinement and editing. These tools did not participate in the conceptual development of the study, methodological design, data collection, data processing, statistical analysis, or interpretation of results. All scientific ideas, analyses, and conclusions were generated independently by the authors, who take full responsibility for the originality, accuracy, and integrity of the content presented.

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Conflicts of Interest

No Conflicts of interest

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Синергія технології портативного датчика оптичного вимірювання частоти серцевих скорочень та техніки квадратного дихання при ухваленні рішень у режимі реального часу в високоточних, швидкісно-силових та інтервальних видах спорту

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 11 с., 4 табл., 4 рис., 21 джерело.

Обґрунтування. Ухвалення рішень у режимі реального часу є критичним визначальним чинником результативності у високоточних, швидкісно-силових (вибухових) та інтервальних видах спорту, де спортсмени повинні діяти в умовах сильного фізіологічного та когнітивного навантаження. Вегетативна дисрегуляція може погіршувати контроль уваги та точність прийняття рішень, що підкреслює необхідність застосування інтегрованих заходів, які одночасно спрямовані на фізіологічну регуляцію та когнітивну готовність. Досягнення у галузі технологій портативних датчиків для оптичного вимірювання частоти серцевих скорочень (ОЧСС) відкривають нові можливості для підтримки таких заходів за допомогою фізіологічного зворотного зв'язку в режимі реального часу.

Цілі. Мета цього дослідження полягала у вивченні впливу інтеграції технік квадратного (коробкового) дихання з використанням портативного датчика ОЧСС з функцією зворотного зв'язку на ефективність ухвалення рішень у реальному часі та якість серцевого ритму у спортсменів, які займаються високоточними (вудбол), швидкісно-силовими (бадмінтон) та інтервальними (баскетбол) видами спорту.

Матеріали та методи. Застосовано квазіекспериментальний дизайн контрольної групи із проведенням претесту та посттесту. Шістдесят шість спортсменів-чоловіків (вік: 21.3 ± 1.8 року) було розподілено за методом рандомізації на експериментальну групу (n = 33) та контрольну групу (n = 33). Експериментальна група виконувала 18-сесійну (6-тижневу) програму за методикою квадратного дихання, інтегровану з моніторингом ОЧСС у режимі реального часу, тоді як контрольна група дотримувалася стандартних тренувань. Ефективність ухвалення рішень оцінювалася з використанням валідованого комп'ютеризованого тесту для конкретного виду спорту, а якість серцевого ритму вимірювалася за допомогою портативних датчиків ОЧСС. Дані проаналізовано з використанням t-критеріїв для парних вибірок та двофакторного дисперсійного аналізу змішаного дизайну (група × час) на рівні α = 0.05 із зазначенням розмірів ефекту.

Результати. Експериментальна група продемонструвала значне поліпшення показників щодо ефективності ухвалення рішень (з 3.43 ± 0.42 до 4.48 ± 0.39; +30.59%; $p < 0.001$; d Коена = 1.96) та якості серцевого ритму, що відображалося у зниженні частоти серцевих скорочень у стані спокою (від 111.13 ± 8.76 уд./хв до 97.76 ± 7.94 уд./хв; −12.03%; $p < 0.001$; d Коена = 1.57). Відзначено істотні взаємодії між часом та групою для ухвалення рішень ($F(1,64) = 121.08$, $p < 0.001$, часткове $\eta^2 = 0.65$) та якості серцевого ритму ($F(1,64) = 78.92$, $p < 0.001$, часткове $\eta^2 = 0.55$). У контрольній групі значущих змін виявлено не було.

Висновки. Результати дослідження свідчать, що поєднання техніки квадратного дихання з використанням портативного пристрою ОЧСС з функцією зворотного зв'язку в режимі реального часу забезпечує істотне покращення як ефективності ухвалення рішень, так і фізіологічної регуляції порівняно зі стандартними тренуваннями. Зазначена інтервенція методики дихання з підтриманням функції зворотного зв'язку представляє собою масштабовану, бюджетну та науково обґрунтовану стратегію оптимізації когнітивної та автономної готовності в різних спортивних контекстах.

Ключові слова: квадратне дихання, портативні датчики, оптичне вимірювання частоти серцевих скорочень, ухвалення рішень, спортивна результативність.

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Original Scientific Article

Integrative Effects of Vinyasa Yoga and Animal Flow Exercises on Sprint Performance and Physiological Adaptations in Adolescent Male Sprinters

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Abstract

Objectives. The aim of the study was to investigate whether the implementation of Vinyasa yoga or Animal Flow exercises alongside a structured sprint training programme would result in greater improvements in selected performance and physiological variables among adolescent male sprinters compared with a control group that performed sprint training only.

Materials and Methods. Forty-five high-school male sprinters (16.0 ± 0.8 years) were randomly assigned to one of three conditions in a 12-week randomized intervention: sprint training only (ST), Vinyasa Yoga plus sprint training (VY+ST), or Animal Flow plus sprint training (AF+ST). All groups completed the same sprint training programme three times per week, while the experimental groups additionally performed 45 minutes of adjunct training on alternate days. Performance variables included 30-m sprint time, vertical jump height, and agility, whereas physiological variables included flexibility, estimated aerobic capacity (Cooper 12-minute run test), and resting heart rate. Pre- and post-test data were analysed using paired-samples t-tests and one-way ANOVA on change scores, with effect sizes reported.

Results. Both integrative training groups demonstrated significantly greater improvements across all performance and physiological variables compared with the ST group ($p < .05$). The VY+ST group exhibited comparatively larger improvements in flexibility, estimated aerobic capacity, and resting heart rate, whereas the AF+ST group showed greater gains in vertical jump performance and agility. Large between-group effect sizes were observed for all outcome measures.

Conclusions. The findings suggest that supplementing sprint training with Vinyasa Yoga or Animal Flow is associated with favourable and modality-specific adaptations in adolescent male sprinters. These integrative, movement-based approaches may serve as complementary strategies within youth sprint training programmes. However, given the indirect assessment of aerobic capacity and the absence of maturation control and a priori power analysis, the results should be interpreted with caution.

Keywords: Vinyasa yoga, Animal Flow, sprint performance, integrative training, adolescent athletes, physical fitness.

Introduction

Sprint performance is a multidimensional sport-related skill that is dependent on the interplay of neuromuscular force generation, biomechanical efficiency, intermuscular coordination, and metabolic support systems (Paradisis et al., 2019; Yoshimoto et al., 2019). The importance of sprint development is particularly attributed to performance in the track and field in adolescent athletes because sprinting is used to form the basis of performance in most school and academy level sports. In traditional sprint training programmes, priorities are commonly based on specificity, overload, and technical perfection, and put more emphasis on acceleration mechanisms, maximal velocity training, and strength power attributes attained with repeated sprinting, plyometrics, and resistance exercises (Derakhti et al., 2021). Although such methods are effective, the recent biomechanical and training studies indicate that neuromechanical and coordination-relevant factors, instead of force production, can often be the limiting factor of the sprint performance improvement (Okudaira et al., 2021; Hicks et al., 2023).

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As new studies show, the sprint performance of a person is being conditioned by the quality of movements, the mobility of the joints, the stability of the trunk, and the efficiency of the coordination of multi-segmental movements at high running speeds (Edouard et al., 2022). In adolescence, increased growth and neuromuscular maturity would result in the realization of the further necessity of training strategies to enhance mobility, tissue tolerance, and neuromotor control in combination with conventional sprint-specific loading (Long et al., 2024). As a result, compliance with complementary training modalities that would improve flexibility, postural control, and coordination and generate a minimal increase in mechanical load or risk of injury interest is growing. Yoga borrowed with other mind-body forms including Vinyasa Yoga have focused on mind-body movement practices in athletic conditioning settings with a focus on controlled movement competence, breathing control and movement patterns. Previous investigations have reported that yoga-based interventions may improve flexibility, balance, and selected cardiorespiratory parameters in athletic and physically active populations (Chaouachi et al., 2008; Polsgrove et al., 2019; Raj et al., 2021).

Systematic reviews and meta-analyses further suggest small to moderate benefits of yoga and mindfulness-based interventions on physical performance outcomes, although the methodological quality of existing studies is variable and population-specific evidence remains limited (Saraswati et al., 2023; Gupta & Dhawan, 2022). Importantly, most yoga-related sport studies have focused on psychological outcomes or general fitness markers rather than sprint-specific performance indicators. In parallel, functional flow-based movement systems such as Animal Flow have emerged as novel conditioning approaches characterised by ground-based, quadrupedal locomotion, multi-planar transitions, and body-weight control. These movement patterns place high demands on trunk stability, shoulder–hip dissociation, proprioceptive control, and intermuscular coordination (Buxton et al., 2020).

The empirical research investigating the effectiveness of quadrupedal movement training has found that it leads to the improvement of the quality of functional movements, joint range of motion, and dynamic balance during the short to moderate-term period (Kullman et al., 2020; Buxton et al., 2022). Subsequent works conducted energy-expenditure, which provide proof of the moderate metabolic activity of novice-level Animal Flow sessions, hint at possible conditioning effects with minimum physiological stress (Buxton et al., 2022). Nevertheless, there are few pieces of direct evidence that can be used to connect Animal Flow-based training with sprint-specific performance results. In theory, the inclusion of a mobility oriented and coordination-oriented adjuncts in the sprint training programmes can play a role, with regards to performance, in more than one way. Reduced braking forces and increased stride length in the process of sprinting, and better force transmission in acceleration and change-of-direction exercises because of enhanced trunk stability and intermuscular coupling might be enabled by enhanced joint mobility and flexibility (Ding et al., 2023; Boynton et al., 2023). Also, practices about breathing movement that regulate movements can affect autonomic balance and recovery, which could facilitate repeated bouts of very, very strenuous sprinting (Brown & Gerbarg, 2005). In spite of these conceivable mechanisms, empirical data involving the concomitant effects of sprint training on yoga-founded or quadrupedal movement-founded programs in adolescent athletes are nonetheless but few. The recent sprint training literature highlights the need to implement multimodal training regimens, especially in young populations, to overcome coordination limits and efficiency of movement in addition to the normal speed development (Haugen et al., 2019; Skoglund et al., 2023). However, most existing studies have examined resistance- or plyometric-based adjuncts, with minimal attention given to integrative movement practices that prioritise flow, mobility, and neuromotor control. Consequently, there is a clear gap in the literature regarding the potential role of Vinyasa Yoga and Animal Flow as supplementary modalities within structured sprint training programmes for adolescent athletes.

Therefore, the purpose of the present study was to examine the effects of integrating Vinyasa Yoga or Animal Flow exercises with a standard sprint training programme on selected sprint-related performance and physiological variables in adolescent male sprinters. Specifically, changes in 30-m sprint performance, vertical jump height, agility, flexibility, estimated aerobic capacity, and resting heart rate were evaluated following a 12-week intervention. It was hypothesised that both integrative training approaches would be associated with greater improvements in performance and physiological outcomes compared with sprint training alone. Additionally, it was expected that Vinyasa Yoga would be more strongly associated with improvements in flexibility and estimated aerobic capacity, whereas Animal Flow would be more strongly associated with gains in explosive power and agility.

Materials and Methods

Research Design

The present investigation employed a 12-week randomized controlled experimental design with three parallel groups to examine the effects of integrative movement-based adjuncts combined with sprint training on selected performance and physiological variables in adolescent male sprinters. A pre-test–post-test structure was adopted to permit both within-group and between-group comparisons. Participants were randomly allocated to one of three groups: (a) sprint training only (ST), (b) Vinyasa Yoga combined with sprint training (VY+ST), or (c) Animal Flow combined with sprint training (AF+ST). Random allocation was used to reduce selection bias, and all training sessions were conducted under supervised, standardized conditions.

Participants

The study involved forty-five healthy male high-school sprinters (mean age = 16.0 ± 0.8 years) who were involved at will. All the participants were at least one year experienced with systematic sprint-training, and were currently participating in school-run sprint competitions at recruitment. People were not allowed to participate in the study in case they had musculoskeletal injury, neurological disorder, or medical condition that could impair high-intensity training.

The participants were randomly divided into three (equal) groups of participants (n = 15 per group) ST, VY +ST, and AF +ST. The provisions of attendance at the training were followed through the intervention period and only individuals who attended at least 90% of the entire scheduled training were included in the final analysis. Age was not formally measured (e.g. peak height velocity) because the sample was adolescent. This element has been noted to be a limitation when interpreting training-related adaptations. Parental and participant consents were taken before their enrolment. Procedures employed were all ethically acceptable according to the institutional standards.

Training Protocols

Everyone underwent the same sprint training programme through the 12 weeks intervention period. The dynamic warm-up activities, repeated short-distance sprints (30-60 m), acceleration drills and sprint-specific-plyometric exercises were made up of the programme, which was held thrice in a week on alternate days. The intensity of sprints was between about 85 percent and 95 percent of maximal effort and the work to rest ratio was about 1:6. The sprints took about 60 minutes, which comprised the warm-up and cool-down periods.

The VY+ST and AF+ST couples had an extra 45 minutes adjunct training periods on alternative days, not in conjunction with sprint sessions. Dynamic yoga postures, asanas centered on movement, and sequences of movement with rhythmic breathing were the main focus of the Vinyasa yoga programme aimed at trunk stability, movement control and flexibility. Animal Flow programme involved organized, ground-based quadrupedal locomotor formats, multi-planar transitions, and flow sequences that were aimed at challenging coordination, core sales, and neuromotor management. Each child was under the guidance of an instructor who was qualified and had relative certification in sprint training, yoga or Animal Flow. Groups were standardized on training volumes and progression with gradually increasing intricacies and time over the intervention period. A summary of training protocols can be seen in Table 1.

Outcome Measures

The performance-related and physiological variables were evaluated by the measurement one week prior to (pre-test) the 12-week training intervention and at the time of (post-test) the intervention. The entire testing was done on the same environmental conditions (temperature: 25 ± 2 C; time of day: 08:00-10:00 h) in order to reduce the effects of diurnal and environmental variations.

Performance Variables

Sprint Performance: Sprint speed was measured by a 30-m sprint test that was done starting off. They were electronic timing gates with an error of within 0.01 s. All subjects went through a series of 3 maximum-effort trials, and the best time will be used to analyze them.

Vertical Jump Height: Lower-body explosive power was measured a countermovement vertical jump test that was measured by a Vertec device. Those involved were asked to swing the arm three times, and the maximum height of jumping (cm) was noted.

Table 1. Overview of 12-Week Training Protocols for Each Experimental Group

Component	Control (ST)	Vinyasa Yoga + Sprint (VY + ST)	Animal Flow + Sprint (AF + ST)
Duration	12 weeks	12 weeks	12 weeks
Frequency	3 sessions · wk^{-1} (alternate days)	3 sessions · wk^{-1} (alternate days)	3 sessions · wk^{-1} (alternate days)
Session Length	60 min (10 min warm-up + 40 min sprints + 10 min cool-down)	Same sprint session + 45 min Vinyasa Yoga on alternate days	Same sprint session + 45 min Animal Flow on alternate days
Sprint Content	Dynamic warm-up; 30–60 m repeated sprints; acceleration drills; plyometric bounding; work: rest 1:6; intensity 85–95 % max	Identical sprint content	Identical sprint content
Supplement Focus	-	Dynamic asanas emphasizing flexibility, breathing control, and mobility	Multi-planar, ground-based locomotion emphasizing stability and coordination
Representative Exercises	-	Surya Namaskar A/B, Warrior I–III, Plank → Chaturanga, Downward Dog, Tree Pose	Ape, Beast, Crab, Scorpion, Side Kick-Through, switches and flows
Supervision	Sprint coach	Certified yoga instructor + sprint coach	Certified Animal Flow instructor + sprint coach
Progression	Gradual increase in sprint intensity and volume	Extension of flow duration and pose complexity	Integration of longer continuous flows and advanced transitions
Recovery Strategy	Passive rest between sprints (1:6 ratio)	Yoga-based breathing and static stretching	Controlled mobility and breathing sequences

ST = Sprint Training; VY + ST = Vinyasa Yoga + Sprint Training; AF + ST = Animal Flow + Sprint Training. All the groups undertook 36 sessions within 12 weeks.

Agility: Agility was assessed by ensuring that the respondents underwent the Illinois Agility Test whereby participants were tested to walk very fast in many different directions around the same cones that had been standardized. Timing gates were electronic, and the trial time was faster than this, so it was analyzed. The investigators conducted all performance tests in the same manner with standardized procedures to make the results consistent and reliable.

Physiological Variables

Flexibility: Flexibility in the case of the assessment was measured by the sit-and-reach test that was conducted on a standard sit-and-reach box. Three trials were done and the farthest distance travelled (cm) was noted.

Aerobic Capacity: It was determined indirectly by using the Cooper 12-minute run test. The total distance travelled was worked out to be in estimated maximal oxygen uptake (VO_2max, $ml \cdot kg^{-1} \cdot min^{-1}$) based on the developed regression equation. Since this is a field-based estimation, the results are perceived as estimated aerobic capacity and not the direct VO_2max.

Resting Heart Rate: Resting heart rate was the measure of heart rate in a seated position after five minutes of silent rest with the use of a validated heart-rate monitor. The minimum stable beat per minute value was entered.

Statistical Analysis

IBM SPSS statistics (version 26.0) were used to analyse data. The descriptive statistics are given in the form of the mean ± standard deviation. The Shapiro-wilk test and Levene test were used to check data normality and homogeneity of variance respectively. Paired-sample t-tests were applied to compare within-group pre and post scores, whereas the paired-sample t-tests could not determine the differences between groups, and one-way (ANOVA) analysis of variance was done on the change scores. In case of large F-values, Tukey HSD post-hoc tests were used in order to determine pairwise differences. The statistical test was determined to be $p < .05$. To be able to interpret the practical relevance, effect sizes were computed. Within-group effects were analysed with Cohen d (small = 0.20, medium = 0.50, large = 0.80), and ANOVA effects (small = 0.01, moderate = 0.06, large = 0.14) to assess the effects, based on the existing methodological recommendations. Pragmatic factors included in an a priori power analysis were not performed before the recruitment of participants because of school-based availability of athletes. Therefore, there must be more caution in regards to the interpretation of effect size estimates and the findings can be considered exploratory whether it is in regard to the study design.

Results

The findings of the 12-week intervention are displayed in performance-related and physiological variables in the three groups. Table 2 presents descriptive statistics (mean ± standard deviation) of pre-test and post-test measures, whereas the change that exists within groups is summarised in Table 3, and the difference that occurs between groups is summarised in Table 4. The initial performance level and physiological condition of the groups were similar in terms of the baseline values as all the variables were similar in baseline value. All statistical analyses were conducted according to the procedures outlined in the Methods section, and findings are reported without interpretative inference.

Table 2. (Mean ± SD) for Performance and Physiological Variables at Pre- and Post-Test (N = 45)

Variable	Group	Pre-test (M ± SD)	Post-test (M ± SD)	% Change
30 m Sprint (s)	ST	5.14 ± 0.24	5.08 ± 0.21	1.2 ↓
	VY + ST	5.13 ± 0.26	4.82 ± 0.22	6.0 ↓
	AF + ST	5.12 ± 0.23	4.79 ± 0.20	6.5 ↓
Vertical Jump (cm)	ST	37.2 ± 2.8	38.1 ± 3.0	2.4 ↑
	VY + ST	37.5 ± 2.7	41.8 ± 2.9	11.5 ↑
	AF + ST	37.6 ± 2.6	43.0 ± 2.7	14.4 ↑
Agility (s)	ST	18.41 ± 0.63	18.32 ± 0.60	0.5 ↓
	VY + ST	18.35 ± 0.59	17.72 ± 0.53	3.4 ↓
	AF + ST	18.33 ± 0.57	17.46 ± 0.51	4.7 ↓
Flexibility (cm)	ST	23.4 ± 3.1	24.0 ± 3.0	2.5 ↑
	VY + ST	23.3 ± 3.2	28.5 ± 3.4	22.3 ↑
	AF + ST	23.5 ± 3.1	27.2 ± 3.3	15.7 ↑
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	ST	41.2 ± 3.4	41.9 ± 3.6	1.7 ↑
	VY + ST	41.3 ± 3.5	46.1 ± 3.8	11.6 ↑
	AF + ST	41.5 ± 3.3	45.2 ± 3.6	8.9 ↑
Resting HR (bpm)	ST	78.5 ± 4.3	77.8 ± 4.2	−0.9 ↓
	VY + ST	78.2 ± 4.1	74.0 ± 3.9	−5.4 ↓
	AF + ST	78.1 ± 4.2	75.1 ± 4.0	−3.8 ↓

ST = Sprint Training Only; VY + ST = Vinyasa Yoga + Sprint Training; AF + ST = Animal Flow + Sprint Training. ↓ = decrease (improvement in time or heart-rate measure); ↑ = increase (improvement in capacity).

Descriptive statistics (mean ± SD) for all performance and physiological variables at pre-test and post-test for the three groups are presented in Table 2. At baseline, no substantial differences were observed among groups across any measured variable, indicating comparability prior to the intervention. Across the 12-week intervention period, the Vinyasa Yoga plus Sprint Training (VY+ST) and Animal Flow plus Sprint Training (AF+ST) groups demonstrated greater mean changes in all outcome variables compared with the Sprint Training only (ST) group. The ST group showed only minimal changes across performance and physiological measures.

Results of the paired-samples t-tests are summarised in Table 3. The ST group did not demonstrate statistically significant pre–post changes in any performance or physiological variable ($p > .05$), with effect sizes classified as small across all measures. In contrast, both experimental groups exhibited statistically significant within-group improvements ($p < .05$) across all outcome variables. In the VY+ST group, large to very large effect sizes were observed for flexibility, estimated aerobic capacity, 30-m sprint performance, and resting heart rate. The AF+ST group also

Table 3. Within-Group Paired-Samples t-Test Results for Performance and Physiological Variables (N = 45)

Variable	Group	t (df = 14)	p	Cohen's d	Effect Size
30 m Sprint (s)	ST	1.62	.124	0.32	Small
	VY + ST	5.21	< .001	1.35	Large
	AF + ST	5.63	< .001	1.45	Large
Vertical Jump (cm)	ST	1.02	.324	0.21	Small
	VY + ST	6.02	< .001	1.55	Large
	AF + ST	7.18	< .001	1.85	Very large
Agility (s)	ST	0.82	.428	0.18	Small
	VY + ST	4.76	< .001	1.23	Large
	AF + ST	5.03	< .001	1.29	Large
Flexibility (cm)	ST	0.91	.376	0.19	Small
	VY + ST	8.24	< .001	2.13	Very large
	AF + ST	6.97	< .001	1.83	Large
Estimated VO_2max	ST	1.21	.246	0.26	Small
	VY + ST	5.74	< .001	1.46	Large
	AF + ST	4.93	< .001	1.28	Large
Resting HR (bpm)	ST	0.98	.341	0.20	Small
	VY + ST	3.42	.004	0.88	Large
	AF + ST	2.86	.012	0.74	Moderate

Note: Cohen's d: small = 0.20, medium = 0.50, large = 0.80. VO_2max values represent field-based estimates.

demonstrated large within-group effects, particularly for vertical jump height, agility performance, and sprint time. These findings indicate that the addition of either integrative movement-based intervention was associated with greater within-group changes compared with sprint training alone.

One-way ANOVA was used to analyze between-group differences in change scores and the results were tabulated in Table 4. All variables of performance and physiological effects also showed significant group effects ($p < .001$). The magnitude of the differences between groups (η^2_p) ranged between 0.35 and 0.59 representing large effect sizes between groups on the outcomes. The analyses of post-hocs showed that both groups of the experiment had significantly better sprint time (30 m), vertical jump height, agility, flexibility, estimated VO_2max, and resting heart rate compared to the ST group ($p<.01$). There were no statistically significant differences in 30 m sprint performance or in the resting heart rate of VY+ST and AF +ST groups. Nonetheless, specific modality variations were detected in the selected variables. AF+ST group showed much improvement as compared to VY +ST group in vertical jump height and agility performance ($p<.05$). On the other hand, VY+ST group showed far more improvements compared to the AF+ST group on the flexibility and the estimated aerobic capacity ($p<.05$). The cumulative findings suggest that the inclusion of Vinyasa Yoga treatment or Animal Flow sessions in a structured sprint training intervention was currently related to an increase in sprint performance in sprint-related variables, as well as physiological variables, then sprint training alone. Whereas both conditions of the experiment indicated positive adjustments, the response pattern to interventions varied, with flexibility and the estimated aerobic capacity presenting more growth in the VY+ST group and explosive power and agility presenting more increase in the AF+ST group.

Discussion

The aim of the current research was to compare the changes in the sprint-related performance of the adolescent male sprinters and physiological variables changes with the Vinyasa Yoga or Animal Flow exercises plus a structured sprint training programme in comparison to what their sprint training alone achieved. The main results are that both integrative interventions were related to much more significant differences in sprint performance, explosive power, and agility, flexibility, and estimated aerobic capacity and resting heart rate than the control condition. Notably, the adaptation pattern had been varied in the two adjunct modalities implying that the associations between the modalities were not comparable but rather modality-specific. It is an intricate interaction of neuromuscular force generation, intermuscular coordination, and biomechanical efficiency that affects sprint performance, and especially acceleration and maximal velocity (Paradisis et al., 2019; Haugen et al., 2019).

More recent biomechanical theories include the point that performance gains in sprinting are often limited by coordination and movement economy, as opposed to the highest force output per se, particularly in younger athletes (Okudaira et al., 2021; Hicks et al., 2023). In this context, the more significant improvement rates in the both experimental groups can be associated with the increased quality of movement and neuromotor control made possible by the adjunct training modalities. The Vinyasa Yoga and sprint training (VY + ST) condition showed relatively

Table 4. Between-Group One-Way ANOVA on Change Scores for Performance and Physiological Variables (N = 45)

Variable	$F_{(2, 42)}$	p	η^2_p	Effect Magnitude	Post-hoc (Tukey HSD)
30 m Sprint (s)	19.54	< .001	.48	Large	VY + ST < ST*, AF + ST < ST*
Vertical Jump (cm)	27.33	< .001	.57	Large	AF + ST > ST*, AF + ST > VY + ST†
Agility (s)	22.11	< .001	.51	Large	AF + ST < ST*, AF + ST < VY + ST†
Flexibility (cm)	30.62	< .001	.59	Large	VY + ST > ST*, VY + ST > AF + ST†
Estimated VO_2max	24.85	< .001	.54	Large	VY + ST > ST*, VY + ST > AF + ST†
Resting HR (bpm)	11.07	< .001	.35	Large	VY + ST < ST*, AF + ST < ST*

Note: $p < .01$ vs Sprint Training only (ST). † $p < .05$ between experimental groups. $\eta^2_p \geq 0.14$ indicates a large effect.

bigger changes in flexibilities, estimated aerobic capacity and resting heart rate. Unstable joint vascularisation, trunk stability as well as breath-coordinated movements are the focus of dynamic yoga exercises, which can promote more effective movement patterns and autonomic responses (Chaouachi et al., 2008; Polsgrove et al., 2019). Flexibility has been found to increase and various cardiorespiratory variables found to improve with yoga-based interventions in groups of athletes and physically active individuals, but different meta-duration of yoga interventions and intensity result in varying outcomes (Raj et al., 2021; Brunelle et al., 2015).

These current data are aligned with this literature and indicate that the Vinyasa Yoga incorporation can be helpful in terms of physiology adaptation, especially in case of the repeated high-intensity training where recovery and movement economy is of concern. On the contrary, the state of Animal Flow plus sprint training (AF+ST) was related to more positive changes in the vertical jump performance and agility. Movement systems that are quadrupedal and flow-based are demanding on the trunk stiffness, shoulder hip dissociation, and multiplanar force transmission which are essential in explosive and change of direction tasks (Buxton et al., 2020; Ding et al., 2023). It has been shown empirically that quadrupedal movement training has the potential to positively impact the quality of functional movement, dynamic balance, and neuromuscular coordination within rather brief intervention timeframes (Kullman et al., 2020; Buxton et al., 2022). These adjustments can perhaps be converted to high-performance lower limb power expression and agility, as, in the current study, observed. Developmentally, adolescence is a high-growth neuromuscular and musculoskeletal phase, and during it, training responses can be subject to maturation-related factors (Long et al., 2024).

The present study did not directly measure biological maturation and thus, the differences among the observed groups only indicate that integrative movement-based adjuncts can be incorporated to be used alongside traditional sprint training to satisfy the demands of coordination and mobility which are not always comprehensively addressed with the use of sprint-specific drills only. In the development of sprint race in youth, the application of multimodal training methods to lessen the coordination limitation and maximize the movement efficiency has received more support (Nicholson et al., 2021; Skoglund et al., 2023). The found changes in the resting heart rate and the enhancement of estimated aerobic capacity of the VY+ST group are to be seen with some caution. The test was conducted in an indirect way, by measuring aerobic capacity by Cooper 12 minutes run test instead of direct gas analysis, and, thus, indicates the field-based estimates of the true maximal oxygen uptake (Bandyopadhyay, 2014). However, the convergent changes in resting heart rate and predicted aerobic capacity might be evidence of favourable cardiovascular changes or enhanced autonomic balance that have been attributed to mind awake and breathing controlled interventions (Brown & Gerbarg, 2005). These adaptations can help to ensure recovery between sprint bouts and not necessarily raise sprint speed per se.

A number of methodological strengths underlie internal consistency of current findings. The reliability of the observed group differences is enhanced through the use of a randomised controlled design where training protocols are standardised, and tests are carried out under a standard environment. Moreover, the performance-related and physiological variables made it possible to examine training-related adaptations in a wider range without using a single result measure. Presentation of the effect sizes in addition to statistical significance contributes to interpreting practical relevance as well, which is consistent with the modern methodological principles. Yet, there are critical limitations that should be admitted. To begin with, an a priori power analysis has not been performed and the small size of the sample requires the large effect sizes to be interpreted with caution. Second, the biological maturation status was not evaluated and this might have had some effect on the neuromuscular and physiological adaptation in this adolescent group. Third, the aerobic capacity was estimated indirectly and biomechanical or neuromuscular outcomes (e.g., electro-myography or kinematic analysis) were not used to clarify the underlying mechanisms of change. It, therefore, makes it impossible to draw causal conclusions about a particular physiological or biomechanical pathway.

Practically, the results indicate that the inclusion of adjuncts to sprint training programmes which are focused on low- to moderate-intensity movement which does not require a significant increase in training load is a potentially feasible strategy in facilitating performance-related improvements in adolescent athletes. Vinyasa Yoga can be more appropriate at the stage when mobility or recovery needs to be optimal and overall physiological readiness, and Animal Flow can be more appropriate at the stage when explosive power and agility have to be prioritized. Nonetheless, practice should be customised according to the maturity of athletes, their trainings, and work values in general. A number of gaps in the current research are the subject of future research. Relationships between dose and response of integrative movement interventions ought to be investigated and maturation indices should be added to enhance better interpretation among youth population like peak height velocity.

Also, such combinations of field-based performance assessment testing and biomechanical and neuromuscular measurements would allow a better understanding of the mechanisms behind the observed adaptations. External validity would be further benefited by replication of such protocols in female athletes and other sports, which consist primarily of sprint events. Overall, despite the methodological limitations, it is possible to say that the current study has demonstrated that adding Vinyasa yoga or Animal Flow to sprint training is linked with specific and possibly complementary changes in male adolescent sprinters. These results add to the existing research on multimodal and movement-quality-oriented interventions on the athletic development of youth.

Conclusions

The results of the current study are conducive to the point that the combination of Vinyasa Yoga/Animal Flow activities with a strength sprint training programme had higher increases on the chosen variables of performance and physiological parameters in teenage male sprinters than usual sprint training alone did. It was both integrative methods that were associated with positive improvements in sprint performance, explosive power, agility, flexibility, estimated aerobic capacity, and resting heart rate and changes through the 12 weeks intervention. There were clear differences in patterns of adaptation between the two of the adjunct modalities. The conditions of Vinyasa Yoga plus sprint training were more related to the availability of the improvement of flexibility and estimated aerobic capacity alongside the resting HR, and the condition of Animal Flow plus sprint training was more related to the achievement of vertical jumping performance and agility. These results suggest that adjuncts that involve movement can be modality-specific in benefits that can be used as complementary to standard sprint training when implemented in a guided and monitored application. The data must be taken with a grain of salt considering the age of the test subjects who were adolescents, the indirect method of testing aerobic capacity; and the lack of maturation analysis and pre-research power analysis. However, the current research provides the initial evidence in accordance with the possible role of integrative movement practices as the additional portions of youth sprint training programmes. Future studies that use maturation indices, biomechanical studies, and populations should be considered to determine the mechanisms and how to use over patient situations and in other contexts of sport.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Ethical Approval

This study was approved by the Institutional Research Ethics Committee of the Hindustan Institute of Technology and Science (Deemed to be University), Chennai, India (Approval No.: HITS/CRC/004/20603034), and conducted in accordance with the Declaration of Helsinki (2013 revision). Written informed consent and parental consent (for participants under 18 years) were obtained.

Declaration on AI Use

Artificial intelligence–assisted tools were not used in the collection, analysis, or interpretation of data, nor in the generation of scientific content or conclusions. Any language editing, if performed, did not affect the scientific integrity of the manuscript. All scientific responsibility rests solely with the authors.

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Інтегративний вплив вправ Vinyasa Yoga та Animal Flow на спринтерську результативність і фізіологічні адаптації у юних спринтерів чоловічої статі

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 9 с., 4 табл., 24 джерела.

Мета. Метою дослідження було з'ясувати, чи впровадження вправ Vinyasa Yoga або Animal Flow у поєднанні зі структурованою програмою спринтерського тренування забезпечує більші зміни вибраних показників рухової результативності та фізіологічних характеристик у юних спринтерів чоловічої статі порівняно з контрольною групою, яка виконувала лише спринтерське тренування.

Матеріали та методи. У дослідженні взяли участь 45 учнів-спринтерів чоловічої статі старших класів (16,0 ± 0,8 року), яких було випадковим чином розподілено на три групи в межах 12-тижневого рандомізованого експерименту: лише спринтерське тренування (ST), Vinyasa Yoga у поєднанні зі спринтерським тренуванням (VY+ST) та Animal Flow у поєднанні зі спринтерським тренуванням (AF+ST). Усі групи виконували однакову програму спринтерського тренування тричі на тиждень, тоді як експериментальні групи додатково виконували 45-хвилинні допоміжні тренування через день. До показників рухової результативності належали час бігу на 30 м, висота вертикального стрибка та спритність, а до фізіологічних показників — гнучкість, оцінена аеробна працездатність (12-хвилинний біговий тест Купера) та частота серцевих скорочень у стані спокою. Дані до та після експерименту аналізували з використанням парних t-тестів і однофакторного дисперсійного аналізу (ANOVA) для показників змін, із поданням величин ефекту.

Результати. Обидві інтегративні тренувальні групи продемонстрували статистично значуще більші покращення за всіма показниками рухової результативності та фізіологічними змінними порівняно з групою ST ($p < 0,05$). Група VY+ST виявила відносно більші покращення показників гнучкості, оціненої аеробної працездатності та частоти серцевих скорочень у стані спокою, тоді як група AF+ST продемонструвала більший приріст висоти вертикального стрибка та спритності. Для всіх результативних показників зафіксовано великі міжгрупові величини ефекту.

Висновки. Отримані результати свідчать, що доповнення спринтерського тренування вправами Vinyasa Yoga або Animal Flow асоціюється зі сприятливими та модально-специфічними адаптаціями у юних спринтерів чоловічої статі. Такі інтегративні, рухово-орієнтовані підходи можуть слугувати комплементарними стратегіями в системі підготовки юних спринтерів. Водночас, з огляду на непрямий характер оцінки аеробної працездатності, а також відсутність контролю процесів біологічного дозрівання та a priori аналізу статистичної потужності, отримані результати слід інтерпретувати з обережністю.

Ключові слова: Vinyasa Yoga, Animal Flow, спринтерська результативність, інтегративне тренування, юні спортсмени, фізична підготовленість.

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Original Scientific Article

Post-Activation Performance Enhancement in Badminton Players: A Randomized Crossover Study Comparing the Acute Effects of Four Squat Protocols on CMJ Performance

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Abstract

Objectives. The objective of this study was to compare the acute post-activation performance enhancement (PAPE) effects of four squat-based conditioning protocols—bodyweight squats, BOSU-ball squats, resistance-band squats, and weighted-vest squats—on countermovement jump (CMJ) performance in trained badminton players.

Materials and Methods. Twelve competitive badminton players (8 males, 4 females; age 21.5 ± 2.1 years) with a minimum of five years of playing experience participated in this randomized crossover study. Each athlete completed all four squat protocols in a counterbalanced order, separated by 48-hour washout periods. CMJ height was measured at baseline and at 4, 8, and 12 minutes post-conditioning using an inertial motion sensor (BTS G-Walk, Italy). A two-way repeated-measures ANOVA (Protocol × Time) with Bonferroni-adjusted comparisons was applied to determine the effects of each protocol and recovery interval on CMJ height.

Results. Significant main effects of Protocol ($p = .001$), Time ($p = .004$), as well as a significant Protocol × Time interaction ($p < .001$), were observed. The weighted-vest protocol produced the greatest PAPE response, with CMJ height increasing from 29.7 ± 0.9 cm at baseline to 33.2 ± 0.8 cm at 8 minutes (an 11.8% improvement; $p < .01$). The resistance-band protocol elicited a moderate enhancement, peaking at 31.1 ± 1.3 cm at 8 minutes ($p < .05$). Bodyweight and BOSU-ball squats produced minimal, non-significant variations in CMJ performance. The 8-minute interval consistently yielded the highest potentiation across the effective protocols.

Conclusions. Squat-based conditioning activities using external loading—particularly weighted-vest squats—induce superior post-activation performance enhancement in badminton players compared with bodyweight or unstable-surface squats. The findings indicate that a recovery interval of approximately eight minutes optimizes CMJ potentiation. Weighted-vest squats may therefore be recommended as an effective pre-competition activation strategy for improving explosive lower-limb performance in badminton athletes.

Keywords: post-activation performance enhancement, squat protocols, weighted vest, resistance band, countermovement jump, badminton players, crossover design.

Introduction

Post-activation performance enhancement (PAPE) refers to the acute improvement in muscular power or strength following a high-intensity conditioning activity. It is increasingly recognised as a valuable strategy in explosive sports to optimise performance in actions such as jumping, sprinting, and rapid directional changes (Barreto et al., 2023; Guo et al., 2022; Tillin & Bishop, 2009). PAPE's physiological mechanisms involve increased muscle temperature, blood flow, activation, and muscle-tendon stiffness (Đurović et al., 2022). Post-activation potentiation, a key component of PAPE, is influenced by enhanced phosphorylation of myosin regulatory light chains and greater recruitment of high-order motor units (Tillin & Bishop, 2009).

In badminton, characterised by intermittent power actions, including high-intensity jumps, turns, and lunges, the ability to generate explosive force is crucial for both offensive and defensive manoeuvres (Sudhakaran et al., 2025). Recent studies have shown that resistance priming

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and dynamic warm-ups designed to induce PAPE can significantly enhance key performance variables in badminton, such as agility, peak power, and change-of-direction speed, offering athletes a competitive edge during match play (Chua et al., 2021; Sudhakaran et al., 2025). These findings underscore the practical relevance of PAPE protocols for badminton players, as improvements in these physical qualities directly translate to better on-court performance and responsiveness.

Squat exercises of varying modalities have been widely investigated as conditioning activities to elicit PAPE effects on subsequent explosive performance. Three sets of ten bodyweight squats have been shown to induce significant improvements in CMJ height at both 2 min (30.8 ± 5.6 cm vs. baseline 29.5 ± 6.4 cm, $p = 0.045$) and 4 min (30.8 ± 6.1 cm, $p = 0.037$) post-conditioning in team-sport athletes, indicating that even unloaded squats can provide sufficient stimulus for acute potentiation (Bampouras & Esformes, 2020). Squats performed on unstable surfaces (e.g., BOSU ball) yield PAPE effects on CMJ and sprint performance comparable to those of stable-surface squats, although they impose greater balance demands and may increase injury risk if the technique is not rigorously controlled (Gómez & Rojas-Jaramillo, 2025). Incorporating elastic bands to create variable resistance during back squats (20–30% of the total load from bands) at 85% 1RM has been demonstrated to significantly enhance short sprint times (3 m, 5 m, and 10 m) and vertical jump metrics, with the BAND30 protocol producing the largest effect sizes ($g = 1.08$ for SJ height) 4 min post-conditioning (Krčmár et al., 2020). Weighted-vest squats, using external loads of approximately 10%–15% body mass, have been explored in warm-up contexts and shown to maintain or slightly enhance lower-body power and change-of-direction speed, although CMJ improvements are generally not superior to traditional warm-ups and may depend on adequate rest intervals (5–8 min) to balance potentiation against fatigue (Ioannides et al., 2024; Kaçoğlu & Kırkaya, 2020).

Post-activation performance enhancement (PAPE) manifests as a transient improvement in explosive muscle actions, such as countermovement jump (CMJ), when an optimal rest interval follows a high-intensity conditioning activity; meta-analytic evidence indicates that rest intervals of 4–7 minutes yield the most significant increases in CMJ height (mean difference [MD] ≈ 0.03 m; 95% CI: 0.01–0.04; $p < 0.01$)(Chen et al., 2023; Li et al., 2024), while intervals of 8–9 minutes remain beneficial (Cohen's $d = 0.26$; $p = 0.02$) (Chen et al., 2023) and very short (0–1 min) or prolonged (> 10 min) intervals show no potentiation or may even impair performance (MD ≈ 0.00; $p = 0.70$ for 1–3 min; MD = –0.01; $p = 0.15$ for 10–24 min)(Li et al., 2024). Kinetic analyses further reveal that concentric peak force potentiates earlier (mean 6.6 ± 2.9 min) than eccentric variables (8.6 ± 3.6 min), underscoring distinct time courses for different contractile properties and highlighting considerable interindividual variability in peak potentiation timing (Maroto-Izquierdo et al., 2020).

Despite the recognised importance of PAPE for enhancing explosive performance, investigations specific to badminton remain scarce, with only a handful of studies examining squat-based potentiation in elite shuttlers (Chua et al., 2021). Moreover, to date, no research has directly compared multiple squat modalities (e.g., bodyweight, unstable surface, resistance band, weighted vest) within a single randomised crossover design, leaving practitioners without evidence to guide the selection of the most effective conditioning activity for badminton athletes. Finally, although the time course of PAPE effects has been mapped following heavy squats in other sports, there is limited data on how different squat protocols interact with rest intervals (e.g., 4, 8, 12 minutes) in the same group of badminton players, preventing clear recommendations on optimal timing for jump potentiation in this population (Chua et al., 2021; Sudhakaran et al., 2025).

The primary aim of this randomised crossover investigation was to compare the acute post-activation performance enhancement (PAPE) effects of four squat-based conditioning protocols—bodyweight, BOSU-ball (unstable surface), resistance-band (variable resistance), and weighted-vest (≈10–15% body mass) squats—on countermovement jump (CMJ) height in trained badminton players (Baus et al., 2024; Peng et al., 2020; Sæterbakken & Fimland, 2012). It was hypothesised that external-load modalities (weighted vest and resistance band) would elicit a greater potentiation magnitude than bodyweight or BOSU conditions.

Materials and Methods

Study Design

A randomised crossover design was employed to compare the acute effects of four squat-based conditioning protocols on PAPE in trained badminton players. Each participant completed all four protocols in randomised order, with a minimum 48-hour washout period between sessions to minimise carryover and residual potentiation effects.

Study Participants

Twelve competitive badminton players (8 male, 4 female; age 21.5 ± 2.1 years; weight 68.7 ± 5.9 kg) with ≥ 5 years' playing experience and no lower-limb injury in the past six months were recruited. Each participant provided voluntary consent to participate in the study, and ethical approval was obtained from the concerned institutional authority. The sample size was guided by feasibility and by the efficiency of the randomised crossover design, in which each participant completed all four protocols and served as their own control, reducing inter-individual variability and improving precision for detecting acute changes in CMJ performance; similar acute PAPE/priming studies have used small samples due to intensive repeated-testing demands (e.g., $n = 9$ and $n = 8$) (Ioannides et al., 2024; Sudhakaran et al., 2025).

Study Organisation

Each participant performed four conditioning protocols after general warm-up in randomised order:

Bodyweight Squats: 3 × 10 reps on a stable surface, 90° knee flexion, self-paced tempo.

BOSU-Ball Squats: 3 × 10 reps on a BOSU balance trainer, identical tempo and depth.

Resistance-Band Squats: 3 × 10 reps with elastic bands (~30% of body weight).

Weighted-Vest Squats: 3 × 10 reps wearing a vest loaded to 10–15% of body weight.

Repetitions in each set were separated by 30 seconds of passive rest; all protocols were conducted under the researcher's supervision to ensure technique consistency.

Administration of the Test: As illustrated in Figure 1, participants first attended a familiarisation session to standardise and practice proper squat depth and countermovement jump (CMJ) using an inertial moment sensor (BTS G-walk, Italy), ensuring consistency and minimising learning effects during subsequent testing. Before baseline CMJ testing, all participants completed a general warm-up to prepare their bodies for maximal effort and reduce the risk of injury. Baseline CMJ testing involved three maximal CMJs, with the highest jump height recorded as the baseline value for later comparison. Immediately after establishing the baseline, participants performed their assigned squat protocol as the conditioning activity, tailored according to the experimental design. To assess the acute effects of this conditioning, CMJ height was measured at 4-, 8-, and 12-minute post-conditioning; at each time point, participants performed three CMJs, and the best value from each set was used for analysis. To minimise the risk of additional fatigue influencing results, participants remained seated between measurements. A 48-hour washout period was implemented between sessions to prevent carryover effects and ensure complete recovery. Throughout the study, protocol allocation was randomised to minimise selection bias, and data analysts were blinded to the participants' assigned conditions, ensuring an objective and unbiased analysis of the outcomes.

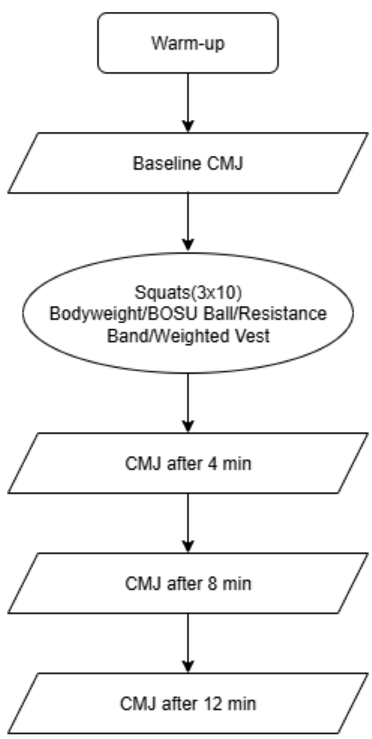

Fig. 1 Experimental flow of warm-up, activation protocols, and CMJ assessments

Statistical Analysis

CMJ height data were analysed via two-way repeated measures ANOVA (Protocol × Time). Sphericity was assessed using Mauchly's Test; Greenhouse–Geisser correction was applied where violations occurred. Bonferroni-adjusted pairwise comparisons followed significant main and interaction effects. Effect sizes were reported as partial η^2 for ANOVA and Hedges' g for pairwise contrasts. Statistical significance was set at $p < 0.05$, and analyses were performed in SPSS v27.

Results

Table 1. Mean ± SD (95% CI) of CMJ Height (cm) Across Protocols and Time Points

Protocol	Baseline	4 min	8 min	12 min
Bodyweight	29.2±0.9 (28.6-29.8)	29.8±1.1 (29.1-30.5)	30.1±1.2 (29.3-30.9)	29.7±1.0 (29.1-30.3)
BOSU	28.7±1.0 (28.1-29.3)	29.3±0.9 (28.7-29.9)	29.6±1.1 (28.9-30.3)	29.1±1.0 (28.5-29.7)
Resistance Band	29.5±1.2 (28.7-30.3)	30.4±1.1 (29.7-31.1)	31.1±1.3 (30.3-31.9)	30.5±1.0 (29.9-31.1)
Weighted Vest	29.7±0.9 (29.1-30.3)	31.3±0.9 (30.7-31.9)	33.2±0.8 (32.7-33.7)	32.1±0.9 (31.5-32.7)

Descriptive statistics for countermovement jump (CMJ) height across all four post-activation performance enhancement (PAPE) protocols—Bodyweight, BOSU, Resistance Band, and Weighted Vest—at four-time intervals (Baseline, 4 min, 8 min, 12 min) are presented in Table 1. Values are presented as mean ± SD with 95% confidence intervals (CI). The Weighted Vest protocol at 8 minutes post-activation yielded the highest mean CMJ height (M = 33.2 cm, SD = 0.8), indicating a pronounced PAPE effect. The Bodyweight and BOSU protocols showed minimal changes across time points, while the Resistance Band protocol demonstrated a moderate increase, particularly at 8 minutes illustrated in figure 2.

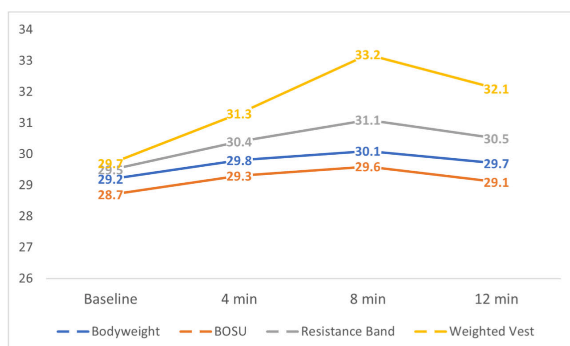

Fig. 2 Changes in countermovement jump height following four activation protocols over time

Before conducting the inferential analysis, Mauchly's Test of Sphericity was performed to verify the assumption of sphericity for the within-subjects factors (Protocol, Time, and their interaction) presented in Table 2. The assumption was met for the main effects of Protocol and Time but violated for the Protocol × Time interaction, necessitating the Greenhouse-Geisser correction for this effect.

Table 2. Mauchly's Test of Sphericity for Within-Subject Effects

Effect	Chi-Square (χ^2)	df	p	Sphericity Met?	Adjustment
Protocol	7.31	5	.198	Yes	None
Time	4.84	5	.304	Yes	None
Protocol × Time	124.57	69	.003	No	Greenhouse-Geisser applied

As illustrated in Table 3, a two-way repeated measures ANOVA was performed to examine the effects of Protocol (4 levels) and Time (4 levels) on CMJ height. Significant main effects were observed for both Protocol and Time, as well as a significant interaction between Protocol and Time. Partial eta squared (η^2) values indicated large effect sizes for Protocol (0.42), Time (0.33), and their interaction (0.30), reflecting substantial and practically meaningful differences in CMJ height attributable to both protocol type and timing.

Table 3. Two-Way Repeated Measures ANOVA for CMJ Height

Effect	df	F	p	Partial η^2
Protocol	3,33	7.82	.001	0.42
Time	3,33	5.49	.004	0.33
Protocol × Time	9,99	4.65	<.001	0.30

Bonferroni-adjusted pairwise comparisons revealed that the Weighted Vest protocol at 8 minutes post-activation resulted in significantly higher CMJ height compared to all other protocol-time combinations ($p < .01$). The Resistance Band protocol at 8 minutes also showed a significant improvement compared to its baseline ($p < .05$). In contrast, no significant changes were observed within the Bodyweight and BOSU protocols.

Discussion

The purpose of this study was to compare the acute effects of four squat-based post-activation performance enhancement (PAPE) protocols and their time course on countermovement jump (CMJ) height in trained badminton players. As hypothesised, the externally loaded conditions produced greater potentiation than bodyweight or unstable-surface squats: CMJ increased by 11.8% at 8 min after weighted-vest squats and by 5.4% at 8 min after resistance-band squats, whereas bodyweight and BOSU conditions showed only small, non-significant changes. These results support the practical importance of pairing an adequately intense conditioning activity with an appropriate recovery interval.

The weighted-vest protocol produced the largest improvement, which is consistent with the concept that greater mechanical loading can enhance neuromuscular activation when sufficient recovery is provided. Ioannides et al. (2024) reported limited CMJ change following weighted-vest warm-ups in kumite karate athletes when recovery was not optimised, suggesting that fatigue can mask potentiation. In our players, the peak response at 8 min is in line with evidence that moderate rest intervals (approximately 4–9 min) are typically favourable for CMJ potentiation after a conditioning stimulus (Chen et al., 2023; Li et al., 2024).

The resistance-band condition also enhanced CMJ, peaking at 8 min. This agrees with prior work showing that variable resistance during squats can increase concentric force demands and support subsequent jump performance (Krčmár et al., 2020; Peng et al., 2020). The smaller magnitude observed here may reflect differences in training status, band tension relative to strength levels, and individual responsiveness to band-based loading.

Bodyweight squats produced only a small, short-lived change, with the highest mean CMJ at 4 min. This pattern is consistent with reports that low-load conditioning can elicit mild potentiation with earlier peaks because metabolic fatigue is limited (Bampouras & Esformes, 2020). In practical settings, bodyweight squats may be useful when external loads are unavailable, although the expected performance benefit appears modest.

BOSU-ball squats did not meaningfully improve CMJ. While unstable-surface exercises may increase balance and stabiliser demands, the added instability can reduce the capacity to generate high concentric force and rate of force development, which are central to jump potentiation. This interpretation is consistent with the mixed evidence on unstable-surface PAPE and the higher technical demands reported for these conditions (Gómez & Rojas-Jaramillo, 2025; Sæterbakken & Fimland, 2012).

Overall, the findings suggest that when the goal is acute enhancement of explosive performance, externally loaded squats (weighted vests or bands) are preferable to unstable-surface squats, and a recovery interval of about 8 min is likely to be effective for most badminton players. These results also align with work indicating that accommodating resistance can be beneficial for eliciting potentiation when recovery time is limited (Masel & Maciejczyk, 2023).

Despite the practical relevance of the present findings, several limitations should be acknowledged. First, the relatively small sample size (n = 12) may limit the generalisability of the results to broader badminton populations. However, this sample size is comparable to previous acute PAPE and priming studies employing repeated-measures or crossover designs, where intensive testing protocols and strict control of fatigue constrain participant recruitment. Importantly, the randomised crossover design used in this study allowed each participant to serve as their own control, thereby reducing inter-individual variability and enhancing statistical sensitivity for detecting acute changes in CMJ performance. Nevertheless, subtle effects—particularly within the bodyweight and BOSU conditions—may have remained undetected, and future studies with larger samples are warranted to confirm these findings. Second, although both male and female players were included, sex-specific analyses were not conducted due to the limited sample, and potential differences in PAPE responsiveness between sexes cannot be ruled out. Finally, only CMJ height was assessed as an outcome measure; while this variable is highly relevant to badminton performance, future research should incorporate additional sport-specific performance indicators and individualised recovery intervals to refine practical PAPE recommendations further.

Conclusions

The present randomized crossover study investigated the acute post-activation performance enhancement (PAPE) effects of four squat-based conditioning protocols on countermovement jump (CMJ) height in trained badminton players. The findings clearly demonstrate that squat modalities involving external loading—particularly weighted-vest squats—produce the most substantial potentiation, with CMJ performance peaking at approximately eight minutes post-activation. Weighted-vest squats resulted in an 11.8% improvement in CMJ height, significantly outperforming resistance-band squats, which generated moderate enhancement, and bodyweight and BOSU-ball squats, which failed to elicit meaningful changes.

These results highlight the importance of selecting an appropriately intense conditioning activity to maximise neuromuscular potentiation while allowing adequate recovery time to offset fatigue. The consistent peak at eight minutes across effective protocols aligns with previous meta-analytic evidence suggesting that 4–9 minutes is optimal for achieving PAPE in explosive movements.

Practically, this study suggests that coaches and practitioners working with badminton athletes can incorporate weighted-vest squats (10–15% body mass) as part of their pre-match warm-up routines to acutely enhance lower-limb power. Importantly, such squats should be used specifically as an activation strategy rather than as part of regular strength training, as their purpose is to potentiate immediate performance rather than induce long-term adaptations. Resistance-band squats may be considered a secondary alternative when weighted vests are unavailable, while bodyweight and unstable-surface squats are not recommended for eliciting PAPE in competitive badminton contexts.

Overall, this study provides evidence-based guidance for integrating PAPE protocols into badminton warm-ups to improve explosive actions such as jumping, rapid directional changes, and on-court reactivity. Future research may explore long-term applications, sport-specific performance metrics, and individual responsiveness to further refine activation strategies for racket-sport athletes.

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Conflict of Interest

Authors declare no conflict of interest

Data Availability Statement

The datasets generated and analysed during the current study are not publicly available due to institutional and participant confidentiality considerations but are available from the corresponding author upon reasonable request.

AI Transparency Statement

AI–based tools were used solely to assist with language editing and grammatical refinement of the manuscript. No AI tools were used for data analysis, interpretation of results, figure preparation, or generation of scientific content. All scientific decisions, analyses, and conclusions remain the responsibility of the authors.

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Постактиваційне підсилення працездатності у гравців у бадмінтон: рандомізоване кросовер-дослідження порівняння гострих ефектів чотирьох присідальних протоколів на показники стрибка з контррухом

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Реферат. Стаття: 7 с., 3 табл., 2 рис., 18 джерел.

Мета. Метою цього дослідження було порівняти гострі ефекти постактиваційного підсилення працездатності (post-activation performance enhancement, PAPE) чотирьох кондиційних протоколів на основі присідань — присідань з власною масою тіла, присідань на BOSU-платформі, присідань з еластичною стрічкою опору та присідань у жилеті з додатковою вагою — на показники стрибка з контррухом (countermovement jump, CMJ) у підготовлених гравців у бадмінтон.

Матеріали і методи. У рандомізованому кросовер-дослідженні взяли участь дванадцять кваліфікованих гравців у бадмінтон (8 чоловіків, 4 жінки; вік 21,5 ± 2,1 року) з мінімальним ігровим стажем п'ять років. Кожен спортсмен виконав усі чотири протоколи присідань у збалансованій послідовності з інтервалами «вимивання» тривалістю 48 годин. Висоту CMJ вимірювали на вихідному рівні, а також через 4, 8 і 12 хвилин після кондиційного впливу з використанням інерціального датчика руху (BTS G-Walk, Італія). Для визначення впливу кожного протоколу та інтервалу відновлення на висоту CMJ застосовували двофакторний дисперсійний аналіз із повторними вимірюваннями (Protocol × Time) з поправкою Бонферроні для множинних порівнянь.

Результати. Виявлено статистично значущі основні ефекти чинників Protocol ($p = 0,001$) і Time ($p = 0,004$), а також значущу взаємодію Protocol × Time ($p < 0,001$). Протокол із використанням жилета з додатковою вагою забезпечив найбільш виражений ефект PAPE: висота CMJ зросла з 29,7 ± 0,9 см на вихідному рівні до 33,2 ± 0,8 см через 8 хвилин (покращення на 11,8%; $p < 0,01$). Протокол з еластичною стрічкою опору викликав помірне підвищення показників, максимальне значення яких становило 31,1 ± 1,3 см через 8 хвилин ($p < 0,05$). Присідання з власною масою тіла та присідання на BOSU-платформі спричинили мінімальні, статистично незначущі зміни показників CMJ. Інтервал у 8 хвилин стабільно забезпечував найвищий рівень потенціювання для ефективних протоколів.

Висновки. Кондиційні вправи на основі присідань із зовнішнім навантаженням — особливо присідання у жилеті з додатковою вагою — забезпечують вищий рівень постактиваційного підсилення працездатності у гравців у бадмінтон порівняно з присіданнями з власною масою тіла або на нестабільній опорі. Отримані результати свідчать, що інтервал відновлення тривалістю близько восьми хвилин є оптимальним для потенціювання CMJ. Таким чином, присідання у жилеті з додатковою вагою можуть бути рекомендовані як ефективна передзмагальна активаційна стратегія для підвищення вибухової сили м'язів нижніх кінцівок у бадмінтоністів.

Ключові слова: постактиваційне підсилення працездатності, протоколи присідань, жилет з додатковою вагою, еластична стрічка опору, стрибок з контррухом, гравці у бадмінтон, кросовер-дизайн.

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Personal Factors of Referees in Football Influencing the Formation of Refereeing Styles

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Abstract

Objectives. The study aimed to determine the psychological characteristics of football referees that influence the formation of their refereeing styles.

Materials and Methods. Twenty-five football referees from professional leagues in Ukraine (aged 25–40 years, with 7–17 years of refereeing experience) participated in the study. The sample included 12 referees from the Ukrainian Premier League, 6 from the First League of the Professional Football League (PFL), and 7 female referees. A battery of psychological diagnostic methods was used, including the Self-Assessment of Stress Resistance scale, Eysenck's Personality Questionnaire (EPQ), Hall's Emotional Intelligence Assessment, and Amirkhan's Coping Strategy Indicator.

Results. The assessment of stress resistance revealed that female referees scored 10.2% higher than male referees (33.3 vs. 36.7 points, respectively). The study of coping strategies showed that subjects, overall, were characterized by an average level of Problem Focusing and Seeking Social Support, but a low level of Avoidance. In general, football referees exhibited a low level of Managing one's emotions and Recognition of others' emotions (median score: 6 points). The remaining indicators corresponded to the average level. Fifty-two percent (52.0%) of the subjects demonstrated a low level of emotional intelligence, while the remaining 48.0% displayed an average level.

Conclusions. The findings have established that, in general, football referees demonstrate an average level of stress resistance; however, this feature does not statistically significantly affect the choice of refereeing style. Statistically significant ($p<0.050$) correlations have been identified between referees' coping strategies and their officiating styles, indicating that the coping strategies used by officials to manage stress have a direct impact on their approach to match management. In particular, referees who tend to actively engage in problem-solving and seek effective solutions are more likely to demonstrate an authoritarian refereeing style. Simultaneously, referees who tend to avoid problems are more likely to exhibit a liberal refereeing style. No statistical relationship was found between the democratic style and coping strategies.

Keywords: temperament types, stress resistance, coping strategies, emotional intelligence, authoritarian refereeing style, democratic refereeing style, liberal refereeing style, football referees.

Introduction

Experts quite often emphasize the need to study the variability in the application of the Laws of the Game and cases of subjective interpretation of individual episodes of a match by different referees depending on many circumstances and factors (Gomes et al, 2021; Wang et al, 2024; Abdula, Marulin, 2025). These may be external factors that influence certain decisions, but for the most part, it is the internal manifestations of referees, their personal qualities, temperament, reactions, and feelings that play a significant role in the manner of conducting the game, i.e., the so-called "refereeing style" (Yıldız, Yıldız, 2020; Pizzera et al, 2022; Popovych et al, 2022).

It is noted that the existing possibilities for subjective interpretation of the Laws of the Game in football are also made possible by differences in refereeing styles. This refers to the characteristics inherent in certain referees, as well as the refereeing techniques they typically use in a particular

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episode of a particular match (Slack et al, 2014). It should be noted that an individual refereeing style is formed on the basis of a general management style, taking into account certain working conditions, but one cannot ignore the personal psychological and professional characteristics of the referee.

If we follow the existing opinion that the referee is the manager on the field and the leader of the team among the match officials, we should also take into account their style of refereeing. By refereeing style, we mean not only managing the players and the game, but also managing the assistants, leading the teamwork of the refereeing team, behavioral characteristics during the match, etc. Thus, "management style is defined as a set of the most characteristic and consistent techniques used in the process of management activity" (Pryshchak, Lesko, 2016).

As for the research on the profession of football referees, the scientists note that most of the highlighted styles correspond to the existing characteristics of management styles, namely the "Rule book" – authoritarian, "Common sense" – democratic and "Laissez-faire style" – liberal. In particular, referees who adhere to the "Rule book" (authoritarian) refereeing style follow the Laws of the Game rigidly, without exception. For them, all game situations are perceived as clearly defined and immutable. This firm stance and reluctance to adjust decisions according to the game's context often lead to confrontations with players and team representatives, which in turn increases the number of disciplinary sanctions issued specifically for dissent. Proponents of the "Common sense" (democratic) refereeing style adhere to the Laws of the Game by applying them contextually, ensuring they do not disrupt the flow of the match. Such referees are confident that they can keep the game under control, feel the pace of the game that is comfortable for the athletes to maintain, follow the play, and intervene only when necessary. Referees who adopt a "Laissez-faire style" (liberal) allow players to compete without giving specific instructions, relying on the fact that the players themselves will adjust the pace and resolve controversial situations among themselves. However, this refereeing style is only appropriate if the players are capable of controlling the situation, adhering to the Laws of the Game, and maintaining mutual respect between the teams (Bernal et al, 2012; Warner et al, 2013).

It has been established that, alongside a football referee's personal qualities, other factors influence the formation of their refereeing style. Drawing on existing scientific literature, these include: adaptability, understanding of football, suggestibility, motivation, and experience (Korolchuk, 2018; Margiyan et al, 2022; Hamamcioglu, Acar, 2024).

According to American researchers, the effectiveness of the decision-making process itself depends on the personality of the decision-maker. Therefore, the methods used in the decision-making process are important, and personality traits remain a decisive factor (Shiloh et al, 2001).

According to the characteristics of temperament, people differ not in the final result of their actions, but in the way they achieve those results. To establish a connection between the manner of action and individual typological traits, a study was conducted to investigate individual activity style as a way of achieving results or solving specific tasks, determined mainly by the type of the nervous system. The results of the research show that, regardless of the subjects' characteristics or the experimental situations where their behavioral patterns were analyzed, the type of nervous processes is the leading factor in forming a specific activity style (Mazaraki et al, 2007).

Various psychological aspects of athletes and coaches in football have been discussed in our previous scientific works (Voronova et al, 2021, 2024; Petrovska, Sova, Voronova et al, 2022; Vozniuk, Shchepotina et al, 2021). However, unfortunately, there are very few studies in the scientific literature aimed at studying factors, specific qualities, or personality characteristics and their impact on various aspects of refereeing in general and decision-making in particular in today's conditions. Thus, a significant proportion of scientific works are devoted to the study of external influences on decision-making by referees, such as crowd composition, proximity to the pitch, home advantage, social pressure, etc. (Dohmen, 2008; Dawson, Dobson, 2010; Moriconi, De Cima, 2021). Furthermore, the analyzed literature suggests that many authors view refereeing style as a largely innate trait that remains resistant to change; however, practical experience emphasizes the importance of acquired characteristics (Loghmani et al, 2021; Webb et al, 2023).

The question of whether a referee can adapt their style between matches or even during a single match warrants further exploration. It is plausible that refereeing style evolves over time with experience, as personal qualities are not static and remain subject to adjustment. Consequently, a refined style becomes intrinsic to a specific referee, who then applies it consistently, regardless of external circumstances. To determine whether a connection exists between these factors, special attention and further study should be directed toward the personal qualities of football referees and their influence on the perception of match incidents, interpretation of the Laws of the Game, and match management. Furthermore, their interaction with match participants (players, coaches, fans, etc.) and fellow match officials (assistants, observers, etc.) is crucial, as these elements collectively form the so-called "refereeing style." Unfortunately, the question of which match management style and interpretation of game episodes a referee selects based on their personal qualities remains largely understudied.

Study hypothesis: By studying existing refereeing styles, the personal qualities of football referees, and the connection between them, we can acquire the knowledge necessary to facilitate the training and forecasting of referees' future activities at the very beginning of their careers. Furthermore, this data will enable the rational selection of referees for matches of varying levels of complexity and specificity.

The purpose of the study is to identify the psychological characteristics of football referees that influence the formation of their refereeing styles.

Materials and Methods

Participants

Twenty-five football referees from professional Ukrainian leagues (aged 25–40 years, with 7–17 years of refereeing experience) participated in the study. The sample included 12 referees from the Ukrainian Premier League, 6 from the First League of the Professional Football League (PFL), and 7 female referees. The study was approved by the Ethics Committee of the National University of Physical Education and Sports of Ukraine, and all procedures complied with the Declaration of Helsinki. Informed consent to participate in study was obtained from all participants prior to data collection.

Procedures

The study of football referees was conducted using a battery of psychological diagnostic methods (the Self-Assessment of Stress Resistance scale, Eysenck's Personality Questionnaire (EPQ), Hall's Emotional Intelligence Assessment, and Amirkhan's Coping Strategy Indicator).

The psychological characteristics of the referees' temperaments were determined using the EPQ method developed by H.J. Eysenck, who, when developing the test material, took into account three individual-typological components that are part of the personality structure, namely: extraversion/introversion (a preference for being among people, a desire for recognition, having many friends, and impulsiveness regardless of the consequences of decisions); introversion (a person's immersion in themselves, predominant self-analysis, introspection, reflection, and making thoughtful decisions after a detailed analysis of the consequences, etc.); and neuroticism (high emotionality, expressive emotional reactions to stimuli, increased anxiety, and instability of the nervous system). The test items, which require a clear 'yes' or 'no' response, include questions designed to determine the truthfulness of the respondent's answers. A match between the subject's response and the 'key' proposed in the methodology is scored as 1 point. The total score obtained for the specified indicators (extraversion/introversion, neuroticism) is then used to determine the individual's temperament type (Eysenck, Eysenck, 1975). These methods make it possible to predict the behavior of referees in various match situations, the speed and form of their reactions, and their officiating and leadership styles based on their temperament type.

The method for determining stress resistance involves the respondent analyzing their own behavior in stressful emotional situations, quantifying and qualifying it on a three-point scale (rarely – 1, sometimes – 2, often – 3). The processed scores determine the individual's overall level of stress resistance on a three-point scale (low, medium, high). Establishing the level of stress resistance, along with other personal characteristics of referees, allowed the study to determine the peculiarities of their behavior under the significant cognitive loads associated with professional activities in the context of football matches (Maksymenko et al, 2004).

The identified level of stress resistance in football referees guided the further direction of research to establish behavioral strategies and ways for referees to overcome stressful situations, commonly referred to as coping strategies. These include personal manifestations obtained through life experiences that combine knowledge, emotional responses, and human behavior as the basis for counteracting various stressors. If the coping strategies chosen by a person are effective (adaptive), they help minimize the negative impact of situations and accelerate recovery. Adaptive strategies enable referees to understand and adjust to harmful stress influences, maintain self-confidence and emotional balance, and preserve mutual understanding and support from others (Lazarus, Folkman, 1984; Voronova, Romaniuk, 2024).

The Coping Strategy Indicator methodology (Amirkhan, 1990) applied for this purpose aims to establish the basic behavioral strategy an individual chooses when faced with stressful situations. The test developer, based on the assumption that such strategies are formed and consolidated throughout life, divides them into three groups: the problem-solving strategy, the social support-seeking strategy, and the avoidance strategy. When completing the questionnaire items, respondents must select one of the proposed options: 'completely agree', 'agree', or 'disagree', which is taken into account during score calculation.

Using the Emotional Intelligence Assessment (Hall, 2006), we identify the aspects of a person's life that influence their ability to understand their own emotional experiences and, by managing their emotional sphere, make appropriate decisions. The items in the test provide a quantitative characterization of five scales: emotional awareness, management of one's own emotions, self-motivation, empathy, and recognition of others' emotions. Points (ranging from -3 to +3) are calculated based on the respondent" selected answer: 'completely disagree', 'mostly disagree', 'partially disagree', 'partially agree', 'mostly agree', or 'completely agree'.

Statistical analysis

Statistical analysis was performed using standard methods commonly applied in sports and pedagogical research (Byshevets et al., 2019; Bai & Bai, 2021; Jones, 2022). Descriptive statistics were calculated to characterize the sample, including the mean (M), standard deviation (SD), and median (Me). Data normality for small sample groups ($n < 30$) was assessed using the Shapiro–Wilk W test. The distribution of stress resistance among high-level referees did not significantly deviate from normality ($p > 0.05$) in either male or female groups, which was confirmed by the Shapiro–Wilk test results and visual inspection of distribution histograms (Fig. 1).

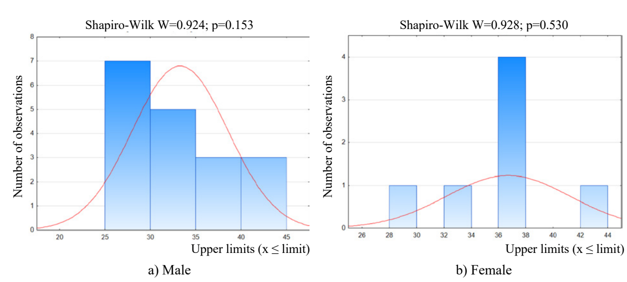

Fig. 1. Testing the hypothesis of normal distribution for stress resistance data according to gender (output from the STATISTICA 10.0 program window)

Similarly, all observed data were examined for their adherence to the normal distribution. Based on this testing (using the Shapiro-Wilk W-test), the appropriate criteria for further analysis were selected: the parametric Student's t-test or the Mann-Whitney U-test, depending on whether the data followed a normal distribution (for independent samples). In addition, pairwise comparisons were performed using the paired Student's t-test (for dependent samples) or the Wilcoxon signed-rank test (for dependent samples).

To assess the influence of football referees' personal characteristics and behavior on their refereeing style, Pearson's parametric correlation coefficient (r) was used when the data were normally distributed, while Spearman's coefficient (ρ) was applied in other cases.

A value of p<0.05 was accepted as the level of statistical significance. Data analysis was performed using MS Excel and the Statistica software package (StatSoft, USA).

Results

The development and formation of personality during life activities are based on innate psychophysiological properties, including neurodynamic and psychological manifestations of temperament. In the current study, when determining the predominance of a specific temperament type, it was not possible to identify a connection between temperament type and refereeing style. This was due to the small number of individuals identified with different types among the referees. The highest frequency (three referees) concerned the "open sanguine" type. There were two other cases where referees were classified as "communicative sanguine" and "cautious phlegmatic." However, the temperament types of the remaining study participants were varied and did not align with these clusters (Fig. 2).

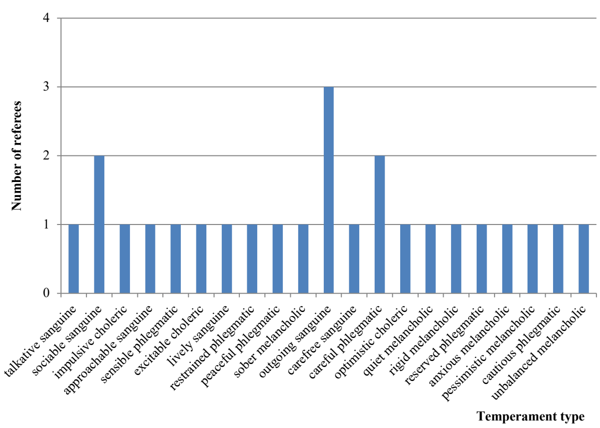

Fig. 2. Distribution of football referees by temperament type (n=25)

It should be noted that a more detailed analysis of the indicators determining the temperament type of the respondents showed that the psychological property of extraversion in football referees was 12 (11.0; 14.0), and neuroticism was 10.0 (8.0; 18.0) points, where the data is presented as Me (25%; 75%). This can be interpreted as moderate extraversion and moderate neuroticism. At the same time, no statistically significant differences between the manifestation of extraversion and neuroticism in football referees were recorded (T=145.0; p=0.638). Similarly, it has not been proven that football referees differ in terms of extraversion according to gender (U=35.0; p=0.096). Likewise, the test groups of different genders did not show statistically significant differences in the manifestation of neuroticism (U=47.5; p=0.364).

Studying stress resistance in football referees, we identified the following characteristics (Table 1). The stress resistance rating for female referees was 10.2% higher than that for male referees (33.3 vs. 36.7 points, respectively); however, these differences were not statistically significant (p=0.144).

Regarding the distribution of football referees by stress resistance levels, the following has been established. The resistance level of most referees varies either slightly above or slightly below the average, with 76.0% of the subjects concentrated within this range (Fig. 3).

Table 1. Comparative analysis of stress resistance among study participants by gender (n=25)

Gender	Statistical indicators				
	M	SD	t	df	p
Male, points	33.3	5.2	-1.151	23	0.144
Female, points	36.7	4.5			

Note: t – Student's t-test for independent samples; df – degrees of freedom; p – level of statistical significance

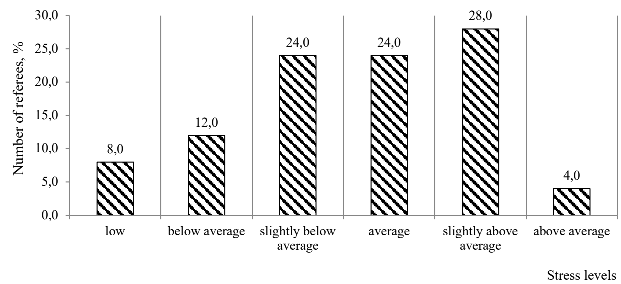

Fig. 3. Distribution of football referees by stress resistance levels (n=25)

A study of the coping strategies used by football referees showed that, compared to men, women are more inclined to utilize the Problem Focusing or Avoidance strategies, while the Seeking Social Support strategy among men is slightly higher. Simultaneously, no statistically significant differences (p>0.050) were found between male and female referees (Table 2).

Analysis of the obtained data suggests that, overall, the subjects are characterized by an average level of Problem Focusing, an average level of Seeking Social Support, and a low level of Avoidance (Fig. 4).

Investigating the relationship between the selected coping strategies and refereeing styles revealed the following statistically significant (p<0.050) correlations:

- the democratic refereeing style ("Common sense") is not significantly associated with the behavioral characteristics of football referees;
- the ability to solve problems and the tendency to avoid them directly correlate with the authoritarian refereeing style ("Rule book"): Pearson's correlation coefficients were 0.595 and 0.436, respectively;
- the liberal refereeing style ("Laissez-faire style") has a direct statistically significant relationship with Avoidance (r=0.448).

Table 2. Comparative analysis of coping strategies among football referees by gender (n=25)

Coping Strategy Indicator	Statistical indicators						
	Central tendency and dispersion				Results of comparative analysis		
	Male (n=18)		Female (n=7)				
	M	SD	M	SD	t	df	p
Problem Focusing, points	24.4	3.2	25.0	3.5	-0.381	23	0.707
Seeking Social Support, points	19.8	4.8	18.4	4.5	0.638	23	0.530
Avoidance, points	18.1	3.2	19.1	4.5	-0.685	23	0.500

Note: t – Student's t-test for independent samples; df – degrees of freedom; p – level of statistical significance

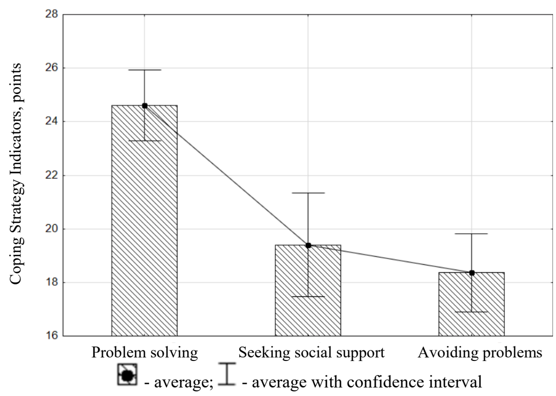

Fig. 4. Average indicators of coping strategies among football referees (n=25)

Since the analysis of emotional intelligence and its connection to refereeing styles established that not all emotional intelligence indicators (based on Hall's methodology) followed a normal distribution (W ranging from 0.880 to 0.936), the median (Me) and the 25th and 75th percentiles were used to represent the central tendency and dispersion. Consequently, nonparametric criteria were employed for further analysis.

As in previous cases, the indicators of the level of emotional intelligence integration in football referees did not differ statistically significantly ($p>0.050$) depending on gender (Table 3).

When analyzing the median of emotional intelligence indicators, we found that football referees received the lowest scores for the 'Managing one's emotions' indicator (Me = 4 points), and the highest scores for emotional awareness (Me=12 points) (Fig. 5).

The interpretation of the scores indicates that, in general, football referees exhibit a low level of emotional control. They also display a low level of recognition of others' emotions: the median score was 6 points. The remaining indicators correspond to the average level. Fifty-two percent (52.0 %) of the subjects are characterized by a low level of emotional intelligence, while the remaining 48.0 % demonstrate an average level.

Table 3. Comparative analysis of emotional intelligence of football referees by gender (n=25)

Emotional Intelligence Indicators	Statistical indicators			
	Sum of ranks		Results of comparative analysis	
	male (n=18)	female (n=7)	U	p
Emotional awareness, points	203.0	122.0	32.0	0.065
Managing one's emotions, points	261.5	63.5	35.5	0.102
Self-motivation, points	235.5	89.5	61.5	0.952
Empathy, points	218.0	107.0	47.0	0.348
Recognition of other's emotions, points	223.5	76.5	48.5	0.505
Integral level, points	248.5	76.5	48.5	0.397

Note: U – Mann-Whitney U-test; p – level of statistical significance

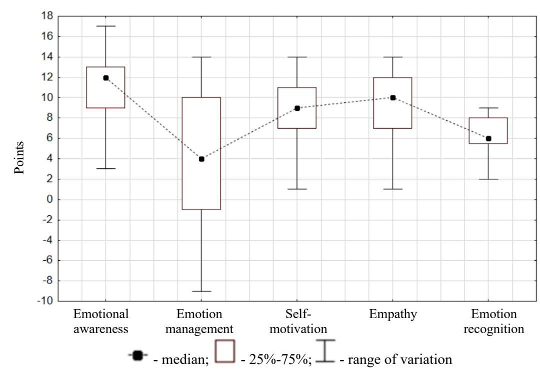

Fig. 5. Emotional intelligence indicators of football referees (n=25)

Regarding the determination of the influence of emotional intelligence components on the refereeing style, the following correlations were established using Spearman's rank correlation coefficient:

- emotional awareness directly correlates statistically ($\rho=0.544$; $p<0.050$) with the authoritarian refereeing style;
- the liberal refereeing style has a statistically significant inverse correlation with managing one's emotions ($\rho=-0.595$; $p<0.050$) and self-motivation ($\rho=-0.658$; $p<0.050$);
- the democratic refereeing style is not significantly associated with the emotional intelligence of football referees.

Discussion

Any profession requires an individual to possess specific mental qualities, the presence of which is a necessary condition for effective development in that particular field of activity. Some professions demand a high level of attention, others require quick reactions to changing circumstances and flexible thinking, and still others necessitate emotional stability and stress resistance. These requirements of an activity cannot be changed at will; they are objectively determined by the content and organization of the activity itself. Furthermore, within the context of a specific professional activity, an individual's personal qualities, mental processes, opportunities and traits determine their readiness for work and the successful performance of their duties. While the same result can be achieved through various methods, the most common way for a person to adapt to the requirements of an activity is through the development of an individual activity style. The individual activity style involves the formation of a system of techniques and skills during professional development that becomes a distinctive characteristic of the individual, defining their unique approach to performing tasks and achieving successful outcomes (Mazaraki et al, 2007; Pryshchak, Lesko, 2016).

Applying these concepts to the present discussion, it can be concluded that a connection exists between a referee's chosen match management style and their individual typological personal qualities. However, a critical question arises: is a refereeing style stable, or can it evolve, incorporate features of other styles, and vary according to the circumstances, match importance or team relations? In examining this issue, researchers note that referees, acting as officials, may employ different styles depending on the level of competition and the dynamics of the game (Bernal et al., 2012).

In our opinion, the absence of a statistically significant relationship between temperament type and refereeing style of the football referees is due to the fact that other factors likely play a more significant role in the formation of a referee's work style than innate features of the nervous system. These factors include stress resistance, developed personal qualities, and behavioral coping strategies, which are formed and consolidated during the process of professional development. This conclusion is also supported by previous studies that observed an interaction between decision-making style and a referee's qualifications — essentially, their experience (Wang et al, 2024).

The study showed that football referees demonstrate an average level of both extraversion and neuroticism. This allows us to characterize referees as sociable individuals, yet simultaneously prone to anxiety and worry. These results complement existing data, which indicates that referees possess strong communication skills, and in terms of moral values, are attentive, moderate, and cautious (Yıldız, Yıldız, 2020).

Any football match is not only a competition of players' physical and technical-tactical preparedness, but also one of endurance and emotional tension. Often, excessive emotions in acute stressful situations lead to verbal abuse and sometimes even physical altercations. In such cases, the referee's role shifts from assessing technical errors to determining guilt for violating the Laws of the Game and established ethical standards of player behavior. An adequate subjective attitude toward the incident requires the referee to possess personal emotional stability, remain calm, and assess the situation correctly (Gomes et al, 2021; Pizzera et al, 2022). Consequently, the connection between stress resistance and refereeing styles was included in the scope of our study.

The results of the study revealed that stress resistance levels in male referees are slightly above average, while in female referees, they are average, suggesting a generally high capacity for managing pressure. Overall, referees demonstrate resilience, which supports them in stressful match situations. This is evidenced by the fact that no subjects exhibited 'high' or 'very high' stress resistance levels, with only 4.0% scoring above average. Conversely, 8.0% demonstrated a low level of stress resistance. These findings complement previous data on the individual psychological characteristics of both male and female referees in team sports (Popovych et al, 2022); however, unlike our study, the aforementioned work presented generalized data on anxiety, aggression, and locus of control as key factors affecting officiating objectivity.

The establishment of behavioral strategies and methods for referees to overcome stressful situations is of significant practical importance. Since, according to the results of the correlation analysis, the democratic refereeing style ("Common sense") is not associated with football referees' behavioral characteristics, this may indicate that this style is influenced by other factors, such as sufficient professional experience, training, or specific personality traits. Furthermore, the identified features of coping strategies in football referees can serve as a guide for self-improvement of professional skills, as well as for the Referees Committee of the Ukrainian Football Association (UAF) to facilitate a more effective selection of officiating teams for matches of varying levels of complexity and specificity.

The results of our study indicate that emotional intelligence — specifically its individual components — has a significant impact on the refereeing style in football. The direct correlation found between emotional awareness and the authoritarian refereeing style suggests that officials who better understand their own and others' emotions are inclined toward a more authoritative decision-making style. The inverse correlation between managing one's emotions, self-motivation, and the liberal refereeing style indicates that referees capable of regulating their emotions and possessing high self-motivation levels more frequently employ a liberal style. The absence of a statistically significant relationship between the democratic refereeing style and emotional intelligence leads us to believe that this refereeing style may be influenced by other factors, such as experience, education level, or specific personality traits.

Conclusions

1. A number of specific complex factors — such as the transience of circumstances, high levels of physical and psychological stress, high social responsibility for decisions made, working directly with numerous athletes simultaneously, the need to resolve psychological and physical conflicts, the irreversibility of decisions made, and, in general, the internal experiences of the individual referee during a match — require representatives of the 'football judiciary' to possess and develop specific psychological qualities that will help them ensure their professional suitability for such a demanding activity. An analysis of specialized literature has identified the following personal qualities as crucial: stress resistance, sociability, integrity, confidence, courage, willpower, leadership skills, emotional intelligence, self-control, etc.

2. It has been established that, in general, football referees demonstrate an average level of stress resistance; however, this feature does not statistically significantly affect the choice of refereeing style. Statistically significant (p<0.050) correlations found between referees' coping strategies and their officiating styles indicate that the coping strategies used by officials to overcome stress and solve problems have a direct impact on their approach to their refereeing style. In particular, referees who tend to actively engage in problem-solving and seek effective solutions are more likely to demonstrate an authoritarian refereeing style. Simultaneously, referees who tend to avoid problems are more likely to exhibit a liberal refereeing style. No statistical relationship was found between the democratic style and coping strategies.

Ethics Approval

The study was conducted in accordance with the ethical standards of the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee of the National University of Ukraine on Physical Education and Sport.

Informed Consent

Written informed consent to participate in the study was obtained from all participants prior to data collection.

Data Availability Statement

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

AI Transparency Statement

The authors did not use artificial intelligence (AI) tools for data collection, data analysis, or interpretation of the results. AI-assisted tools were not used during the preparation of this manuscript.

Conflicts of Interest

The authors declare that there are no potential conflicts of interest.

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Особистісні фактори арбітрів у футболі, що впливають на формування стилів суддівства

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 9 с., 3 табл., 5 рис., 33 джерела.

Мета дослідження – визначити психологічні властивості особистості футбольних арбітрів, що впливають на формування у них стилів суддівства.

Матеріал і методи. В дослідженні взяли участь 25 футбольних арбітрів професіональних ліг України (вік 25-40 років, досвід 7-17 років арбітражу). Серед них 12 арбітрів Прем'єр-ліги України, 6 арбітрів Першої ліги ПФЛ, 7 арбітрів-жінок. Методи психологічної діагностики (самооцінка стійкості до стресу, тест EPQ Айзенка, емоційний інтелект за Холл, копінг-стратегії за Амірхан).

Результати. Оцінка стійкості до стресу в жінок-арбітрів на 10,2 % переважає цей показник у чоловіків-арбітрів – 33,3 проти 36,7 балів. Вивчення особливостей копінг-стратегій футбольних арбітрів показало, що для випробуваних у цілому характерний середній рівень вирішення проблем, середній рівень пошуку соціальної підтримки та низький рівень уникнення проблем. У цілому в футбольних арбітрів низький рівень керування емоціями, низький рівень розпізнавання емоцій інших людей (медіанна оцінки показника становила 6 балів). Решта показників відповідають середньому рівню. 52,0 % випробуваних характеризуються низьким, а решта 48,0 % – середнім рівнем емоційного інтелекту.

Висновки. Встановлено, що загалом футбольні арбітри демонструють середній рівень стійкості до стресу, проте ця особливість статистично значуще не впливає на вибір стилю суддівства футбольних арбітрів. Статистично значущі ($p<0,050$) кореляції між копінг-стратегіями поведінки арбітрів і їх стилями суддівства вказують на те, що копінг-стратегії, які використовують футбольні арбітри для подолання стресу та вирішення проблем, мають прямий вплив на їхній стиль суддівства. Зокрема, арбітри, які схильні до активного вирішення проблем і пошуку ефективних рішень, частіше демонструють авторитарний стиль суддівства. Водночас, арбітри, які схильні до уникнення проблем, частіше демонструють ліберальний стиль суддівства. Статистичного зв'язку між демократичним стилем та копінг-стратегіями не виявлено.

Ключові слова: типи темпераменту, стресостійкість, копінг-стратегії, емоційний інтелект, авторитарний стиль суддівства, демократичний стиль суддівства, ліберальний стиль суддівства, футбольні арбітри.

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Original Scientific Article

High-Intensity Interval Training Outperforms Fartlek and Continuous Training in Aerobic and Running-Mechanics Adaptations: Evidence from Athletics Education

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Abstract

Background. Aerobic capacity and biomechanical efficiency are central determinants of performance in athletics. However, empirical evidence directly comparing different training modalities using an integrative assessment of physiological, biomechanical, and cardiovascular recovery variables remains limited, particularly within structured athletics training environments.

Objectives. This study aimed to compare the effectiveness of Fartlek, High Intensity Interval Training (HIIT), and Moderate Continuous Training (MCT) on aerobic capacity, running efficiency, and cardiovascular recovery in sports science students enrolled in athletics courses, thereby providing novel insight into evidence-based conditioning strategies relevant to athletics training.

Materials and Methods. A total of 102 sports science students taking athletics coursework were randomly assigned to HIIT ($n = 34$), Fartlek ($n = 34$), or MCT ($n = 34$). The eight-week intervention consisted of three weekly sessions. Measured outcomes included VO_2max, vVO_2max, running economy, stride mechanics, and heart rate recovery (HRR1–HRR3). Data were analyzed using paired t-tests, one-way ANOVA, LSD post-hoc tests, and effect size calculations (Cohen's d; partial η^2).

Results. All training models produced significant improvements across all parameters ($p < 0.001$). HIIT yielded the most substantial gains in VO_2max, vVO_2max, running economy, stride length, ground contact time, and HRR indices. ANOVA revealed significant between-group differences on all primary variables ($p < 0.001$; $\eta^2 = 0.27–0.47$), indicating the superior adaptive response of HIIT compared with Fartlek and MCT in the athletics training context.

Conclusions. The findings confirm that HIIT showed the greatest enhancements in aerobic capacity, mechanical running efficiency, and cardiovascular recovery among the training methods examined in this cohort of sports science students. Its superiority stems from structured high-intensity stimuli that maximize cardiovascular stress, mitochondrial adaptation, lactate tolerance, and neuromuscular recruitment. Further research should investigate responses in competitive athletes, extend intervention duration, and incorporate advanced metabolic and neuromuscular analyses to deepen understanding of HIIT-driven adaptations in athletics.

Keywords: fartlek training, high intensity interval training (HIIT), athletics training, aerobic capacity, running economy, stride mechanics, cardiovascular recovery, VO_2max.

Introduction

The aerobic capacity represented by maximal oxygen uptake (VO_2max) constitutes a central physiological determinant within athletics because it reflects the integrated function of the cardiovascular, respiratory, and skeletal muscle systems in supporting maximal oxidative energy production (Idnani et al., 2025; Kamarudin et al., 2024a). VO_2max not only denotes an athlete's fundamental work capacity but also shapes key performance-related variables such as running economy, maximal aerobic velocity (vVO_2max), lactate threshold tolerance, and inter-interval recovery efficiency

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(Perdana et al., 2025; Sopyan et al., 2023). Accordingly, strength and conditioning (S&C) practitioners routinely employ VO_2max as a primary indicator for designing training programs that integrate endurance, speed, and biomechanical efficiency components (Fahmi Hidayat et al., 2025; Kamarudin et al., 2024).

Multiple aerobic training modalities have been examined across the literature and applied in athletic preparation, yet their adaptive responses show considerable variability (Z. Wang & Wang, 2024). For instance, (Satria et al., 2024) reported that both Fartlek and high-intensity interval training (HIIT) enhanced VO_2max in futsal players; however, the findings were derived from non-athletics populations and excluded biomechanical assessments or running economy metrics that are directly relevant to track performance. Similar results were documented by (Bermeo Guamán et al., 2023), who compared Fartlek with continuous running in recreational runners and found greater and faster improvements in VO_2max in the Fartlek group. Nevertheless, the absence of performance-specific measures such as race-pace velocity or stride efficiency limits the extent to which these findings can be translated to competitive athletics contexts (Bermeo Guamán et al., 2023).

Research by (Karthikeyan, 2025) on adolescent athletes likewise demonstrated VO_2max improvements following both Fartlek and continuous training, with Fartlek producing superior gains. This study was constrained by a small sample size and the lack of advanced performance indicators such as vVO_2max or competitive running speed. Similarly, (Festiawan et al., 2020) reported that Fartlek elicited higher VO_2max responses compared with interval training among football players, although differences did not reach statistical significance. Because the cohorts in these studies were not composed of trained runners and lacked analyses of recovery or movement economy, their applicability to athletics performance remains limited.

In long-distance running populations, (Susiono et al., 2025) observed that sprint interval training improved VO_2max and race performance such as 3,000-m time and time to exhaustion relative to conventional endurance training. However, the interpretability of these results is narrowed by (Tegegne Nigussie, 2024) the short intervention period (six weeks), small sample size, and absence of biomechanical or long-term recovery analyses. Another randomized trial in recreational runners reported differential responses to interval versus continuous training across running economy (RE), maximal aerobic speed (MAS), and stride kinematics, although the extremely small sample size and inadequate control of training intensity warrant caution when interpreting the findings (Tegegne Nigussie, 2024). A separate investigation by (Bici & Kasa, 2025) concluded that HIIT yielded larger gains in VO_2max compared with fartlek. Even so, substantial limitations including a sample of only eight participants, lack of cardiovascular-recovery or running-economy assessments, and no evaluation of sustained aerobic adaptation constrain the generalizability of the results. Thus, although HIIT and Fartlek appears promising in elevating aerobic capacity, definitive conclusions necessitate studies with stronger designs and broader physiological assessments.

Collectively, limitations across prior research underscore a critical scientific gap, particularly within the domain of athletics training. No comparative study has systematically evaluated HIIT and Fartlek using an integrated framework that simultaneously examines cardiorespiratory responses and performance-relevant variables. Key aspects including running economy, stride pattern and quality, heart rate recovery stability, and the transfer of training adaptations to race-specific speeds remain insufficiently investigated. Moreover, many earlier studies relied on simple pre-post designs without real-time intensity monitoring, making it difficult to characterize the actual physiological stimulus elicited by each training modality.

To address these shortcomings, the present study was designed as a controlled experiment with methodological rigor that surpasses previous investigations. Beyond comparing HIIT and Fartlek based on VO_2max, the study incorporated performance-critical indicators such as vVO_2max, running economy, stride efficiency, and cardiovascular recovery. The use of precise real-time intensity monitoring, comprehensive physiological instrumentation, and direct evaluation of adaptation transfer to race-related performance renders this study more holistic and more aligned with applied S&C practice in running-based events.

Additionally, the study included a larger sample size than most comparable research, thereby enhancing statistical power, effect-size precision, and generalizability. The combination of a rigorous experimental design, broad physiological coverage, and a more representative participant sample positions this study as a substantive contribution to evidence-based training methodology within athletics. However, given that the participants were non-athlete university students, the generalizability of these findings to trained or elite populations remains limited.

The novelty of this study can be articulated across three dimensions. First, to the authors' knowledge, this is the first investigation to directly compare HIIT and Fartlek in running athletes using an integrative analytical approach spanning VO_2max, cardiorespiratory responses, and biomechanical parameters. To maintain conceptual accuracy, these findings should be interpreted within the context of physical-education students rather than competitive athletes. Second, the simultaneous assessment of physiological variables (e.g., heart rate, recovery kinetics, oxidative capacity) and biomechanical variables (e.g., stride length, stride frequency, running economy) enables a more comprehensive understanding of training adaptation mechanisms. Third, the findings provide actionable implications for S&C coaches by identifying the training method that appears more effective within this sample, particularly in jointly enhancing aerobic capacity and race-specific performance, while acknowledging that these effects are bounded by the study design and population characteristics.

The scientific urgency of this research lies in its relevance to improving training prescriptions for university-level runners, a population for whom empirical evidence remains relatively limited. Accordingly, this study formulates explicit hypotheses to guide the comparative analysis: (H1) HIIT will produce greater improvements in VO_2max than Fartlek and continuous training among non-athlete university students; (H2) HIIT will elicit more pronounced adaptations in running biomechanics including stride parameters and running economy compared with the other training modalities; and (H3) HIIT will induce more favorable cardiorespiratory responses, reflected in heart-rate kinetics and recovery patterns, relative to Fartlek and continuous training. These hypotheses are aligned with previous literature and anchored in the physiological rationale underlying each training method.

Consequently, the primary aim of the present study is to evaluate and compare the effectiveness of High-Intensity Interval Training (HIIT) and Fartlek on cardiorespiratory responses and key performance indicators. Rather than claiming absolute superiority, the present analysis seeks to identify which training method demonstrates greater effectiveness within the constraints of this specific population and experimental design, thereby generating evidence-based recommendations for S&C practitioners working with similar student cohorts.

Materials and Methods

Participants

The study population comprised all active students enrolled in the sports science program at the Vocational Faculty of Universitas Negeri Surabaya. The eligible population consisted of 414 students who fulfilled administrative requirements and represented a broad distribution across early- to late-semester cohorts, with varying levels of physical activity experience and fitness status. Based on an a priori power analysis conducted using G*Power 3.1 with a moderate effect size ($f = 0.25$), $\alpha = 0.05$, and a power of 0.80, the minimum required sample size was determined to be 102 participants. The available population was subsequently aligned with this requirement, and following a systematic selection process grounded in predefined inclusion and exclusion criteria, 102 students were recruited through simple random sampling and deemed eligible for participation.

To address these gaps, the present study implemented a structured comparative intervention with a sufficiently powered sample of sports science students. Given that the participants were non-athlete university students, all interpretations regarding training effectiveness are confined to similar populations and cannot be generalized to trained or elite athletes. The study sought not to claim absolute superiority of any model but rather to determine which modality demonstrates greater effectiveness within the scope of this population and research design.

The novelty of this investigation rests on three dimensions: (1) the direct comparison of HIIT, Fartlek, and continuous training using integrative physiological and biomechanical metrics, including VO_2max, heart-rate kinetics, stride parameters, and running economy; (2) the simultaneous analysis of cardiorespiratory and mechanical adaptations, enabling a more comprehensive interpretation of training-induced changes; and (3) the practical relevance of identifying the training model that produces the most meaningful improvements in a collegiate setting, providing evidence-based guidance for instructors and S&C practitioners.

Inclusion criteria consisted of being an active student aged 18–20 years, currently taking or having previously completed the Athletics course, being in good physical health, and not participating in any concurrent high-intensity training program that could confound physiological responses. Exclusion criteria encompassed sustaining an injury during the study period, attending fewer than 80% of the intervention sessions, the use of medications influencing physiological parameters, or any medical condition that could interfere with study procedures or compromise participant safety.

Study Design

This study employed an inferential experimental design using a randomized controlled trial (RCT) approach. A total of 102 participants were randomly allocated into three groups: the Fartlek group (n = 34), the High-Intensity Interval Training (HIIT) group (n = 34), and the Moderate Continuous Training (MCT) group, which served as the control condition (n = 34).

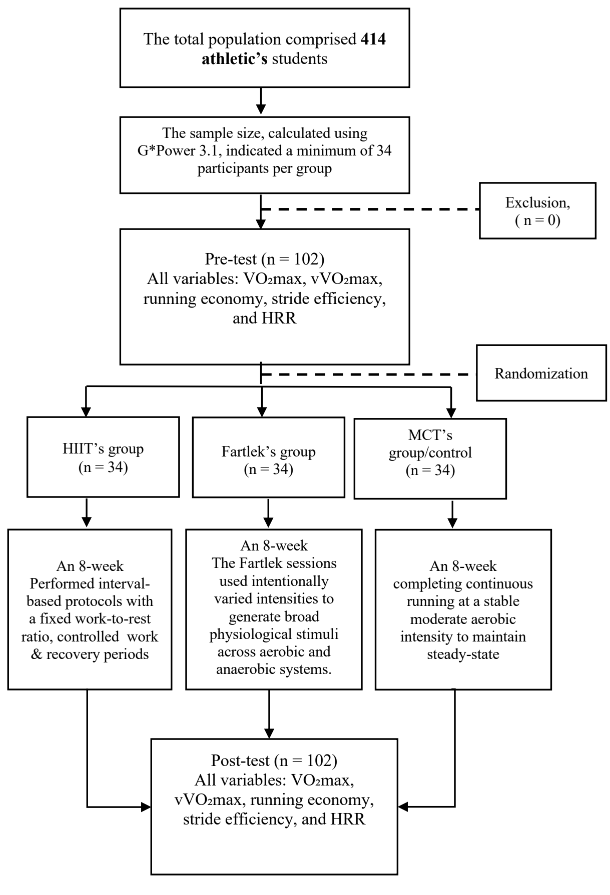

Fig. 1. Flowchart of the study

Research Procedures

The training intervention was administered over an eight-week period, with each session lasting 30–40 minutes. Each training modality featured a distinct intensity structure and session pattern designed to target improvements in aerobic capacity and mechanical running efficiency. Prior to the intervention, all participants completed a standardized pre-test assessment, and following six weeks of training, post-test evaluations were conducted using identical protocols to

Table 1. Summary of the Three-Intervention Groups Training Program

Group	Training Structure	Intensity	Session Duration	Weekly Frequency	Key Characteristics
Fartlek	Warm-up 10 minutes; Speed Play with a variety of sprints, mediums, short sprints, and recovery jogs; 10-minute cooldown	Varies 60–95% HRmax	50 minutes	3x/week	Random variations in rhythm and intensity to trigger aerobic and anaerobic adaptations
High Intensity Interval Training (HIIT)	1:1 interval training between the work phase and active rest	Working: 85–95% HRmax; Rest: 60–65% HRmax	50 minutes	3x/week	Focus on intense stimuli to increase VO2max and anaerobic capacity
MCT (Control)	Stable continuous road	65–75% HRmax	50 minutes	3x/week	Moderate aerobic exercise for basic cardiorespiratory capacity improvement

ensure comparability of physiological and biomechanical outcomes.

Each training session was structured according to the specific characteristics of the assigned modality. The Fartlek sessions employed a deliberately unstructured fluctuation of intensities to elicit broad and variable physiological stimuli across aerobic and anaerobic domains. The HIIT group performed interval-based protocols with a fixed work-to-rest ratio, ensuring consistent exposure to high-intensity bouts followed by controlled recovery periods. In contrast, the MCT group served as a comparative control, completing continuous running at a stable moderate aerobic intensity to maintain steady-state physiological loading.

Instruments

Maximal oxygen uptake (VO_2max) was assessed using the 20 m Shuttle Run Test (Beep Test), which provides an established field-based estimation of aerobic capacity based on the final level attained. Maximal aerobic velocity (vVO_2max) was measured through a progressive running test on a standard 400 m track, in which speed was increased every two minutes until participants were unable to maintain the prescribed pace. Running economy (RE) was evaluated by determining oxygen consumption during steady-state submaximal running (10–12 $km \cdot h^{-1}$) over a six-minute bout, with VO_2 values analyzed during minutes four through six to ensure metabolic stabilization. Stride efficiency was quantified using high-speed video capture or biomechanical sensors over a 30 m runway, enabling the extraction of stride length, stride frequency, and ground contact time (GCT). Heart rate recovery (HRR) was recorded following a three-minute high-intensity running bout at 85–90% of HRmax, during which HRpeak and recovery values at one, two, and three minutes post-exercise (HRR1, HRR2, HRR3) were obtained.

Ethical Clearance

This study was conducted in accordance with institutional and international ethical standards. Ethical approval was obtained from the Research Ethics Committee of Universitas 'Aisyiyah Surakarta (AISKA) under approval number KEP/UNI-AISKA/199/2025/010225, following initial endorsement by the Ethics Committee of the Faculty of Sport Sciences. All participants provided written informed consent after receiving a full explanation of the study objectives, procedures, potential benefits, and associated risks.

Data Analysis

All pre-test and post-test data were analyzed using IBM SPSS Statistics. Preliminary analyses included assessment of parametric assumptions through the Shapiro–Wilk test for normality and Levene's test for homogeneity of variance across groups. Within-group intervention effects for the Fartlek, High-Intensity Interval Training (HIIT), and MCT groups were examined using paired-samples t-tests to determine significant changes in VO_2max, vVO_2max, running economy, stride efficiency, and heart rate recovery (HRR). Between-group comparisons were conducted using independent-samples t-tests, while differences across the three training modalities were evaluated using one-way ANOVA on change scores (Δ). When ANOVA indicated significant effects ($p < 0.05$), Tukey's HSD post-hoc analyses were applied. To enhance practical interpretation, effect sizes were calculated using Cohen's d for t-tests and partial eta squared (η^2) for ANOVA. All results are presented as mean ± standard deviation, with statistical significance set at $p < 0.05$.

Result

A total of 102 participants met all eligibility criteria and were randomly allocated into the three intervention groups: Fartlek (n = 34), HIIT (n = 34), and Moderate Continuous Training (MCT) as the control group (n = 34). All participants completed the six-week intervention with full adherence and no dropout, allowing the analyses to be performed using a complete-case approach.

A total of 102 male sports science students aged 19–21 years were enrolled and randomly allocated into three training groups, each comprising 34 participants. Baseline

Table 2. Characteristics of Study Participants

Variable	HIIT Group (n = 34)	Fartlek Group (n = 34)	MCT Group (n = 34)
Gender	34 male	34 male	34 male
Age (years)	20.1 ± 0.6	20.0 ± 0.7	20.2 ± 0.5
BMI (kg/m²)	22.4 ± 1.8	22.1 ± 1.9	22.3 ± 1.7

characteristics were relatively homogeneous across groups, with an average age of approximately 20 years, body mass index within the ideal range, and physical activity levels classified as active (moderate to vigorous). This homogeneity strengthens the internal validity of the study by ensuring that observed differences in outcomes primarily reflect the effects of the respective training interventions.

Table 3. Participant Characteristics at Baseline

Variable	Fartlek (n = 34)	HIIT (n = 34)	MCT (n = 34)	p
Age (years)	20.6 ± 1.4	20.4 ± 1.5	20.5 ± 1.3	0.812
Body Mass Index (BMI; kg/m²)	22.1 ± 1.8	22.4 ± 2.1	22.0 ± 1.9	0.673
HRmax (bpm)	193.4 ± 6.1	194.1 ± 5.8	193.7 ± 6.3	0.889
Physical Readiness Questionnaire (PR-Q)	91.2 ± 4.8	92.0 ± 5.1	91.6 ± 4.6	0.742

All baseline variables showed $p > 0.05$, which means there was no significant difference between groups. Thus, all subjects were declared homogeneous before the intervention, in accordance with the principles of experimental research design and RCTs.

The results of the paired t-test showed that all three types of fartleek, HIIT, and MCT exercises resulted in significant improvements in the majority of physiological and biomechanical variables. Fartlek and HIIT resulted in the largest increases in VO_2max, vVO_2max, stride length, stride frequency, decreased running economy, and ground contact time, with both showing stronger changes than MCTs. Meanwhile, MCTs also showed significant improvements, but with smaller effects, and one of the variables (stride frequency) was not significant. In addition, the entire group showed significant improvements in cardiovascular recovery capacity (HRR1, HRR2, HRR3), with fartlek and HIIT again providing a greater adaptive response. Overall, fartlek and HIIT show higher effectiveness than MCTs in improving performance parameters and running efficiency.

Post-hoc LSD comparisons revealed distinct adaptive responses across the three training modalities. For VO_2max, HIIT demonstrated a small but statistically significant advantage over Fartlek ($\Delta = +0.80$, $p = 0.041$), while both HIIT and Fartlek produced markedly greater improvements than MCT ($\Delta = +3.35$ and $+4.15$, respectively; $p < 0.001$), indicating that interval-based training elicited superior aerobic gains relative to continuous moderate exercise.

Table 4. Within-Group Effects (Paired Sample t-Test) for Fartlek, HIIT, and MCT Groups

Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	t-value	p-value
VO_2max (ml·kg^{-1}·min^{-1})	Fartlek	38.55 ± 3.20	43.20 ± 3.30	11.42	<0.001
	HIIT	38.60 ± 3.15	44.10 ± 3.28	13.92	<0.001
	MCT	38.10 ± 3.05	39.85 ± 3.20	5.44	<0.001
vVO_2max (km/h)	Fartlek	11.3 ± 1.1	13.0 ± 1.2	9.58	<0.001
	HIIT	11.4 ± 1.3	13.3 ± 1.2	11.01	<0.001
	MCT	11.2 ± 1.1	11.9 ± 1.2	4.88	<0.001
Running Economy (VO_2 ml/kg/min)	Fartlek	36.2 ± 2.7	34.1 ± 2.5	−6.44	<0.001
	HIIT	36.0 ± 2.9	34.0 ± 2.6	−7.44	<0.001
	MCT	36.1 ± 2.8	35.3 ± 2.7	−3.12	0.004
Stride Length (m)	Fartlek	1.22 ± 0.11	1.30 ± 0.12	7.01	<0.001
	HIIT	1.20 ± 0.10	1.29 ± 0.11	8.02	<0.001
	MCT	1.21 ± 0.10	1.24 ± 0.11	3.40	0.002
Stride Frequency (steps/min)	Fartlek	169.1 ± 7.8	173.4 ± 7.5	5.45	<0.001
	HIIT	168.2 ± 8.4	173.5 ± 8.0	6.77	<0.001
	MCT	168.0 ± 8.0	169.5 ± 7.8	2.02	0.051 (ns)
Ground Contact Time (ms)	Fartlek	249.2 ± 17.5	234.0 ± 16.9	−8.12	<0.001
	HIIT	247.8 ± 18.2	233.5 ± 17.8	−9.35	<0.001
	MCT	248.0 ± 18.6	243.2 ± 18.0	−3.55	0.001
HRR1 (bpm)	Fartlek	21.4 ± 4.6	28.2 ± 4.7	9.88	<0.001
	HIIT	21.1 ± 4.5	28.5 ± 4.9	11.55	<0.001
	MCT	21.2 ± 4.7	23.5 ± 4.9	3.88	<0.001
HRR2 (bpm)	Fartlek	34.8 ± 5.0	41.8 ± 4.9	10.01	<0.001
	HIIT	34.5 ± 5.2	42.0 ± 4.8	11.21	<0.001
	MCT	34.7 ± 5.1	37.8 ± 5.0	4.02	<0.001
HRR3 (bpm)	Fartlek	42.0 ± 5.1	49.1 ± 5.2	9.77	<0.001
	HIIT	42.3 ± 5.4	49.5 ± 5.1	10.68	<0.001
	MCT	42.0 ± 5.3	45.2 ± 5.1	3.91	<0.001

Table 5. LSD Post-Hoc Comparison Between Groups Based

Variable	Group Comparison	Mean Difference (Δ)	95% CI	p-value (LSD)
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	HIIT vs Fartlek	+0.80	0.02 to 1.58	0.041
	Fartlek vs MCT	+4.15	3.10 to 5.20	<0.001
	HIIT vs MCT	+3.35	2.30 to 4.40	<0.001
vVO_2max ($km \cdot h^{-1}$)	HIIT vs Fartlek	+0.30	0.01 to 0.59	0.049
	Fartlek vs MCT	+1.10	0.70 to 1.50	<0.001
	HIIT vs MCT	+0.80	0.40 to 1.20	<0.001
Running Economy (↓ better)	HIIT vs Fartlek	−0.30	−0.63 to 0.03	0.062
	Fartlek vs MCT	−2.10	−2.80 to −1.40	<0.001
	HIIT vs MCT	−1.80	−2.50 to −1.10	<0.001
Stride Length (m)	HIIT vs Fartlek	+0.03	0.00 to 0.06	0.038
	Fartlek vs MCT	+0.07	0.04 to 0.10	<0.001
	HIIT vs MCT	+0.04	0.02 to 0.06	<0.001
Stride Frequency ($steps \cdot min^{-1}$)	HIIT vs Fartlek	+0.60	−0.05 to 1.25	0.071
	Fartlek vs MCT	+3.20	1.50 to 4.90	0.001
	HIIT vs MCT	+2.60	1.00 to 4.20	0.003
Ground Contact Time (ms; ↓better)	HIIT vs Fartlek	−1.90	−3.85 to 0.05	0.051
	Fartlek vs MCT	−9.10	−11.50 to −6.70	<0.001
	HIIT vs MCT	−7.20	−9.30 to −5.10	<0.001
HRR1 (bpm)	HIIT vs Fartlek	+0.50	−0.03 to 1.03	0.062
	Fartlek vs MCT	+3.90	2.60 to 5.20	<0.001
	HIIT vs MCT	+3.40	2.20 to 4.60	<0.001
HRR2 (bpm)	HIIT vs Fartlek	+0.20	−0.02 to 0.42	0.081
	Fartlek vs MCT	+3.50	2.30 to 4.70	<0.001
	HIIT vs MCT	+3.30	2.10 to 4.50	<0.001
HRR3 (bpm)	HIIT vs Fartlek	0.00	−0.42 to 0.42	0.998
	Fartlek vs MCT	+3.80	2.60 to 5.00	<0.001
	HIIT vs MCT	+3.80	2.60 to 5.00	<0.001

Table 6. One-Way ANOVA on Change Scores (Δ) Between Groups (Fartlek, High Intensity Interval Training (HIIT), MCT)

Variable	Between-three groups	df	MS	F	p-value	Partial η^2
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	214.2	2	107.10	45.6	<0.001	0.47
vVO_2max ($km \cdot h^{-1}$)	18.7	2	9.35	31.2	<0.001	0.38
Running Economy (VO_2 $ml \cdot kg^{-1} \cdot min^{-1}$; ↓better)	67.4	2	33.70	24.8	<0.001	0.35
Stride Length (m)	0.032	2	0.016	18.1	<0.001	0.27
Stride Frequency ($steps \cdot min^{-1}$)	245.6	2	122.8	6.2	0.003	0.11
Ground Contact Time (ms; ↓better)	8311.0	2	4155.5	39.4	<0.001	0.44
HRR1 (bpm)	329.4	2	164.7	32.7	<0.001	0.39
HRR2 (bpm)	446.1	2	223.0	34.9	<0.001	0.40
HRR3 (bpm)	386.8	2	193.4	28.5	<0.001	0.36

A similar pattern was observed for vVO_2max, where HIIT outperformed Fartlek with a modest yet significant difference (Δ = +0.30, p = 0.049), and both high-intensity modalities produced substantially higher improvements than MCT.

For running economy, although the difference between HIIT and Fartlek did not reach statistical significance (p = 0.062), both groups outperformed MCT with large effect magnitudes, reflected by lower oxygen cost at submaximal speeds. Stride length showed a significant advantage for HIIT over Fartlek (Δ = +0.03, p = 0.038), while both HIIT and Fartlek yielded greater stride length improvements than MCT. In terms of stride frequency, differences between HIIT and Fartlek were not statistically significant (p = 0.071), yet both modalities demonstrated superior adaptations compared with MCT ($p \leq 0.003$).

Ground contact time (GCT) improved more prominently in both HIIT and Fartlek compared with MCT ($p < 0.001$), with the HIIT–Fartlek comparison approaching but not reaching significance (p = 0.051), suggesting comparable efficiency gains in lower-limb elastic utilization. For HRR1–HRR3, the differences between HIIT and Fartlek were non-significant across all indices (p = 0.062–0.998). Nevertheless, both HIIT and Fartlek displayed significantly greater parasympathetic reactivation following exercise when compared to MCT ($p < 0.001$), illustrating the clear superiority of high-intensity methods in enhancing autonomic recovery.

Taken together, the post-hoc findings indicate that HIIT and Fartlek consistently induce greater physiological and biomechanical adaptations than moderate continuous training. Although the two high-intensity modalities share many overlapping benefits, HIIT demonstrates a slight edge over Fartlek in several key performance indicators, particularly VO_2max, vVO_2max, and stride length, underscoring its efficacy as a potent stimulus for aerobic and neuromuscular enhancement.

The results of the one-way ANOVA test of nine performance variables showed significant differences between the three exercise groups ($p < 0.001$ for most variables). Consistently, the HIIT group showed the greatest improvement in physiological and biomechanical performance compared to the other two groups.

On the VO_2max variable, the HIIT group recorded the highest increase with very strong effects ($F = 45.6$, $p < 0.001$, partial $\eta^2 = 0.47$), suggesting that the HIIT intervention provided a much greater cardiorespiratory adaptation than the other two groups. A similar pattern was seen in vVO_2max ($F = 31.2$, $p < 0.001$, $\eta^2 = 0.38$), reinforcing that HIIT resulted in a superior increase in maximum aerobic speed capacity.

In terms of running economy, the HIIT group showed the most efficient reduction in VO_2 ($F = 24.8$, $p < 0.001$, $\eta^2 = 0.35$), which indicates more economical energy use at a given speed. Biomechanical components that support performance such as stride length ($F = 18.1$, $p < 0.001$, $\eta^2 = 0.27$) also increased the most in the HIIT group, while stride frequency also showed HIIT superiority even with moderate effects ($F = 6.2$, $p = 0.003$, $\eta^2 = 0.11$).

In the neuromuscular variables related to running efficiency, the HIIT group showed the greatest decrease in ground contact time ($F = 39.4$, $p < 0.001$, $\eta^2 = 0.44$), indicating better elasticity and mechanical efficiency than the other groups.

In addition, cardiovascular recovery ability measured through HRR1, HRR2, and HRR3 also showed that the HIIT group had the best acceleration of heart rate recovery (HRR1: $F = 32.7$, $p < 0.001$, $\eta^2 = 0.39$; HRR2: $F = 34.9$, $p < 0.001$, $\eta^2 = 0.40$; HRR3: $F = 28.5$, $p < 0.001$, $\eta^2 = 0.36$).

Overall, the pattern of findings across all variables suggests that the HIIT group produces the most comprehensive physiological, biomechanical, and cardiovascular adaptations, with large to very large effect size values on most key parameters. These findings suggest that HIIT demonstrates greater effectiveness relative to the other training modalities examined in this study in improving aerobic performance, running efficiency, and recovery ability.

Discussion

The findings of this study demonstrate that all three training modalities Fartlek, High-Intensity Interval Training (HIIT), and Moderate Continuous Training (MCT) produced significant improvements in physiological and biomechanical variables following eight weeks of intervention. However, HIIT consistently yielded the greatest magnitude of adaptation within the present sample, indicating a higher effectiveness for enhancing aerobic and biomechanical performance in this educational context. Physiologically, the marked improvement in VO_2max observed in the HIIT group reflects enhanced cardiovascular and respiratory capacity through increases in stroke volume, cardiac output, and skeletal muscle capillarization, coherent with established mechanisms of high-intensity exertion (Sopyan et al., 2023). The superior gains in vVO_2max also indicate improved metabolic efficiency and lactate tolerance, hallmarks of interval-based training that demands robust neuromuscular coordination. These improvements align with core mechanisms of interval training, particularly the repeated exposure to high-intensity bouts that generate substantial metabolic stress, stimulate mitochondrial biogenesis, and recruit both type I and type II fibers, thereby producing a broader adaptive signal than MCT or Fartlek (Atakan, Li, et al., 2021).

Although some previous studies have reported comparable improvements between MCT and HIIT, such as the original research conducted in runners populations by (Z. Wang & Wang, 2024), these findings are limited by heterogeneous protocols and small sample sizes. The present study addressed these limitations by employing a larger sample ($n = 102$) of healthy young adults and incorporating more comprehensive physiological and biomechanical assessments. As a result, the current findings offer stronger evidence that HIIT provides the most potent physiological stimulus within populations that are highly responsive to high-intensity workloads (Tian et al., 2023).

From a biomechanical perspective, the HIIT group exhibited the greatest enhancements. High-intensity accelerations likely facilitated enhanced motor-unit synchronization and improved elastic energy utilization. These adaptations reflect improved mechanical efficiency and neuromuscular performance elicited by repeated exposure to high-intensity accelerations (Gao et al., 2024; Preece et al., 2019). The reduction in ground contact time in the HIIT group indicates more efficient force application, consistent with research showing that shorter contact times are associated with reduced submaximal oxygen consumption. The reduction in ground contact time is particularly meaningful, as shorter contact reflects greater leg stiffness, faster force transmission, and reduced submaximal oxygen cost, all of which translate into more economical running patterns (Dolci et al., 2021; Penichet-Tomas, 2024). Such biomechanical optimization provides an additional performance advantage for HIIT beyond its physiological benefits (Gao et al., 2024; Jin et al., 2025).

Running economy improved across all groups but was most pronounced in the HIIT condition. The reduction in submaximal VO_2 during steady-state running indicates enhanced metabolic efficiency, aligning with evidence that high-intensity interval exposure induces superior energy utilization strategies and neuromuscular economy. Repeated recruitment of high-threshold motor units during HIIT likely increased oxidative capacity within type II fibers traditionally more glycolytic which improves energy turnover efficiency at lower intensities, explaining the superior running economy adaptations compared with Fartlek and MCT (Feng et al., 2025; Olaya-Cuartero, Lopez-Arbues, et al., 2024). Compared with Fartlek and MCT, the structured intensity profile of HIIT delivers stronger metabolic adaptation due to the repeated recruitment of large motor units and high oxidative demand (Tsai et al., 2021).

Cardiovascular recovery (HRR1–HRR3) improved in all groups; however, HIIT produced the largest enhancements, indicating faster parasympathetic reactivation following exertion. The accelerated heart-rate recovery indicates faster parasympathetic reactivation and reduced sympathetic persistence, suggesting more efficient autonomic regulation following high-intensity exertion (L. Wang et al., 2021). This accelerated recovery reflects improved autonomic balance and vagal responsiveness, which are critical for repeated high-intensity efforts (Wu et al., 2021). Enhanced HRR is especially relevant in athletic contexts, as it supports superior tolerance to successive training sessions and reduces accumulated fatigue (Zhao & Sim, 2023). The absolute changes and effect size estimates revealed that HIIT consistently produced the greatest adaptations. Although it is recognized that interval and continuous training may yield comparable benefits when matched for energy expenditure (Zanini et al., 2025), the metabolic oscillation and sympathetic parasympathetic cycling inherent to HIIT deliver an autonomic stimulus that continuous training does not replicate. The structured high-intensity demands of HIIT provide an additional stimulus that is not replicated by unstructured variability or continuous moderate intensity (W. Wang et al., 2025).

Large effect sizes were observed for key variables such as VO_2max ($\eta^2 = 0.47$), ground contact time ($\eta^2 = 0.44$), and HRR2 ($\eta^2 = 0.40$), indicating that the physiological and biomechanical adaptations were not only statistically significant but also practically meaningful. These outcomes strengthen the conclusion that HIIT elicits the most substantial training effects within a comparable intervention duration (Möhler et al., 2021). Such efficiency is particularly relevant for practitioners and athletes who require rapid adaptation within constrained training timeframes (Litleskare et al., 2020).

Although both MCT and Fartlek contributed to measurable improvements (Prasanna & Vaithianathan, 2019), their effect sizes tended to be moderate or small relative to HIIT (Arsadi et al., 2025a). Continuous training remains valuable for foundational endurance development, yet its lower metabolic stress and predominantly type I fiber recruitment produce slower adaptive rates (Engelbrecht et al., 2024). In contrast, HIIT training offers a more efficient and time-effective approach for achieving substantial improvements in aerobic and mechanical performance (Kelemen et al., 2023).

The superiority of HIIT can be attributed to its unique physiological mechanisms, which combine intensive aerobic and anaerobic stimulation (Feng et al., 2025). Increases in VO_2max and vVO_2max in the HIIT group reflect improved oxygen transport, mitochondrial efficiency, and elevated lactate threshold, consistent with the adaptive profile of high-intensity workloads (Xie et al., 2024). Concurrent activation of type I and type II muscle fibers during HIIT supports stronger neuromuscular adaptation, enhancing mechanical and metabolic efficiency (Costache et al., 2024). The present findings are aligned with literature demonstrating accelerated aerobic and mechanical gains from high-intensity interval training in young adults (Ai et al., 2021). Variability in previous studies largely reflects differences in participant characteristics, intervention duration, and measurement protocols. By incorporating a comprehensive set of physiological and biomechanical assessments, the present study offers a more holistic representation of training adaptations.

Some studies report minimal differences between HIIT and continuous training when interventions are brief or matched strictly by volume (Atakan, Güzel, et al., 2021). However, these studies often neglect biomechanical metrics and recovery indices. The current findings bridge this gap by including stride length, ground contact time, and HRR, providing a more complete understanding of training-induced adaptations.

Biomechanical improvements such as greater stride length and reduced contact time in the HIIT group suggest that this protocol not only enhances aerobic capacity but also optimizes mechanical running efficiency (Olaya-Cuartero, Pueo, et al., 2024). Although Fartlek produced notable improvements (Arsadi et al., 2025), the structured nature of HIIT resulted in more targeted neuromuscular adaptation (Cáceres-Diego et al., 2025). This supports theoretical models proposing that structured high-intensity intervals are superior to unstructured variable-intensity running for improving mechanical efficiency (Shingala & Shukla, 2024).

Stride frequency improved moderately in both HIIT and Fartlek, with minimal changes in MCT. The balance between stride frequency and stride length is essential for optimal running performance. Improvements in stride frequency across HIIT and Fartlek further demonstrate refined motor control and rhythm regulation, which are essential for efficient running mechanics (Llanos-Lagos et al., 2024). These findings further reinforce the superiority of HIIT in integrating neuromuscular and technical adaptations (Strepp et al., 2024). Running economy improved most significantly in the HIIT group. The superior running economy observed in the HIIT group is consistent with evidence that interval training enhances intermuscular coordination, reduces co-contraction, and improves energy-conserving movement patterns, contributing to a lower oxygen cost during submaximal effort (Dolci et al., 2021; Feng et al., 2025). Prior studies highlight that high-intensity intervals promote enhanced motor efficiency and energy conservation (Zanini et al., 2025), aligning with the robust improvements observed in this study.

The faster parasympathetic recovery demonstrated by HRR1 to HRR3 in the HIIT group suggests superior autonomic regulation, linked to enhanced vagal reactivation and reduced sympathetic drive. Additionally, greater parasympathetic rebound and reduced sympathetic strain following HIIT likely contribute to better overall load management and reduced neuromuscular fatigue (Moro et al., 2020). This adaptation is critical for maintaining performance capacity and reducing fatigue during successive high-intensity sessions (D'Alleva et al., 2023). Although external variables such as nutrition, sleep, and unmonitored physical activity were difficult to control despite standardized instructions, the randomized controlled design and comprehensive measurements enhanced the robustness of these findings. The sample was limited to healthy young adults, and caution is warranted when generalizing findings to older or elite populations.

Overall, the results clearly indicate that HIIT showed the most pronounced improvements in physiological and biomechanical performance among the training protocols examined in this cohort of young adult students. Its combination of high metabolic stress, broad motor-unit recruitment, enhanced mitochondrial and neuromuscular adaptation, and superior autonomic recovery explains its superiority over Fartlek and MCT. Variability in previous studies is largely explained by differences in sample and protocol characteristics, whereas the present findings provide coherent and comprehensive evidence of HIIT's superiority. Collectively, the study highlights the importance of integrating physiological and biomechanical adaptations within high-intensity training (Gao et al., 2024; L. Wang et al., 2021; Z. Wang & Wang, 2024). HIIT not only enhances aerobic capacity but also optimizes stride mechanics and ground contact variables, producing highly efficient running patterns (Dolci et al., 2021; Gao et al., 2024a). These findings provide practical implications for coaches and practitioners to design time-efficient, high-impact training programs.

Future research should explore the effects of HIIT in competitive athletes, youth populations, and individuals with metabolic conditions. Further studies integrating physiological, biomechanical, and psychological markers such as lactate tolerance, neuromuscular activation, and mental fatigue are warranted. Investigations into optimal interval structures could also refine HIIT protocols for maximizing performance while minimizing injury risk.

Conclusion

The present study provides clear evidence that Fartlek, High-Intensity Interval Training (HIIT), and Moderate Continuous Training (MCT) all contribute to measurable improvements in aerobic performance, running mechanics, and cardiovascular recovery in young adult learners. Among these modalities, HIIT produced the most substantial and multidimensional adaptations, particularly in VO_2max, vVO_2max, stride mechanics, running economy, and HRR indices. These outcomes highlight the potent physiological and neuromuscular stimulus generated by structured high-intensity interval workloads.

From an educational and practical standpoint, the findings emphasize that HIIT represents a highly time-efficient and impactful training option for physical education settings. The structured intervals, clear intensity targets, and strong physiological returns make HIIT suitable for course-based conditioning programs, especially when instructional time is limited. Educators and coaches may use these results to design evidence-based training prescriptions that enhance both fitness and technical running proficiency among students.

Despite its strengths, this study is subject to several limitations. External factors such as sleep, nutritional intake, and unmonitored physical activity could not be fully standardized, potentially influencing training responses. The sample healthy, physically active young adults also limits generalizability to elite athletes, youth, or older populations. Additionally, the study did not include advanced physiological markers such as lactate thresholds, muscle activation patterns, or hormonal responses, which may offer deeper mechanistic insights. Future investigations should expand to diverse populations and athletic levels, incorporate longer intervention durations, and integrate more advanced physiological and biomechanical assessments. Comparisons of different HIIT structures (e.g., work-to-rest ratios, interval duration, and intensity progression) and dose–response analyses will be critical for optimizing training strategies in both educational and sport performance contexts.

Data Availability Statement

The data supporting the findings of this study are not publicly available due to ethical restrictions related to participant privacy and confidentiality. Anonymized or aggregated datasets may be made available by the corresponding author upon reasonable request and subject to institutional and ethical approval.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Transparency Statement

The authors declare that no generative artificial intelligence (AI) tools were used in the collection, analysis, or interpretation of the study data. AI-assisted software (Grammarly) was employed solely for language editing and grammar refinement during manuscript preparation.

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Високоінтенсивне інтервальне тренування перевершує фартлек і метод безперервного тренування за аеробними та біомеханічними адаптаціями бігу: Дані в контексті легкоатлетичної освіти

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Реферат. Стаття: 13 с., 6 табл., 1 рис., 47 джерел.

Обґрунтування. Аеробна здатність та біомеханічна ефективність є ключовими детермінантами результативності в легкій атлетиці. Проте емпіричні дані, що безпосередньо порівнюють різні модальності тренувань за допомогою комплексної оцінки фізіологічних, біомеханічних та кардіоваскулярних показників відновлення, залишаються обмеженими, особливо в межах структурованого навчально-тренувального процесу з легкої атлетики.

Цілі. Метою цього дослідження було порівняти ефективність фартлеку, методів високоінтенсивного інтервального тренування (ВІІТ) та помірного безперервного тренування (ПБТ) щодо впливу на аеробну здатність, ефективність бігу та відновлення серцево-судинної системи у студентів спортивних спеціальностей, які відвідують курси з легкої атлетики, тим самим забезпечуючи нове розуміння доказово обґрунтованих стратегій кондиційної підготовки, актуальних для тренувального процесу в легкій атлетиці.

Матеріали та методи. Загалом 102 студенти спортивних спеціальностей, які проходили курс легкої атлетики, було розподілено за методом рандомізації на групи ВІІТ ($n = 34$), фартлеку ($n = 34$) або ПБТ ($n = 34$). Тривалість інтервенції становила 8 тижнів і складалася з трьох тренувальних сесій на тиждень. Вимірювані показники результативності включали VO_2max (максимальне споживання кисню), vVO_2max (швидкість, що відповідає VO_2max), економічність бігу, механіку кроку та відновлення серцевого ритму (HRR1–HRR3). Дані аналізували за допомогою t-критеріїв для парних вибірок, однофакторного дисперсійного аналізу, post hoc тестів найменшої значущої різниці та розрахунків величини ефекту (d Коена; часткова η^2).

Результати. Усі тренувальні моделі продемонстрували статистично значуще покращення за всіма параметрами ($p < 0.001$). Використання методу високоінтенсивного інтервального тренування забезпечило найбільш суттєвий приріст показників VO_2max, vVO_2max, економічності бігу, довжини кроку, часу контакту з поверхнею та індексів відновлення серцевого ритму. Дисперсійний аналіз виявив значущі міжгрупові відмінності за всіма основними змінними ($p < 0.001$; $\eta^2 = 0.27–0.47$), що свідчить про вищу адаптаційну відповідь організму на ВІІТ порівняно з фартлеком та помірним безперервним тренуванням у контексті легкоатлетичної підготовки.

Висновки. Результати підтверджують, що серед досліджуваних методів тренування саме ВІІТ продемонструвало найбільше покращення показників аеробної здатності, механічної ефективності бігу та відновлення серцево-судинної системи у даної когорти студентів спортивних спеціальностей. Перевага зазначеного методу зумовлена структурованими високоінтенсивними стимулами, що максимально активізують серцево-судинну систему, мітохондріальну адаптацію, лактатну толерантність та рекрутування нервово-м’язових одиниць. Подальші дослідження мають бути спрямовані на вивчення реакцій у професійних атлетів, збільшення тривалості інтервенції та впровадження поглибленого метаболічного й нервово-м’язового аналізу для кращого розуміння адаптаційних процесів, зумовлених ВІІТ у легкій атлетиці.

Ключові слова: тренування з фартлеку, високоінтенсивне інтервальне тренування (ВІІТ), тренування з легкої атлетики, аеробна здатність, економічність бігу, механіка кроку, відновлення серцево-судинної системи, VO_2max.

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Original Scientific Article

Do Warm-Up Strategies Impact the Jumping Performance of Young Female Volleyball Players?

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Abstract

Objectives. The aim of this study was to assess whether a warm-up routine incorporating plyometric exercises promotes greater improvements in jumping performance, power output, and neuromuscular responsiveness compared with warm-up strategies commonly used in volleyball practice.

Materials and Methods. Twenty-four sub-elite female volleyball players (age: 16.3 ± 0.6 years; body mass: 58.7 ± 3.8 kg; height: 165.6 ± 6.8 cm) from a regional club performed three different warm-up protocols, each lasting 20 minutes: traditional warm-up (TWU), neuromuscular warm-up (NWU), and isometric warm-up (IWU). To minimize fatigue effects, three experimental sessions were conducted with 48-hour intervals. Following each warm-up protocol, participants were randomly assessed using the Squat Jump (SJ), Countermovement Jump (CMJ), Standing Long Jump (SLJ), Squat Jump–Block Jump (SJ–BJ), Repeated Countermovement Jump (RCMJ), and Drop Jump (DJ) tests.

Results. Jump performance outcomes demonstrated significantly higher values ($p < 0.001$) following the NWU protocol. Compared with IWU, TWU resulted in higher performance values in SLJ, SJ–BJ, RCMJ, and shorter ground contact time during the DJ test.

Conclusions. Neuromuscular warm-up appears to be particularly effective in sports requiring explosive, high-speed actions, as it may directly enhance training quality and jumping performance during competition. The findings indicate that post-activation performance enhancement (PAPE) can be observed in Under-17 female volleyball players when appropriate warm-up exercises are applied. This study provides practical insights into warm-up strategies for youth volleyball clubs with limited access to resistance training equipment.

Keywords: jump, volleyball, PAPE, neuromuscular integrative exercise, plyometric.

Introduction

Recently, novel approaches and innovative training methodologies have increasingly been developed within the context of team sports (Esposito et al., 2024a; Altavilla et al., 2023; D'Elia, 2023).

Researchers and strength and conditioning coaches have progressively shifted their focus towards scheduling training sessions that reflect performance profiles across different sports (Giardullo et al., 2025; Shalom et al., 2025; Altavilla et al., 2022).

Furthermore, new methodologies have been proposed to enhance physical efficiency (Keoliya, et al., 2024; Esposito et al., 2024b; Deng et al., 2023) and improve the monitoring of training sessions (Hernandez-Martinez et al., 2023; Pawlik & Mroczek, 2022).

The warm-up represents one of the most important phases of a training session and has increasingly attracted attention from both researchers and practitioners (Keskin et al., 2025; Villalon-Gasch et al., 2022; Petisco et al., 2019).

Typically performed at the beginning of the session, the warm-up should include a variety of exercises tailored to the

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training objectives and the functional requirements of the sport (Villalon-Gasch et al., 2022; Seitz et al., 2016).

A well-designed warm-up is widely used in sport environments, as it aims to improve physical performance and reduce the injury risk prior to the main training phase (Keskin et al., 2025; Pérez-Gomez et al., 2022).

Previous studies have highlighted the benefits of appropriately designed warm-up protocols in improving performance (Papagiannis et al., 2024; Foqha et al., 2023; Andrade et al., 2015) and reducing injury risk across various sports (Althomali et al., 2025; Emery et al., 2022; Stojanović et al., 2023).

Despite, the effectiveness of injury prevention programmes has led to the widespread integration of specific warm-up protocols, particularly in team sports characterized by a high incidence of non-contact injuries (Magaña-Ramírez et al., 2024; Lopes et al., 2020).

Although the development of appropriate warm-up protocols has been shown to significantly reduce the injury risk, few studies have investigated their effects on sport-specific performance (Pérez-Gomez et al., 2022).

In light of this, the existing body of evidence supports the development of novel warm-up designs aimed at enhancing the activation of both central and peripheral mechanisms associated with performance improvement. Several authors have emphasized the performance benefits of warm-up routines that elicit Post-Activation Potentation (PAP) and Post-Activation Performance Enhancement (PAPE) across athletes from different sports (Villalon-Gasch et al., 2022; Jarosz et al., 2025; dos Santos Silva et al., 2021) and age groups (Sun et al., 2025; Isla et al., 2021).

The aforementioned neuromuscular phenomena, which are induced by high-intensity voluntary contractions, have been shown to improve players' performance. Although PAP and PAPE provide similar benefits, their underlying mechanisms differ. Notably, PAP is primarily determined by improved actin-myosin coupling, whereas PAPE is more strongly associated with increased muscle temperature and greater motor unit recruitment (Blazevich & Babault, 2019).

Most warm-up protocols have traditionally been prescribed for sports characterized by sprinting and high-intensity running; however, their applicability to sports involving repeated vertical jumping is not well documented (Althomali et al., 2025; dos Santos Silva et al., 2021).

For several decades, the traditional approach has consisted of a general cardiovascular phase lasting 10–20 minutes, followed by stretching exercises and sport-specific tasks (van den Tillar et al., 2019; Falch et al., 2021; Altavilla et al., 2023).

This general approach has been easily applied to sports characterized by different energy systems, bout durations and highly complex sport-specific skills, such as shooting, jumping, sprinting, throwing (Sannicandro et al., 2021).

Previous investigations have examined on isometric exercise within warm-up routines, given their effectiveness in recruiting a large number of motor units and promoting greater muscle fibres activation (Jarosz et al., 2025). Conversely, other studies have investigated warm-up protocols based on sport-specific technical skills performed by high-level athletes (dos Santos Silva et al., 2021).

However, volleyball presents unique performance that clearly differentiate it from other team sports; therefore, each phase of training competitive match should be carefully designed according to its specific performance demands.

A recent study has investigated the effectiveness of different warm-up protocols in volleyball players, by comparing ischemic preconditioning exercises and electromyostimulation of selected lower limb muscles on vertical jump performance (Keskin et al., 2025).

However, neither protocol elicited significant changes in vertical jump performance compared with a traditional warm-up.

Furthermore, other studies have examined the performance benefits elicited by particular warm-up protocols in international-level volleyball players (Villalon-Gasch et al., 2022), including overload-based strategies (Ah Sue et al., 2016; Sygulla & Fountaine, 2014).

In volleyball, muscle power plays a crucial role in key actions such as jumping during both offensive and defensive phases. Therefore, it is essential to identify the most effective warm-up strategy. Therefore, it is essential to identify the most effective warm-up protocol.

Further investigation related to pre-exercise activation is warranted, as improved understanding may help practitioners to optimise performance in both elite and young volleyball players.

Addressing this gap in the literature should be considered a priority for the youth population, as this may contribute to the development of evidence-based guidelines for youth volleyball practitioners.

Moreover, the findings related to PAPE in high-level athletes using free weights and maximal loads may not be transferable to younger players, given the limited availability of heavy-load equipment in youth women's volleyball settings.

Accordingly, warm-up protocols should incorporate strategies based on well-established and easily implementable tasks, considering the limited duration of the preparatory phase (approximately 20 minutes).

Based on the limited evidence currently available, the aim of the present study was to assess the effectiveness of different warm-up protocols on muscle power, vertical and horizontal jump performance in Under-17 volleyball players.

We hypothesized that a warm-up routine incorporating plyometric exercises would promote greater improvements in jumping performance, power output, and neuromuscular responsiveness compared with those commonly performed in the volleyball context.

Materials and Methods

Sample

Prior to the recruitment procedure, a sample size estimation was conducted using G*Power analysis (Düsseldorf, Germany) for a repeated-measures ANOVA design (effect size = 0.31; power = 0.90; α = 0.05). Twenty-four sub-elite female volleyball players (age: 16.3±0.6 years, 58.7±3.8 kg, 165.6±6.8 cm, training age 7.7±1.9 years) belonging to a regional club were involved in the present study. Four participants were excluded from the final sample because they did not complete all three experimental sessions.

The eligibility criteria for this study were: i) participation in at least 90% of training sessions during the month preceding the study; ii) absence of injuries or neuromuscular or musculoskeletal disorders during the same period; iii) regular participation in volleyball training, including jump-specific training, and competitive match during the four weeks prior to the study; iv) no consumption of alcoholic beverages within 72 hours prior to each experimental session; v) participation in all experimental sessions. The study was approved by the club's manager and was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained from the parents or legal guardians, and all participants provided written assent.

Experimental Design

Participants performed three different warm-up protocols, each lasting 20 minutes To minimise potential fatigue effects, three experimental sessions were conducted with 48-hour interval between sessions. All assessments and warm-up protocols were carried out during a mid-season break in the competitive season.

The traditional warm-up (TWU) consisted of an 8-minutes cardiovascular phase, followed by 4 minutes of dynamic stretching and mobility exercises, and 8 minutes of sport-specific drills.

The neuromuscular warm-up (NWU) constisted of an 8-minutes cardiovascular phase, followed by 4 minutes of dynamic stretching and mobility exercises, and 8 minutes of neuromuscular phase including 4 x 3 countermovement jumps (CMJ; 30 s recovery), 4 x 4 pogo jumps (30 s recovery) and 3 x 3 split jumps per leg (45 s recovery)

The isometric warm-up (IWU) consisted of an 8-minutes cardiovascular phase, followed by 4 minutes of dynamic stretching and mobility exercise, and a isometric phase including 4 x 30 s half-squat at 90° holds knee flexion (30 s recovery), 4 x 30 s isometric exercises targeting triceps surae (30 s recovery) and 3 x 30 sec isometric lunges at 90° knee flexion (30 s recovery).

At the end of each warm-up protocol, participants were randomly assessed using the following tests:

- Squat jump (SJ): performed on a force platform (Globus Treviso, Italy), to assess explosive strength through elevation of the centre of mass using exclusively concentric muscle contraction.
- Countermovement Jump (CMJ): performed on a force platform (Globus Treviso, Italy), to assess explosive strength through plyometric contractions.
- Standing long jump (SLJ): used to assess explosive strength in its horizontal component.
- Squat Jump – Block Jump (SJ-BJ): used to assess sport-specific vertical jump performance. Block jump consisted of a two-legged vertical jump with arm swing, simulating a volleyball blocking action (Dopsaj et al., 2012).
- Repeated countermovement jump (RCMJ): performed on a force platform (Globus Treviso, Italy) to assess average jump height (MJH, cm), peak power (PP, W) and average power (MP, W) during jumps measured over 15 second period.
- Drop jump (DJ): performed on a force platform (Globus Treviso, Italy) to assess the elevation of the centre of mass. Participants dropped from a 45 cm box and performed a rebound jump with minimal knee flexion during ground contact (GCT) (Dopsaj et al., 2012).

Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation (SD). Data normality was checked using Shapiro Wilk test. As the variables did not meet the assumption of normality, Friedman test (non-parametric ANOVA for repeated measures) was applied to detect significant differences among conditions. When a significant main effect was observed, Conover's post hoc test with Bonferroni correction was used for pairwise comparisons. Kendall's W effect sizes (WKendall) along with 95% confidence interval (95% CI) were reported. Effect sizes were interpreted according to the following thresholds (Tomczak et al., 2014): 0.1 – < 0.3 (small), 0.3 – < 0.5 (moderate) and ≥ 0.5 (large). Statistical significance was set at $p<0.05$. Statistical analyses were conducted using JASP software (version 0.19.2, Amsterdam, The Netherlands).

Results

Table 1 and 2 report mean values±SD for descriptive statistics and significant differences through non-parametric ANOVA for repeated measures, respectively.

SJ showed significant differences among warm-up conditions, with higher values observed after NWU (29.91±1.64 cm) compared with both TWU (27.92±1.47 cm) and IWU (27.16±1.33 cm) ($p<0.001$ for both comparisons).

SLJ demonstrated significant differences among warm-up conditions. NWU produced significantly greater values (204.28±3.64 cm) compared with TWU (198.07±3.85 cm) and IWU (187.21±5.20 cm), while TWU elicited significantly higher values than IWU ($p<0.001$ for all comparisons).

CMJ reported significant differences among warm-up conditions, with NWU showing significantly greater values (32.98±0.83 cm) than TWU (31.01±1.10 cm) and IWU (30.62±1.9 cm) ($p<0.001$ for both comparisons).

SJ-BJ showed significant differences among warm-up conditions. NWU elicited significantly greater values (37.02±0.88 cm) than TWU (35.54±0.80 cm) and IWU (32.23±3.12 cm), while TWU determined significantly higher values compared with IWU ($p<0.001$ for all comparisons).

No significant differences were found in the number of jumps performed during RCMJ among warm-up conditions, with values of 12.7±0.8 jumps, 12.8±0.9 jumps and 12.5±0.6 jumps following TWU, NWU and IWU, respectively.

MJH recorded during RCMJ significantly differed among warm-up conditions. NWU produced significantly greater values (25.88±1.73 cm) compared with TWU (24.91±1.70 cm) and IWU (24.10±1.66 cm), while TWU reported significantly higher results than IWU ($p<0.001$ for all comparisons).

PP recorded during RCMJ demonstrated significant differences among warm-up conditions. NWU showed significantly greater values (2399.35±269.32 W) compared with both TWU (2389.50±83.33 W) and IWU (2198±107.14 W), while TWU determined significant benefits than IWU ($p<0.001$ for all comparisons).

MP recorded during RCMJ showed significant differences among warm-up conditions, with both TWU (2141.1±176.6 W) and NWU (2241.9±285.9 W) showing higher results than IWU (2002.9±207.9 W) ($p<0.001$ for both comparisons)

Table 1. Mean±SD are reported for descriptive statistics in jump performances

Variable	NWU	TWU	IWU
SJ (cm)	29.91 ± 1.64	27.92 ± 1.47	27.16 ± 1.33
SLJ (cm)	204.28 ± 3.64	198.07 ± 3.85	187.21 ± 5.20
CMJ (cm)	32.98 ± 0.83	31.01 ± 1.10	30.62 ± 1.9
SJ-BJ (cm)	37.02 ± 0.88	35.54 ± 0.80	34.47 ± 0.86
RCMJ (counts)	12.78 ± 0.89	12.85 ± 0.94	12.57 ± 0.64
RCMJ-MJH (cm)	25.88 ± 1.66	24.91 ± 1.70	24.10 ± 1.66
RCMJ-PP (W)	2399.35 ± 269.32	2389.50 ± 83.33	2198.00 ± 107.14
RCMJ-MP (W)	2241.90 ± 285.95	2141.10 ± 176.6	2002.9 ± 207.921
DJ height (cm)	24.58 ± 1.86	22.51 ± 0.92	21.41 ± 0.79
GCT (ms)	259.85 ± 9.67	287.35 ± 16.02	307.78 ± 19.5

Note. SJ: squat jump; SLJ: standing long jump; CMJ: countermovement jump; SJ-BJ: squat jump – block jump; RCMJ: repeated countermovement jump; MJH: average jump height; PP: peak power; MP: average power; DJ: drop jump; GCT: ground contact time

DJ height showed significant differences among warm-up conditions. NWU produced significantly greater values (24.58±1.86 cm) compared with both TWU (22.51±0.92 cm) and IWU (21.41±0.79 cm), while TWU elicited significant advantages than IWU (p<0.001 for all comparisons).

GCT collected during DJ showed significant differences among warm-up conditions . NWU elicited significantly shorter GCT values (259.85±9.67 ms) compared with both TWU (287.35±16.02 ms) and IWU (307.78±19.53), while TWU produced significantly shorter GCT than IWU (p<0.001 for all comparisons).

Figure 1-2-3 summarize the main outcomes in jump performance and power output across the three warm-up protocols (NWU, TWU and IWU).

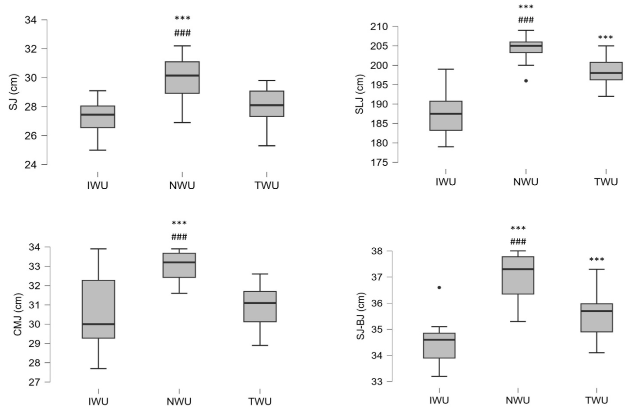

Fig. 1. Jump performance (SJ, SLJ, CMJ, SJ-BJ) after three warm-up protocols. Note. SJ: squat jump; SLJ: standing long jump; CMJ: countermovement jump; SJ-BJ: squat jump – block jump; IWU: isometric warm-up; NWU: neuromuscular warm-up; TWU: traditional warm-up; ***p<0.001 vs. IWU; ### p<0.001 vs. TWU

Table 2. Results of Friedman test for jumping performance

Variable	$\chi^2_{Friedman}$	df	p	$W_{Kendall}$	95% CI
SJ (cm)	28.00	2	<0.001	1.00	[1.00; 1.00]
SLJ (cm)	28.00	2	<0.001	1.00	[1.00; 1.00]
CMJ (cm)	15.64	2	<0.001	0.56	[0.25; 0.63]
SJ – BJ (cm)	28.00	2	<0.001	1.00	[1.00; 1.00]
RCMJ – MJH (cm)	28.00	2	<0.001	1.00	[1.00; 1.00]
RCMJ – PP (W)	22.42	2	<0.001	0.80	[0.50; 1.00]
RCMJ – MP (W)	10.42	2	0.005	0.37	[0.29; 0.60]
DJ (cm)	25.78	2	<0.001	0.92	[1.00; 1.00]
GCT (ms)	28.00	2	<0.001	1.00	[1.00; 1.00]

Note. SJ: squat jump; SLJ: standing long jump; CMJ: countermovement jump; SJ-BJ: squat jump – block jump; RCMJ: repeated countermovement jump; MJH: average jump height; PP: peak power; MP: average power; DJ: drop jump; GCT: ground contact time; χ2: Friedman chi-square statistic; df: degrees of freedom; CI 95%: confidence interval.

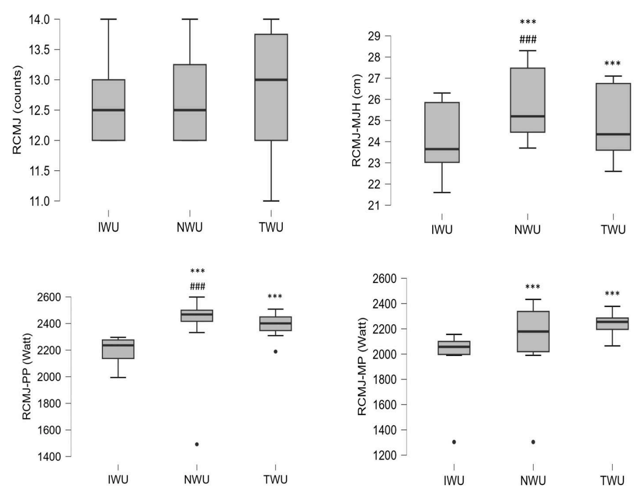

Fig. 2. RCMJ performance after three warm-up protocols. Note. RCMJ: repeated countermovement jump; MJH: average jump height; PP: peak power; MP: average power ***p<0.001 vs. IWU; ### p<0.001 vs. TWU

Discussion

The aim of the present study was to assess the effects of different warm-up protocols on jumping performance and muscle power in Under-17 volleyball players.

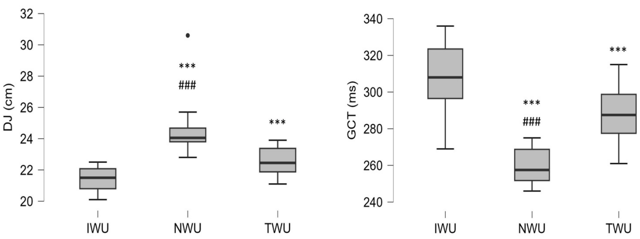

Fig. 3. Drop jump outocomes (height and GCT) after the three warm-up protocols.DJ: drop jump; GCT: ground contact time; ***p<0.001 vs. IWU; ### p<0.001 vs. TWU

The hypothesis that incorporating plyometric exercises into the warm-up routine could induce significant changes in jumping performance, muscle power and neuromuscular responsiveness was supported by the results.

Jumping performance, particularly in the SJ, CMJ, SLF and SJ–BJ tests, demonstrated that U17 players can benefit from a warm-up protocol involving rapid plyometric muscle contractions. Indeed, the neuromuscular warm-up (NWU) elicited significantly higher values across all four jumping assessments compared with both traditional (TWU) and isometric (IWU) warm-up protocols. These findings suggest that the plyometric exercises effectively improve the ability of young volleyball players to elevate their centre of mass. The vertical jump values observed in the present study are consistent with those reported in the literature for Under-16 volleyball players (Bertozzi et al., 2025; Nikolaidis et al., 2012).

Similarly, horizontal jump performance was comparable to, and in some cases exceeded, values reported for volleyball players of similar or slightly older age groups (Deng et al., 2025; Zhu & Cui, 2024; Trajkovic et al., 2024).

These findings may be partially explained by the characteristics of the study sample. Specifically, participants competed at sub-elite level and frequently performed plyometric exercises due to limited access to gyms equipped for resistance training. This contextual factor may have improved their technical execution in plyometric tasks, which require a high levels of neuromuscular control and motor coordination.

However, no significant differences were found in the RCMJ test among the three warm-up protocols. This result may be attributed to the brief duration of the test (15 s), which may have been insufficiently to elicit meaningful differences in jump count. To date, few studies have applied this specific assessment in Under-17 volleyball players, whereas longer repeated jump tests (e.g., 30 s) have primarily been applied in professional athletes (Soslu et al., 2022).

Despite the absence of differences were observed in jump frequency, the NWU elicited greater benefits for MJH, PP and MP outcomes compared with the other warm-up protocols.

These findings reflect the specific physical demands of volleyball, which involve repeated jumps actions while counteracting fatigue and maintaining neuromuscular efficiency throughout the match (Soslu et al., 2022; Hernandez-Martinez et al., 2023).

The inclusion of plyometric exercises in the NWU likely improved the elastic properties of the musculotendinous structures, thereby promoting enhanced mechanical performance during repetead jumping tasks (Papagiannis et al., 2024; Ramirez-Campillo et al., 2022).

According to some authors, repetitive high-intensity jumps may also facilitate more efficient motor unit recruitment and firing patterns, which are essential for generating high levels of force and power (Behrens et al., 2016).

A similar trend in jumping performance was observed following the TWU compared with IWU.

This result may be explained by the inclusion of additional sport-specific plyometric drills during the final phase of the TWU, which likely may have induced greater neuromuscular activation than prolonged isometric contractions.

Comparable effects have been reported in the literature for sprinting, jumping and throwing performance (Seitz et al., 2016).

Overall, the present findings emphasize the importance of carefully planning all phases of the training session. This observation is particularly relevant in sports characterized by ballistic movements, as these are associated with a high risk of non-contact injury (Aquino et al., 2022; Altavilla et al., 2023; Watanabe et al., 2016).

Therefore, it is particularly essential to understand the effects of specific warm-up exercises in youth sports in order to appropriately adapt all phases of the training sessions.

Indeed, literature consistently highlights findings derived from adult populations should not be directly extrapolated to young athletes (Ramirez-Campillo et al., 2023).

During maturation, biological processes such as rapid increases in stature, potential temporary alteration in motor coordination, large increases in fat-free mass and changes to muscle–tendon architecture may influence responsiveness to plyometric exercise (Ramirez-Campillo et al., 2022, 2023).

Conversely, the findings of the present study suggest that isometric exercises applied during warm-up did not provide meaningful benefits for jumping performance in young volleyball players.

Accordingly, greater emphasis should be placed on warm-up protocols incorporating high-speed plyometric movements (e.g., NWU) or partially including them (e.g. TWU), in order to enhance vertical and horizontal jump performance. In contrast, warm-up protocols based primarily on isometric exercises appear to be less effective for improving these performance outcomes.

Similar benefits of plyometric-based warm-up strategies have also been observed in other sports, in which vertical jump performance is nota a primary performance determinant.

In line with this observation, a recent study has revealed that including hops, skipping and sport-specific jumps during warm-up improved CMJ performance for up to 9 minutes post-warm-up (Papagiannis et al., 2024).

Therefore, we suggest incorporating plyometric exercises within the warm-up due to enhanced stretch-reflexes activation, elastic energy reutilization, motor unit recruitment and the rate of force development (Ramirez-Campillo et al., 2022; Wu et al., 2025; Tillaar et al., 2020).

Additionally, combining initial metabolic activation with plyometric exercises, as implemented in the NWU, may be crucial for triggering PAPE. Previous studies have reported that increases in muscle temperature and excitability of high-threshold motor units may persist for up to 20 minutes following warm-up (Villalon-Gasch et al., 2022).

In contrast, the limited effects obtained following the IWU suggest that the role of isometric exercises during warm-up should be carefully reconsidered in volleyball context.

In this regard, while the present findings differ from those reported in soccer players (Jarosz et al., 2025), they align with the results observed in handball players regarding jumping performance (Krzysztofik et al., 2022).

It is worth noting that the present study did not include maximal isometric contractions against external resistance (Helbin et al., 2025); instead, exercises were performed using only body weight and maintained for a prolonged time interval (30 s).

Accordingly, the absence of external resistance and the nature of the isometric stimulus may not have been sufficient to elicit meaningful neuromuscular activation, potentially explaining the limited effectiveness of the IWU.

In conclusion, the type of warm-up appears to be particularly relevant in sports requiring explosive and high-speed actions, since it can directly affect both training quality (e.g., neuromuscular-oriented sessions) and competition performance (Papagiannis et al., 2024).

Therefore, the results of this study demonstrate that PAPE may be observable in Under-17 female volleyball players when appropriate warm-up exercises are selected.

The study could provide insights into warm-up strategies in youth clubs that have limited opportunities to resistance training equipment.

Although this study provides valuable practical applications, it is necessary to note some limitations and be very prudent in interpreting the results for several different reasons.

First, the sample observed had correct jump technique because this type of exercise was frequently used by the staff: this factor may have increased the efficiency of the integrative warm-up strategies.

Second, data collection occurred in a mid-season break, during which training frequency was reduced. Finally, the small sample size limits the generalisability of the findings, which should be considered preliminary.

Further research should investigate NWU protocols with different workloads in order to provide further guidance for practitioners.

Moreover, further analysis must be conducted to understand the volumes of neuromuscular exercise that can be introduced into the warm-up without inducing fatigue in young volleyball players.

Additionally, it may also be interesting to investigate the effectiveness of NWU protocols by comparing elite and sub-elite athletes, as well as to explore how strength and conditioning coaches can integrate supplementary exercises into warm-up routines to optimise performance outcomes in youth volleyball.

Conclusions

The findings of this study indicate that the type of warm-up protocol plays a decisive role in jumping performance and muscle power in Under-17 female volleyball players. A neuromuscular warm-up incorporating high-speed plyometric exercises (NWU) was consistently more effective than traditional and isometric protocols in enhancing vertical and horizontal jump performance. In contrast, warm-up routines based primarily on isometric exercises without external resistance did not provide meaningful performance benefits. These results suggest that appropriately structured plyometric-based warm-up strategies may facilitate PAPE effects in youth volleyball players, particularly in contexts with limited access to resistance training equipment.

Ethics Approval

Ethical approval for this study was granted by the Ethics Committee of the University of Foggia (Approval No. 00149ss/2024, dated October 1, 2024).

Informed Consent

Written informed consent was obtained from all participants involved in the study.

Data Availability Statement

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

AI Transparency Statement

The authors declare that no artificial intelligence (AI)–assisted tools were used in the preparation of this manuscript.

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Conflict of Interest

The authors declare that there is no conflict of interest related to this study.

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Чи впливають стратегії розминки на показники стрибкової працездатності юних волейболісток?

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 9 с., 2 табл., 3 рис., 52 джерела.

Мета. Метою дослідження було оцінити, чи сприяє розминка з включенням пліометричних вправ більшому підвищенню стрибкової працездатності, потужності та нейром'язової реактивності порівняно з розминками, які зазвичай застосовуються у волейбольній практиці.

Матеріали і методи. У дослідженні взяли участь 24 волейболістки субелітарного рівня (вік: 16,3 ± 0,6 року; маса тіла: 58,7 ± 3,8 кг; зріст: 165,6 ± 6,8 см), які представляли регіональний клуб. Учасниці виконували три різні протоколи розминки тривалістю по 20 хвилин кожен: традиційну розминку (TR), нейром'язову розминку (NR) та ізометричну розминку (IR). З метою мінімізації впливу втоми три експериментальні сесії проводилися з інтервалом 48 годин. Після завершення кожного протоколу розминки учасниць у випадковому порядку тестували за допомогою стрибка з напівприсіду (SJ), стрибка з попереднім замахом (CMJ), стрибка в довжину з місця (SLJ), стрибка з напівприсіду – блокувального стрибка (SJ–BJ), повторного стрибка з попереднім замахом (RCMJ) та стрибка вниз (DJ).

Результати. Результати тестів стрибкової працездатності показали вищі та статистично значущі значення (p < 0,001) після застосування нейром'язової розминки. Порівняно з ізометричною розминкою, традиційна розминка забезпечувала вищі показники у тестах SLJ, SJ–BJ, RCMJ, а також менший час контакту з опорою під час виконання тесту DJ.

Висновки. Нейром'язова розминка є особливо ефективною у видах спорту, що вимагають вибухових високошвидкісних рухів, оскільки вона може безпосередньо впливати на якість тренувального процесу та стрибкову працездатність у змагальній діяльності. Отримані результати свідчать про те, що ефект постактиваційного підвищення працездатності (PAPE) може проявлятися у волейболісток до 17 років за умови застосування адекватно підібраних вправ розминки. Дослідження надає практичні орієнтири щодо вибору стратегій розминки у дитячо-юнацьких клубах з обмеженим доступом до силового тренувального обладнання.

Ключові слова: стрибок, волейбол, PAPE, нейром'язова інтегративна вправа, пліометрія.

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Retraction Note

Retraction Note: Evaluating the Effects of Complex Training on Athletic Performance: A Systematic Review (*Physical Education Theory and Methodology, 26*(1). https://doi.org/10.17309/tmfv.2025.5.25)

The Editors have retracted the following article:

Choudhary et al. (2025). Evaluating the Effects of Complex Training on Athletic Performance: A Systematic Review. *Physical Education Theory and Methodology, 25*(5), 1255–1267. https://doi.org/10.17309/tmfv.2025.5.25

Following a formal editorial investigation conducted in accordance with the journal's publication ethics policy and COPE guidelines, the Editors determined that the article contains serious deficiencies in methodological reporting and representation of the study design. Specifically, the article was presented as a systematic review and meta-analysis; however, no verifiable meta-analytic procedures were identified. In addition, statements regarding protocol registration could not be substantiated, and the reported methodological quality assessment was not supported by corresponding data. Furthermore, inconsistencies were identified between the stated study objectives and the inclusion criteria.

These issues compromise the reliability of the findings and the integrity of the scientific record. On this basis, the Editors have decided to retract the article in order to maintain the standards of publication ethics.

This retraction is issued by the Editors of the journal.

The authors did not consent to the retraction of the article.

The retracted article will remain available online to preserve the scholarly record; however, it will be digitally watermarked on each page as "Retracted".

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Choudhary, S., Kumar Choudhary, P., Singh Rajpoot, Y., Singh, D., Hooda, N., & Saini, A. (2025). Evaluating the Effects of Complex Training on Athletic Performance: A Systematic Review. *Physical Education Theory and Methodology, 25*(5), 1255–1267. https://doi.org/10.17309/tmfv.2025.5.25

Повідомлення про відкликання

Повідомлення про відкликання: Evaluating the Effects of Complex Training on Athletic Performance: A Systematic Review (*Physical Education Theory and Methodology, 26*(1). https://doi.org/10.17309/tmfv.2025.5.25)

Редакція журналу відкликає таку статтю:

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За результатами формального редакційного розслідування, проведеного відповідно до політики публікаційної етики журналу та рекомендацій COPE, редакцією встановлено наявність суттєвих недоліків у методологічному звітуванні та представленні дизайну дослідження. Зокрема, статтю було подано як систематичний огляд і метааналіз, однак перевірювані докази фактичного проведення метааналітичних процедур відсутні. Крім того, твердження щодо реєстрації протоколу не були підтверджені, а задекларована оцінка методологічної якості досліджень не була підкріплена відповідними даними. Також виявлено невідповідності між заявленою метою дослідження та критеріями включення.

Зазначені обставини підривають надійність отриманих результатів і цілісність наукового запису. На цій підставі редакція ухвалила рішення про відкликання статті з метою дотримання стандартів публікаційної етики.

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