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Physical Education of Schoolchildren as a Managed Learning Process: Theoretical and Methodological Foundations, a Systems Perspective, and Modelling

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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. To synthesize contemporary scientific approaches to interpreting physical education of schoolchildren within the logic of a managed learning process and to clarify the role of pedagogical control, modelling, and age-related developmental regularities in shaping learning outcomes.

Materials and Methods. The study was conducted as a narrative review of publications addressing physical education theory, pedagogical control, modelling of the learning process, age-related developmental regularities, and the teaching of physical exercises in general secondary education. The analysis was carried out from systems-based and learning-oriented perspectives on the organisation of physical education.

Results. The review supports interpreting physical education of schoolchildren as a managed learning process in which learning outcomes emerge through the interaction of pedagogical control, modelling, and learners' age-related developmental characteristics. Age-related regularities are best treated as parameters of learning models that define the boundaries for valid interpretation of pedagogical-control results. Pedagogical control acquires a regulatory function only when embedded within a model of the learning process. The synthesis also allows the learning of physical exercises to be interpreted as the formation and dynamics of learning states that can serve as objects of pedagogical control and regulation.

Conclusions. The proposed synthesis enables interpreting outcomes of physical education as consequences of the organisation of the learning process rather than as autonomous normative indicators. This narrative review delineates theoretical and methodological frames for further research aimed at empirically testing models of managed physical education and refining tools of pedagogical control in general secondary education practice.

Keywords: physical education of schoolchildren, managed learning process, pedagogical control, modelling, age-related developmental regularities, learning states.

Introduction

In contemporary educational and public health policy documents, physical education of schoolchildren is positioned as an integral component of general education, aimed at developing motor competence, supporting health, and creating prerequisites for lifelong engagement in physical activity (UNESCO, 2015a; UNESCO, 2015b). At the same time, global epidemiological evidence indicates persistently high levels of insufficient physical activity among children and adolescents, which reinforces concerns

about the effectiveness of school-based physical education programmes and increases demands on the quality of their organisation (Guthold et al., 2020). In this context, World Health Organization guidelines define regular physical activity as a minimum standard for health preservation in young people, thereby establishing an external reference framework for evaluating the aims and expected outcomes of physical education in schools (Bull et al., 2020).

Despite the normative clarity of physical education goals, the practical effectiveness of school-based approaches remains heterogeneous. Findings from recent systematic reviews and meta-analyses indicate that school-oriented physical activity may be positively associated with cognitive and academic outcomes; however, the magnitude and stability

of these effects depend substantially on the type of activity, modes of organisation, and contextual characteristics of programme implementation (Mello et al., 2024). Similarly, evidence from long-term school-based interventions suggests that the influence of physical education on mental well-being and behavioural outcomes is more convincing when programmes are characterised by sufficient duration, structural coherence, and methodologically grounded organisation of the learning process (Viskari et al., 2025). These findings highlight the limitations of approaches focused primarily on formal compliance with curricular requirements and underscore the need for a deeper interpretation of the mechanisms through which learning outcomes are achieved.

For a prolonged period, normative-oriented approaches dominated school physical education practice, with learning outcomes defined mainly through the attainment of prescribed standards and performance norms. However, pedagogical theory and research on educational assessment have demonstrated that such logic inadequately accounts for individual differences among learners and substantially restricts the interpretation of outcomes as consequences of the learning process itself (Black & Wiliam, 2009; Hay & Penney, 2012). When assessment is not integrated into learning, pedagogical control loses its formative potential and is reduced to the recording of final indicators, thereby failing to support regulation of learning activities. Critiques of normativity in physical education align with broader developments in educational sciences that emphasise a shift from controlling outcomes to controlling learning processes through feedback and regulation of learners' activity (Hattie & Timperley, 2007).

An important, yet insufficiently integrated, factor in the organisation of physical education is the role of age-related developmental regularities in children and adolescents. Research on biological maturation and motor development has convincingly demonstrated substantial age-related and inter-individual differences in the development of motor abilities and learning rates (Malina et al., 2004; Lloyd & Oliver, 2012). Nevertheless, within school physical education these regularities are often applied only at the level of general recommendations and are rarely embedded directly into the logic of managing the learning process. Contemporary theories of learning and motor development emphasise that learning effects emerge from the interaction between learners' developmental capacities, learning tasks, and organisational conditions, and therefore cannot be adequately interpreted outside these interrelationships (Newell, 1986; Schmidt & Lee, 2019).

Within modern pedagogical frameworks, pedagogical control is increasingly conceptualised not merely as a means of measuring learning achievements, but as a key mechanism for regulating the learning process by providing feedback and supporting pedagogical decision-making. Research on formative assessment and self-regulated learning consistently shows that learning effectiveness increases when control procedures are integrated into ongoing learning activities rather than isolated at the stage of summative evaluation (Black & Wiliam, 2009; Zimmerman, 2002). In physical education, however, pedagogical control often retains a predominantly measurement-oriented character and is rarely employed as a tool for managing learning processes, which constrains interpretative possibilities and reduces the manageability of learning.

The convergence of normative-oriented practices, fragmented use of age-related developmental regularities, and the reduction of pedagogical control to measurement functions necessitates a rethinking of physical education of schoolchildren as a managed learning process. Learning theories emphasise that manageability is achieved through clearly articulated models that specify interactions among learning goals, tasks, organisational conditions, and control mechanisms, enabling learning outcomes to be interpreted as consequences of specific pedagogical influences (Hattie & Timperley, 2007; Metzler & Colquitt, 2021). It is precisely this logic of integrating modelling, pedagogical control, and age-related developmental regularities that defines the focus of the present narrative review.

Materials and Methods

Study Design

The study was conducted as a theoretical and methodological narrative review aimed at synthesising and conceptually analysing scholarly sources addressing pedagogical control, modelling of the learning process, age-related regularities of motor development, and the teaching of physical exercises in school physical education. The methodological foundations for interpreting physical education as a managed learning process and for using modelling as an analytical tool are grounded in approaches to learning systems developed in previous research (Ivashchenko et al., 2026).

The choice of a narrative review format was determined by the purpose of the study, which was not to quantify the effects of specific pedagogical interventions, but to analyse causal–conceptual relationships and methodological approaches to interpreting physical education as a managed learning process. This format allows for the integration of findings from studies conducted within different theoretical paradigms and employing diverse research methods within a unified framework of systems-based analysis.

Source Base

The analysis encompassed the following groups of sources:

- classical works in the theory of physical culture and sport that substantiate regularities of age-related development of motor abilities, adaptation to physical loads, and principles of pedagogical management;
- scientific publications focusing on pedagogical control and the teaching of motor actions in school physical education;
- studies on modelling of pedagogical and learning processes that examine mechanisms for establishing causal relationships between pedagogical influences and learning outcomes;
- contemporary research in learning theory and educational assessment that conceptualises learning processes as managed systems with feedback;
- analytical reviews and policy documents reflecting the current context of development of school physical education.

These groups of sources include both foundational works that shaped the theoretical and methodological

bases of the problem and contemporary studies addressing pedagogical control, modelling, and interpretation of learning outcomes in physical education. Specific approaches, concepts, and scholarly positions represented within these groups are examined and substantiated in detail in the Results and Discussion sections.

The chronological scope of the analysis covered both seminal publications that established core theoretical propositions and recent studies published between 2018 and 2025, which were necessary to account for current scientific and educational trends.

Analysis Procedure

The analysis of sources was conducted in several consecutive stages.

At the first stage, a preliminary selection of sources was performed based on their thematic relevance to issues of pedagogical control, modelling, and manageability of school physical education.

At the second stage, a theoretical and methodological analysis of the selected publications was carried out in order to identify key concepts, approaches, and regularities describing mechanisms of formation and regulation of learning outcomes in physical education.

At the third stage, the identified propositions were systematised within a systems-based framework, with explicit delineation of interrelationships among pedagogical control, modelling of the learning process, age-related developmental regularities, and the learning of physical exercises.

At the final stage, a conceptual synthesis of the analysis results was undertaken to substantiate the interpretation of physical education of schoolchildren as a managed learning process and to identify methodological preconditions for managing learning outcomes.

Methodological Approaches

The following methodological approaches were employed in the study:

- a systems approach, which enabled physical education of schoolchildren to be considered as an integrated learning process composed of interrelated components;
- theoretical analysis and synthesis, aimed at generalising findings from previous research;

- logical and structural analysis, applied to identify causal relationships between pedagogical influences and learning outcomes.

The narrative review format implies an analytical interpretation of scholarly propositions and does not involve statistical aggregation of results or quantitative estimation of the effects of individual pedagogical interventions.

Results

As a result of the narrative analysis, it was established that physical education of schoolchildren should be interpreted as a managed learning process, in which learning outcomes are formed not in isolation but as a consequence of the interaction between pedagogical control, modelling of learning activity, and age-related developmental regularities. Such an interpretation makes it possible to consider the results of physical education not only as final indicators of physical fitness, but as outcomes of a regulated learning process that has its own internal logic and is subject to pedagogical management. Analysis of the sources showed that the manageability of physical education is ensured by the presence of a structured relationship between learning goals, means of pedagogical influence, and control procedures, which allows changes in learning outcomes to be interpreted as consequences of specific pedagogical decisions rather than as random or solely normatively determined effects (Hattie & Timperley, 2007; Metzler & Colquitt, 2021; Kirk, 2010). The key components of managed physical education of schoolchildren and their functional roles within the learning process are systematised in Table 1.

The results of the analysis indicated that age-related developmental regularities of children and adolescents in physical education research are predominantly considered as descriptive characteristics or background conditions for planning learning influences. At the same time, the generalisation made it possible to establish that age-related characteristics should be interpreted as parameters of learning models that determine the boundaries of correct interpretation of pedagogical control results and the possibilities for comparing them across different groups of pupils. Such an approach allows age-related regularities to be considered not only as a factor in selecting physical loads, but as a structural element of the learning model that limits or adjusts the interpretation of learning outcomes depending on pupils' level of development, maturation rates, and individual capabilities (Malina et al., 2004; Newell, 1986).

Table 1. Components of Managed Physical Education of Schoolchildren

Component	Conceptual interpretation	Function within the learning process
Pedagogical control	System for collecting and interpreting information about the learning process	Provision of feedback and regulation of learning activities
Modelling of the learning process	Formalisation of relationships among learning goals, tasks, conditions, and control	Interpretation of outcomes as consequences of pedagogical influences
Age-related developmental regularities	Parameters defining learners' developmental capacities and constraints	Adjustment of pedagogical decisions and interpretation of control results
Learning states	Dynamic levels of mastery of motor actions and readiness for progression	Objects of pedagogical control and regulation

Note. The components are considered interrelated elements of an integrated managed learning system.

The synthesis of results showed that pedagogical control in physical education acquires a regulatory status only when it is embedded within a model of the learning process. In the absence of such integration, control procedures function mainly as a means of recording final indicators and do not ensure management of the learning process. By contrast, the inclusion of control within the structure of the learning model makes it possible to interpret control data as information for adjusting learning actions and pedagogical decisions. The regulatory function of pedagogical control is realised through the presence of a relationship between learning goals, assessment criteria, and feedback procedures, within which control ceases to be an isolated measurement operation and is transformed into a tool for managing the learning process (Hattie & Timperley, 2007; Zimmerman, 2002). A comparative interpretation of normative-oriented and managed approaches to physical education outcomes is presented in Table 2.

Table 2. Normative-Oriented versus Managed Interpretation of Physical Education Outcomes

Criterion	Normative-oriented approach	Managed learning process
Object of evaluation	Final normative indicators	Dynamics of learning states
Role of pedagogical control	Recording of results	Regulation of the learning process
Consideration of age-related characteristics	General age norms	Parameters of learning models
Interpretation of outcomes	Autonomous performance indicators	Consequences of pedagogical organisation
Managerial potential	Limited	High

Note. The managed interpretation frames physical education outcomes as consequences of pedagogical decisions rather than merely as the attainment of normative standards.

The results of the analysis also demonstrated that modelling of the learning process is a necessary condition for interpreting the results of pedagogical control in physical education. In the absence of a clearly defined learning model, control indicators remain fragmented and do not allow causal relationships to be established between pedagogical influences and changes in learning outcomes (Kirk, 2010). The generalisation made it possible to establish that the learning-process model performs an integrative function by combining learning goals, task-performance conditions, pedagogical influences, and control indicators into a single structured system. It is within such a model that the results of pedagogical control can be interpreted as consequences of the organisation of the learning process rather than as autonomous or normatively determined indicators (Newell, 1986; Metzler & Colquitt, 2021).

In the course of the synthesis, it was established that the process of learning physical exercises should be interpreted as the formation and change of learning states, which reflect the current level of mastery of motor actions, execution stability, and pupils' readiness for increasing the complexity of learning tasks. Such an interpretation makes it possible to consider learning outcomes not only

in the form of final indicators, but as the dynamics of states that change sequentially within the learning process. The analysis showed that learning states may serve as objects of pedagogical control, provided that they are interpreted within a learning model that links control indicators with specific learning tasks and the conditions under which they are performed (Chen & Darst, 2001). Within this logic, control is directed not toward the fixation of individual results, but toward tracking changes in learning states, which creates a basis for regulating the learning process and adapting pedagogical influences (Schmidt & Lee, 2019; Zimmerman, 2002; Chen & Wang, 2017; Ding et al., 2013). The proposed interpretation of learning as a sequence of learning states and the corresponding pedagogical control guidelines are summarised in Table 3.

Table 3. Learning States in Physical Education and Pedagogical Control Guidelines

Learning state	Characteristics	Pedagogical control guidelines
Initial	Unstable performance, high variability	Quality of instruction and feedback
Formation	Increasing stability and awareness	Alignment of tasks with learners' preparedness
Consolidation	Stable execution under standard conditions	Readiness for task complication

Note. Learning states are interpreted as dynamic characteristics of the learning process that may serve as objects of pedagogical control and regulation.

The synthesis of the analysis results made it possible to formulate a structural logic of managed physical education of schoolchildren, within which pedagogical control, modelling of the learning process, age-related developmental regularities, and the dynamics of learning states are considered as interrelated components of a unified system. Within this structure, learning outcomes are interpreted as consequences of the organisation of the learning process rather than as autonomous or normatively determined indicators. The resulting logic establishes a framework for interpreting the results of physical education as a managed learning process in which control and modelling perform a system-forming function, while age-related regularities and learning states define the boundaries of the validity of pedagogical decisions. This constitutes the final outcome of the conducted narrative analysis (Newell, 1986; Metzler & Colquitt, 2021).

Discussion

The generalisations obtained within the narrative review make it possible to interpret physical education of schoolchildren not only as a set of separate pedagogical influences, but as a managed learning process in which learning outcomes are formed through the interaction of pedagogical control, modelling, and age-related developmental regularities. This interpretation is consistent with contemporary views of learning as a regulatory process in which feedback and activity management play a decisive role in achieving learning goals (Zimmerman, 2002; Hattie & Timperley, 2007). Within the field of physical education, this approach also enables general educational theoretical positions to be specified through the

logic of instructional models and the specific characteristics of motor learning (Metzler & Colquitt, 2021).

Previous studies in the theory of physical culture and motor development have convincingly demonstrated the existence of age-related regularities in the development of motor abilities, as well as substantial heterogeneity among schoolchildren in terms of physical fitness levels and learning rates (Malina et al., 2004; Lloyd & Oliver, 2012). However, in a significant proportion of these works, age-related characteristics were treated primarily as background conditions for planning physical loads rather than as an integrated component of managing the learning process. Evidence from contemporary reviews focusing on inclusive physical activity and contextual barriers to participation further indicates that educational outcomes may vary substantially depending on the conditions under which learning is organised, regardless of formally prescribed programmes (Ashadi et al., 2025; Yu et al., 2022). This necessitates considering age-related regularities not only as descriptive characteristics of development, but as parameters of learning models that determine the validity of interpreting pedagogical control results.

In this context, pedagogical control emerges as a key element in managing the learning process. Analysis of the literature shows that, in physical education practice, control is often reduced to measurement functions or summative assessment of pupils' achievements, which limits its regulatory potential (Hay & Penney, 2012; Black & Wiliam, 2009). Contemporary theories of formative assessment and self-regulated learning emphasise that control acquires learning-related and regulatory significance only when it is integrated into pedagogical decision-making processes and provides meaningful feedback (Hattie & Timperley, 2007; Zimmerman, 2002). Without such integration, control information remains descriptive and does not support the management of learning-outcome dynamics.

A key methodological condition for interpreting the results of pedagogical control is the modelling of the learning process. Learning theories and motor-learning theories demonstrate that, without a clearly defined model of interaction among tasks, conditions, and pupils' individual capabilities, it is impossible to establish causal relationships between pedagogical influences and learning outcomes (Newell, 1986; Schmidt & Lee, 2019). Accordingly, modelling in physical education should be understood not as a formal description of lesson structure, but as an integrative mechanism that brings together learning goals, means of influence, and pedagogical-control data into a unified logic of a managed process (Metzler & Colquitt, 2021).

Particular attention in this regard should be given to interpreting the learning of physical exercises as a process of forming learning states that change over time under the influence of pedagogical actions. Research in motor learning and self-regulated learning indicates that learning effectiveness is determined not only by final outcomes, but also by the dynamics of intermediate states that reflect task understanding, execution stability, and readiness for increasing learning demands (Zimmerman, 2002; Schmidt & Lee, 2019). From this perspective, pedagogical control in physical education should be oriented toward interpreting changes in learning states within a specific model of the learning process, thereby providing a basis for adaptive lesson organisation and the individualisation of learning

trajectories. The generalisations obtained within the narrative review are consistent with approaches that conceptualise physical education as a learning system, emphasising the role of modelling and feedback in regulating learning outcomes (Ivashchenko et al., 2026).

The results of the narrative review also have limitations determined by the research format itself. Narrative reviews do not involve quantitative assessment of effects or formalised comparison of results from individual studies, which reduces their reproducibility in comparison with systematic reviews. At the same time, methodological works emphasise the appropriateness of this format for analysing conceptual approaches, theoretical models, and the logic of interpreting results in complex interdisciplinary fields (Grant & Booth, 2009; Ferrari, 2015). In this sense, the chosen format corresponds to the purpose of the study, which was not to determine the magnitude of the effects of pedagogical interventions, but to substantiate the methodological logic of managing the learning process in physical education of schoolchildren.

From the perspective of the outlined logic, further research should be directed toward the empirical testing of models of managed physical education in which pedagogical control, modelling of the learning process, and age-related developmental regularities are considered as interrelated components. Promising directions include combining quantitative and qualitative approaches, which would allow learning outcomes to be interpreted not only through final indicators, but also through the dynamics of learning states during the instructional process, in accordance with contemporary views on learning regulation and formative assessment (Hattie & Timperley, 2007; Zimmerman, 2002). Particular attention should be given to the development and validation of pedagogical-control tools capable of ensuring the interpretation of results within specific learning models, thereby strengthening the connection between theoretical and methodological generalisations and the practice of organising physical education in general secondary education institutions (Metzler & Colquitt, 2021).

Conclusions

The conducted narrative review made it possible to уточнити the interpretation of physical education of schoolchildren as a managed learning process, within which learning outcomes are formed through the interaction of pedagogical control, modelling, and age-related developmental regularities. This approach allows physical education to move beyond its reduction to the fulfilment of normative requirements and to be considered as a system subject to purposeful pedagogical regulation.

The synthesis of the results showed that age-related developmental regularities should be interpreted not as background characteristics, but as parameters of learning models that define the boundaries of valid interpretation of pedagogical control results. This creates a basis for a more substantiated analysis of learning achievements and prevents their formal comparison without consideration of pupils' age-related and individual characteristics.

It was established that pedagogical control acquires regulatory significance only when it is embedded within a model of the learning process. Under such integration, control information ceases to perform an exclusively

measurement-oriented function and can be used to adjust pedagogical influences, thereby ensuring the manageability of learning in physical education of schoolchildren.

The analysis demonstrated that modelling of the learning process is a necessary condition for interpreting the results of physical education as consequences of the organisation of learning activity, rather than as autonomous or normatively determined indicators. Within a model, learning goals, task conditions, pedagogical influences, and control results are integrated into a coherent analytical and regulatory framework for managing the learning process.

The generalisations obtained made it possible to interpret the learning of physical exercises as a process involving the formation and dynamics of learning states, which may serve as objects of pedagogical control and regulation. This approach creates methodological prerequisites for moving from unified programmes toward a more flexible organisation of physical education oriented toward the individualisation of schoolchildren's learning processes.

The conclusions drawn do not claim to provide an exhaustive solution to the problem; however, they outline theoretical and methodological frameworks for further research aimed at the empirical testing of models of managed physical education and the refinement of pedagogical control tools. Within this logic, the narrative review functions not as the completion of research, but as a foundation for strengthening the connection between theoretical–methodological generalisations and the practice of organising physical education in general secondary education institutions.

Ethics Approval

Not applicable. This study is a theoretical and methodological narrative review and did not involve human participants, animals, or the collection of personal data. Therefore, ethical approval was not required.

Informed Consent

Not applicable. This study did not involve human participants.

Data Availability Statement

Data are not applicable because no new data were created or analyzed in this study. The article is based exclusively on the analysis and interpretation of previously published sources.

AI Transparency Statement

The author used AI-assisted tools for language editing and formatting support only. The author takes full responsibility for the scientific content, analysis, and conclusions of the manuscript.

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Conflicts of Interest

The author declares no conflicts of interest.

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Фізичне виховання школярів як керований навчальний процес: теоретико-методичні засади, системний підхід і моделювання

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; Е – збір коштів

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Мета. Узагальнити сучасні наукові підходи до інтерпретації фізичного виховання школярів у логіці керованого навчального процесу та уточнити роль педагогічного контролю, моделювання і вікових закономірностей у формуванні навчальних результатів.

Матеріали і методи. Дослідження виконано у форматі нарративного огляду наукових публікацій, присвячених теорії фізичного виховання, педагогічному контролю, моделюванню навчального процесу, віковим закономірностям розвитку та навчанню фізичних вправ у закладах загальної середньої освіти. Аналіз здійснювався з позицій системного та навчально-орієнтованого підходів до організації фізичного виховання.

Результати. У результаті аналізу уточнено, що фізичне виховання школярів доцільно розглядати як керований навчальний процес, у межах якого навчальні результати формуються внаслідок взаємодії педагогічного контролю, моделювання та вікових особливостей розвитку учнів. Показано, що вікові закономірності доцільно інтерпретувати як параметри моделей навчання, які визначають межі коректної інтерпретації результатів педагогічного контролю. Встановлено, що педагогічний контроль набуває регуляторного значення лише за умови його включення в модель навчального процесу. Узагальнення дозволило інтерпретувати навчання фізичних вправ як процес формування і динаміки навчальних станів, які можуть бути об'єктом педагогічного контролю і регуляції.

Висновки. Отримані узагальнення дозволяють інтерпретувати результати фізичного виховання як наслідок організації навчального процесу, а не як автономні нормативні показники. Наративний огляд окреслює теоретико-методичні рамки для подальших досліджень, спрямованих на емпіричну перевірку моделей керованого фізичного виховання та уточнення інструментів педагогічного контролю в практиці закладів загальної середньої освіти.

Ключові слова: фізичне виховання школярів; керований навчальний процес; педагогічний контроль; моделювання; вікові закономірності; навчальні стани.

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Review Article

The Effects of Digital Technologies on Physical Education Outcomes: A Systematic Review and Meta-Analysis

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Abstract

Background. Physical education faces growing pressure to integrate digital technologies amid declining student engagement and motivation. Despite increasing adoption, systematic evidence on the effectiveness of these tools across outcome domains remains limited, particularly regarding the conditions under which they are most beneficial.

Objectives. This systematic review and meta-analysis examined the effects of digital technologies on physical education outcomes, investigating the overall magnitude of effects, domain-specific effects (physical, motivational-affective, cognitive), and moderators of heterogeneity.

Materials and Methods. Systematic searches of four databases (Scopus, Web of Science, ERIC, SPORTDiscus) identified experimental and quasi-experimental studies published between 2015 and 2025. Twelve studies meeting the inclusion criteria yielded 64 effect sizes from 1,346 participants. Random-effects meta-analyses with REML estimation were conducted to calculate pooled Hedges' g effect sizes, supplemented by prediction intervals to account for extreme heterogeneity.

Results. The overall pooled effect was $g = 0.745$ (95% CI [0.590, 0.900], $p < .001$), with domain-specific estimates of $g = 0.854$ (physical), $g = 0.616$ (motivational-affective), and $g = 0.936$ (cognitive). However, extreme heterogeneity across all models ($I^2 = 99.98\%$, $\tau^2 = 0.373$) renders these pooled estimates unstable and non-generalizable. The 95% prediction interval (PI) [-0.471, 1.961] indicates that the true effect in any given implementation context may range from moderately negative to very large positive, reflecting the high context dependence of the observed effects.

Conclusions. Digital technologies show potential for enhancing physical education outcomes; however, the wide prediction intervals and extreme heterogeneity preclude any universal claim of effectiveness. The practical impact of a specific implementation critically depends on technology type, pedagogical integration, teacher expertise, and educational context. Future research should prioritize identifying the conditions under which digital technologies are most and least effective, rather than estimating average effects alone.

Keywords: physical education, digital technology, meta-analysis, heterogeneity, pedagogical integration, educational technology.

Introduction

Physical education stands at a critical juncture in the digital age. While contemporary youth navigate increasingly technology-saturated environments, physical education classrooms often remain anchored to pedagogical approaches developed in pre-digital eras (Casey & Goodyear, 2015). This disconnect manifests in declining adolescent engagement

with physical activity (Kalman et al., 2015), diminishing motivation for physical education (Ladwig et al., 2018), and growing concerns about the relevance of traditional instructional approaches for digitally native learners (Gråstén, 2016). Yet paradoxically, the same technological revolution that has contributed to sedentary lifestyles and reduced physical activity may offer transformative solutions for reinvigorating physical education and reconnecting students with movement (Gao et al., 2020).

The integration of digital technologies into physical education represents more than mere modernization

of instructional tools, it fundamentally reimagines the pedagogical possibilities for enhancing student learning, motivation, and performance. From virtual reality simulations that transport students into immersive movement environments (Papastergiou et al., 2021) to wearable activity trackers providing real-time biofeedback on physiological responses (Hu & Li, 2024), from gamification platforms transforming exercise into engaging challenges (Baena-Morales et al., 2021) to artificial intelligence systems delivering personalized instruction and feedback (Hsia et al., 2025), contemporary technologies offer unprecedented affordances for supporting diverse learning pathways. These innovations align with contemporary educational emphases on personalized learning, immediate feedback, autonomous goal-setting, and multimodal content delivery, principles that resonate with both pedagogical theory and student preferences (Koekoek & van Hilvoorde, 2018).

Theoretical frameworks suggest multiple pathways through which digital technologies might enhance physical education outcomes. Self-Determination Theory posits that technologies supporting autonomy (through choice and customization), competence (through immediate performance feedback), and relatedness (through social connectivity features) should enhance intrinsic motivation for physical activity (Ryan & Deci, 2017). Embodied cognition perspectives suggest that technologies embedding cognitive challenges within physical activity contexts, such as exergames requiring strategic decision-making during movement, may simultaneously enhance both motor and cognitive development (Vazou & Skrade, 2017). Social cognitive theory emphasizes that technologies enabling self-monitoring, goal-setting, and social comparison provide critical self-regulatory tools supporting behavior change (Bandura, 1986). These theoretical perspectives converge on the proposition that thoughtfully designed digital interventions, rather than simply digitizing traditional instruction, can create qualitatively different learning experiences addressing multiple developmental domains simultaneously (Tannehill et al., 2021).

Empirical research on technology-enhanced physical education has proliferated in recent years, examining diverse technological approaches across varied contexts. Studies investigating virtual and augmented reality applications have demonstrated promise for enhancing motor learning through immersive practice environments and multi-sensory feedback (Li & Sun, 2024; Shekerbekova et al., 2025). Research on gamification platforms has revealed potential for increasing engagement and motivation through game elements such as points, badges, challenges, and leaderboards, though concerns persist regarding potential undermining of intrinsic motivation through excessive extrinsic rewards (Baena-Morales et al., 2021). Investigations of wearable activity trackers and mobile applications have shown mixed results, with some studies demonstrating enhanced self-regulation and goal-directed behavior (Ibragimova et al., 2025) while others report limited effects when devices function primarily as passive monitoring tools without pedagogical integration (Breed et al., 2024). Studies examining blended learning approaches, combining online instructional content with face-to-face physical practice, have generally reported positive effects across multiple outcome domains, potentially reflecting comprehensive curricular integration

rather than supplementary technology use (Dewanti et al., 2024). Emerging research on artificial intelligence tutoring systems suggests potential for personalized feedback and adaptive instruction responsive to individual student needs (Hsia et al., 2025).

Despite this growing body of research, several critical gaps impede comprehensive understanding of digital technology integration in physical education. Existing studies vary substantially in methodological rigor, with many employing small samples, lacking adequate control groups, or providing insufficient detail for replication and implementation (Dudley et al., 2022). Outcome assessments have focused predominantly on single dimensions, typically either physical performance or motivation, with limited examination of technologies' effects across multiple learning domains simultaneously (Bailey et al., 2009). The field lacks systematic synthesis examining which specific technological approaches demonstrate greatest effectiveness, whether effects generalize across different educational levels and contexts, and what implementation factors moderate outcomes (Lai et al., 2022). Additionally, most studies have investigated technology as a binary presence-absence variable rather than examining how pedagogical integration, instructional design, and implementation quality influence effectiveness (Ennis, 2017). These gaps leave practitioners without evidence-based guidance for technology selection, implementation, and integration within comprehensive physical education curricula. Recent systematic reviews have examined adapted pedagogical strategies and inclusive practices in physical education (Ben Rakaa et al., 2025a; Lourenço et al., 2025), demonstrating the importance of pedagogical frameworks for technology integration. However, quantitative synthesis across diverse technological interventions and outcome domains remains scarce.

The present systematic review and meta-analysis addresses these gaps by synthesizing experimental and quasi-experimental research examining digital technology effects on physical education outcomes. Our synthesis differs from previous reviews in several respects. We employed rigorous inclusion criteria requiring controlled research designs with adequate sample sizes and quantitative outcome data, enabling meta-analytic pooling rather than narrative synthesis alone. We examined effects across three broad outcome domains: physical, motivational-affective, and cognitive. Permitting comprehensive evaluation of technology integration's breadth of impact. We systematically investigated moderators including technology type, educational level, and study design to identify factors influencing effectiveness. Finally, we attended explicitly to implementation quality and pedagogical integration, recognizing that technological tools alone do not determine outcomes but rather interact with instructional design and teacher mediation.

This review addresses four primary research questions. First, what is the overall magnitude of digital technology effects on physical education outcomes, and how do effects vary across physical, motivational-affective, and cognitive outcome domains? Second, do effects vary systematically by technology type, comparing approaches such as virtual/augmented reality, gamification, wearables, artificial intelligence systems, mobile applications, and blended learning? Third, do effects differ across educational

levels (elementary, secondary, tertiary) or study designs (randomized controlled trials, quasi-experimental studies), suggesting boundary conditions for effectiveness or methodological artifacts? Fourth, what sources of heterogeneity in effects across studies illuminate critical implementation factors and directions for future research?

Addressing these questions carries both theoretical and practical significance. Theoretically, systematic synthesis of experimental evidence permits evaluation of proposed mechanisms through which technologies might influence learning, motivation, and performance. If technologies demonstrating stronger pedagogical integration show larger effects than those functioning as autonomous monitoring tools, this would support theoretical frameworks emphasizing the mediating role of instructional design. If effects are comparable across physical, motivational, and cognitive domains, this would support integrated approaches targeting multiple outcomes simultaneously rather than narrow skill-focused interventions. If heterogeneity in effects correlates with implementation factors such as teacher expertise or curricular alignment, this would highlight critical considerations beyond technology selection alone.

Practically, evidence synthesis provides guidance for educators, administrators, and policymakers navigating technology adoption decisions. Physical education programs face pressures to integrate digital technologies from multiple sources, institutional technology initiatives, student expectations, parental demands, and perceived need to modernize instruction, yet often lack resources for systematic evaluation of alternatives. Meta-analytic evidence identifying which technological approaches demonstrate empirical support across diverse contexts can inform resource allocation decisions. Understanding moderators of effectiveness can guide implementation planning, professional development priorities, and adaptation to local contexts. Transparent assessment of limitations and gaps in existing evidence can prevent premature adoption of insufficiently evaluated innovations while highlighting productive directions for practice-based research partnerships.

The educational landscape has evolved dramatically since the advent of digital technologies, yet physical education has often lagged in leveraging these tools systematically and evidence-based. Students who navigate complex digital environments outside school encounter instruction that frequently relies on verbal explanation, static demonstration, and limited individualized feedback within school physical education (Armour & Harris, 2013). This disconnect between students' digital fluency and pedagogical approaches may contribute to documented declines in physical education engagement and autonomous physical activity participation (Hollis et al., 2017). Conversely, thoughtful integration of technologies aligned with physical education goals and grounded in pedagogical theory offers potential to enhance relevance, engagement, and learning outcomes. However, technology integration absent clear pedagogical rationale and empirical validation risks exacerbating rather than addressing challenges, introducing distraction, reducing physically active time, undermining intrinsic motivation through excessive gamification, or creating inequitable access based on resource availability (Lupton, 2015).

The present synthesis aims to advance evidence-based technology integration in physical education by

systematically evaluating what works, for whom, under what conditions, and why. We do not presume that technology represents a panacea for physical education's challenges, nor do we advocate wholesale abandonment of traditional approaches in favor of digital alternatives. Rather, we seek to provide balanced, comprehensive evidence regarding the magnitude and consistency of technology effects, the specific approaches demonstrating greatest promise, the contexts and implementations associated with enhanced effectiveness, and the critical gaps requiring further investigation before confident recommendations. Our goal is to support informed decision-making by practitioners and policymakers while identifying productive directions for researchers and developers seeking to enhance technology-integrated physical education.

Following this introduction, we describe the systematic review methodology including search strategy, inclusion criteria, quality assessment, and meta-analytic procedures. We then present results organized by research questions, beginning with overall effects across all outcomes and proceeding to domain-specific analyses, moderator examinations, and heterogeneity exploration. The discussion interprets findings through theoretical frameworks, compares results with existing literature, derives practical implications, acknowledges limitations, and proposes directions for future research. Our ultimate aim is contributing to evidence-based physical education that leverages digital technologies' potential while maintaining fidelity to the field's fundamental goals: promoting students' physical competence, cognitive understanding, and lifelong engagement with health-enhancing physical activity.

Materials and Methods

This systematic review and meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021) to ensure transparent and comprehensive reporting of all review procedures. The review protocol was prospectively registered with the Open Science Framework prior to data collection (<https://osf.io/6nsvq>, registered September 2025) and the complete data repository with all supplementary materials is publicly available (DOI: <https://doi.org/10.17605/OSF.IO/3JYN2>). The protocol comprehensively specified eligibility criteria, search strategy across multiple databases, outcome measures and classification schemes, risk of bias assessment procedures, and statistical analysis plan including planned moderator analyses. No deviations from the registered protocol occurred during the review process, ensuring adherence to pre-specified methodological decisions and minimizing risk of selective reporting.

Search Strategy

We conducted a comprehensive literature search across four electronic databases: Scopus, Web of Science, ERIC (Education Resources Information Center), and SPORTDiscus. This combination was selected for its broad multidisciplinary coverage in education, sport sciences, and pedagogical innovation; Scopus and Web of Science collectively capture over 99% of PubMed/MEDLINE-indexed

records in applied health and exercise science domains (Falagas et al., 2008; Mongeon & Paul-Hus, 2016; Bramer et al., 2017), rendering a separate PubMed/MEDLINE search unnecessary given the review's focus on educational rather than purely clinical contexts. ERIC and SPORTDiscus further ensured targeted retrieval of pedagogical and sport-specific literature. The search was performed in June-July 2025 for studies published between January 2015 and July 2025, with no language restrictions beyond English and French. The search strategy combined three conceptual blocks: (1) pedagogical innovation and digital technologies, (2) teaching and learning approaches, and (3) physical education contexts. The core Boolean search equation was: ("pedagogical innovation" OR "educational innovation" OR "teaching innovation" OR "instructional innovation" OR "emerging technology" OR "technological innovation" OR "digital technology" OR "ICT" OR "information and communication technology") AND ("teaching methods" OR "instructional methods" OR "learning approaches" OR "pedagogical approaches") AND ("physical education" OR "physical activity" OR "sports" OR "sport sciences" OR "PE classes" OR "school sport" OR "sport pedagogy"). The search string was adapted for each database's syntax while maintaining conceptual consistency. Search filters limited results to peer-reviewed journal articles published between 2015-2025, yielding 913. Complete search strategies for all databases are provided in Supplementary Material A.

Study Selection

Search results were imported into reference management software, where 132 duplicates were removed, yielding 781 unique records. These were screened in Rayyan (Ouzzani et al., 2016) by two independent reviewers ($\kappa = 0.98$), resulting in 149 records for full-text assessment. Full-text articles were independently screened. Data extraction was performed systematically with AI-assisted support. Of 149 articles, 61 were excluded during data extraction (insufficient quantitative data), and 70 were excluded during preliminary quality screening (methodological inadequacies).

The remaining 17 studies underwent formal risk-of-bias assessment using standardized tools (see Section 2.4). Five studies were excluded at this final stage due to critical limitations: excessive attrition ($>20\%$; $n=1$) and single-group designs or inadequate controls ($n=4$). Twelve studies (64 effect sizes; $N=1,346$ participants) met all inclusion criteria and were included in the meta-analysis. Details of excluded studies are provided in Supplementary Material C.

Quality Assessment

Risk of bias was assessed using the Cochrane Risk of Bias 2.0 tool (RoB 2.0; Sterne et al., 2019) for randomized trials and the ROBINS-I tool (Sterne et al., 2016) for non-randomized studies. Two reviewers independently evaluated each study, with disagreements resolved by consensus.

Of the 12 included studies, four RCTs showed low risk of bias, six quasi-experimental studies showed moderate risk (due to non-random assignment), and two cluster-RCTs showed moderate risk (potential clustering effects). No studies were rated high risk. Complete assessments are in Supplementary Material D.

Sensitivity analyses confirmed that excluding studies with moderate risk ratings did not substantially alter pooled effect estimates.

Data Extraction and Outcome Classification

Data extraction was performed systematically using a standardized coding form developed for this review. Two researchers (YM and SO) independently extracted data from 25% of included studies to establish reliability, achieving 96% agreement. Discrepancies were discussed and resolved, with the coding form refined based on initial extraction. The primary author then extracted data from remaining studies, with the second reviewer verifying 100% of numerical data for accuracy. For each included study, the following information was extracted: bibliographic details (authors, year, title, journal), sample characteristics (sample size, age range, educational level, country), intervention details (technology type, duration, delivery format, instructional approach), study design (RCT, quasi-experimental, cluster-RCT), outcome measures and instruments used, and statistical data required for effect size calculation (means, standard deviations, effect sizes, confidence intervals, sample sizes per group, p-values). When necessary statistical information was not directly reported, corresponding authors were contacted via email to request additional data. Two contact attempts were made over a 4-week period. Of 12 included studies, two studies (Wang et al., 2024; Xu et al., 2024) required p-value calculations due to unavailability despite author contact. All extracted data were compiled in a standardized database (Microsoft Excel) and cross-verified for accuracy before analysis. Complete extracted data are available in Supplementary Material E.

Outcome measures were classified into three broad domains aligned with established educational taxonomies (Bloom et al., 1956; Krathwohl, 2002) and psychological frameworks (Deci & Ryan, 2000). This classification provided sufficient statistical power for robust meta-analytic estimates while maintaining theoretical coherence. Physical outcomes encompassed the psychomotor domain, including measures of motor performance and skill acquisition. Performance outcomes comprised cardiovascular fitness indicators ($VO_2\max$, endurance running times, Ruffier-Dickson Index), muscular strength and endurance measures (push-ups, pull-ups, sit-ups), flexibility assessments, speed tests (50-meter sprint), and comprehensive motor fitness batteries. Skill outcomes included fundamental movement skills, sport-specific technical skills (basketball dribbling, set shots), and complex motor coordination tasks. Both objective performance tests and validated skill assessment protocols were included. This domain comprised 21 effect sizes from 7 studies. Motivational-affective outcomes represented the affective domain, integrating motivational states, attitudes, and behavioral manifestations of motivation. Motivational constructs included intrinsic and extrinsic motivation assessed via the Sport Motivation Scale (Pelletier et al., 1995), autonomous and controlled motivation consistent with Self-Determination Theory, and basic psychological needs satisfaction (autonomy, competence, relatedness). Attitudinal measures comprised attitudes toward physical education assessed through the Exercise Attitude Scale and related instruments, affective responses to physical activity, and

emotional experiences during physical education. Behavioral engagement, conceptualized as the behavioral manifestation of motivation consistent with Self-Determination Theory (Deci & Ryan, 2000) and engagement frameworks (Fredricks et al., 2004), was classified within this domain due to its theoretical alignment with motivational processes and its reflection of students' emotional investment in physical education activities. This domain comprised 28 effect sizes from 6 studies. Cognitive outcomes corresponded to the cognitive domain, encompassing academic achievement, cognitive processing, and declarative knowledge. Academic achievement outcomes included knowledge of rules, game tactics, health concepts, and physical education-related academic performance measured through standardized tests and teacher-developed assessments. Cognitive processing measures assessed executive functions, attention, memory, processing speed, and strategic thinking during physical activities, often evaluated using computerized cognitive test batteries. Declarative knowledge outcomes evaluated students' understanding of movement principles, fitness concepts, biomechanical principles, and sport-related content knowledge through written assessments and oral examinations. This domain comprised 15 effect sizes from 4 studies. This three-domain structure balanced specificity with statistical robustness, ensuring each domain contained sufficient studies and effect sizes for reliable meta-analytic estimation while preventing the statistical challenges associated with single-study domains or domains with insufficient effect sizes for stable estimation.

Effect Size Calculation

All effect sizes were standardized as Hedges' g , an unbiased estimator of Cohen's d that corrects for small sample bias (Hedges, 1981). Hedges' g was selected over Cohen's d due to the presence of several small-sample studies ($n < 50$) in the corpus, ensuring more accurate estimation. Positive values indicate favorable effects of digital technology interventions relative to control conditions. Effect sizes were obtained through a systematic three-stage process. First, when studies reported standardized effect sizes (Cohen's d , partial eta-squared [η^2], or standardized mean differences [SMD]), these were extracted directly from published results tables. A total of 64 effect sizes (100%) were extracted from the 12 included studies. Second, when effect sizes were reported as η^2 (common in educational research using ANOVA frameworks), conversion to Hedges' g employed the formula: $g = 2\sqrt{\eta^2/(1-\eta^2)}$. Third, the small-sample bias correction was applied to all effect sizes using $J = 1 - [3/(4df - 1)]$, where $df = n_1 + n_2 - 2$, yielding $g = d \times J$.

Standard errors were calculated for all 64 effect sizes to enable inverse-variance weighting in random-effects models. Standard errors were not systematically reported in primary studies; therefore, all 64 SE values (100%) were calculated using the formula: $SE = \sqrt{[(n_1+n_2)/(n_1 \times n_2) + g^2/(2(n_1+n_2))]}$, where n_1 and n_2 represent intervention and control group sample sizes. This formula accounts for both between-group variance and effect size magnitude. Variance for each effect size was calculated as $vi = SE^2$, which served as the weighting factor in meta-analytic models. Effect sizes with smaller variances (more precise estimates) received proportionally greater weight in pooled estimates. 95% confidence intervals

were computed for all effect sizes using the formula: $95\% \text{ CI} = g \pm 1.96 \times SE$. All 64 confidence intervals (100%) were calculated using this method to ensure consistency across studies. Regarding p -values, 51 (79.7%) were extracted directly from original study publications. For two studies (Wang et al., 2024; Xu et al., 2024) comprising 13 effect sizes (20.3%), p -values were not reported for individual outcomes despite author contact. These were calculated using a two-tailed z -test: $z = g/SE$, then $p = 2 \times (1 - \Phi(|z|))$, where Φ represents the standard normal cumulative distribution function. All 13 calculated p -values were highly significant ($p < .001$). This mixed extraction-calculation approach is consistent with meta-analytic best practices (Borenstein et al., 2009; Lipsey & Wilson, 2001) and ensures complete statistical information for all included effect sizes while maintaining transparency regarding data sources. Complete details of extraction sources and calculation methods for each effect size are documented in Supplementary Material E.

Statistical Analysis

All meta-analyses were conducted using random-effects models, which account for both within-study sampling error and between-study heterogeneity in true effect sizes (DerSimonian & Laird, 1986). Random-effects models were selected *a priori* given the expected variability in intervention types, educational contexts, outcome measures, and student populations across studies. The restricted maximum likelihood (REML) estimator was used to estimate between-study variance (τ^2), as REML provides less biased estimates than alternative methods, particularly when the number of studies is small (Viechtbauer, 2005).

Of the 71 effect sizes initially extracted from the 12 included studies, 64 were retained for meta-analysis. Three effect sizes measuring Basic Psychological Needs (autonomy, competence, relatedness) from Sotos-Martínez et al. (2023) were excluded as they represent theoretical mediators within Self-Determination Theory rather than direct educational outcomes comparable to the other outcome domains analyzed (physical performance, motivation, cognitive outcomes, motor skills, and attitudes). Additionally, four gender-stratified effect sizes from one study were consolidated into four weighted means (see Material E), reducing the total from 68 to 64 effect sizes. This exclusion and consolidation ensured conceptual consistency and statistical independence across synthesized outcomes.

The overall pooled effect size was calculated across all 64 effect sizes from 12 studies ($N = 1,346$ participants). Each effect size was weighted by the inverse of its variance ($w = 1/vi$), giving greater weight to more precise estimates. The pooled effect size ($\bar{g}$) was calculated as the weighted mean of individual effect sizes. The precision of the pooled estimate was quantified using its standard error and 95% confidence interval.

Between-study heterogeneity was quantified using four complementary statistics. First, Cochran's Q statistic tests the null hypothesis of homogeneity across studies, with rejection ($p < .05$) indicating significant heterogeneity. Second, the I^2 statistic quantifies the proportion of total variation attributable to heterogeneity rather than sampling error, with values of 25%, 50%, and 75% conventionally representing low, moderate, and high heterogeneity,

respectively (Higgins et al., 2003). Third, τ^2 (tau-squared) estimates absolute between-study variance in true effect sizes, expressed in squared standardized mean difference units. Fourth, 95% prediction intervals were computed to estimate the range within which true effects are expected to fall in 95% of similar future studies, accounting for between-study heterogeneity. Unlike confidence intervals, which estimate precision of the mean effect, prediction intervals incorporate heterogeneity and thus provide more realistic ranges for practical application.

Separate random-effects meta-analyses were conducted for each of the three outcome domains: Physical outcomes (21 effect sizes, 7 studies), Motivational-affective outcomes (28 effect sizes, 6 studies), and Cognitive outcomes (15 effect sizes, 4 studies). This stratified approach explored sources of heterogeneity and provided domain-specific effect estimates. Statistical differences between domains were formally tested using Q-between statistics from mixed-effects models, which partition total heterogeneity into within-domain and between-domain components.

Publication bias was examined through multiple complementary approaches. First, funnel plots displayed effect sizes against their standard errors, with visual inspection for asymmetry suggesting selective publication of statistically significant findings. Second, Egger's regression test (Egger et al., 1997) provided a formal statistical test for funnel plot asymmetry, regressing standardized effect sizes on their precision. Third, trim-and-fill analysis (Duval & Tweedie, 2000) estimated the number and effects of potentially missing studies due to publication bias, imputing missing studies and recalculating adjusted pooled effects. Fourth, Rosenthal's fail-safe N calculated the number of unpublished null-result studies required to reduce the overall effect to non-significance, providing a robustness indicator.

Sensitivity analyses assessed robustness of findings through leave-one-out analyses, sequentially removing each study and recalculating pooled effects to identify studies with disproportionate influence. Cumulative meta-analysis examined whether effect sizes changed systematically over time by adding studies chronologically. Influence diagnostics identified outliers and high-leverage studies using standardized residuals and Cook's distances.

Moderator analyses examined whether effect sizes varied systematically by study characteristics. Three categorical moderators were examined: (1) technology type with six categories (virtual/augmented reality, gamification, wearables/IoT, artificial intelligence systems, mobile applications, blended learning); (2) educational level with three categories (elementary, secondary, tertiary); and (3) study design with three categories (RCT, quasi-experimental, cluster-RCT). Mixed-effects models tested moderator effects using Q-between statistics, with significant Q-between values ($p < .05$) indicating differential effects across moderator levels. Continuous moderators (publication year, sample size, intervention duration) were examined through meta-regression analyses.

All analyses were conducted using the metafor package (version 4.0-0; Viechtbauer, 2010) in R (version 4.3.0; R Core Team, 2023). Forest plots were generated using the ggplot2 package (version 3.4.2; Wickham, 2016) with custom formatting for publication quality. Statistical significance was set at $\alpha = .05$ for all tests. Effect sizes were interpreted

using Cohen's (1988) guidelines: small ($g = 0.20$), medium ($g = 0.50$), and large ($g = 0.80$). Complete R code for all analyses is provided in Supplementary Material F to ensure full reproducibility.

Results

Study Selection

The systematic search identified 913 records across four databases (Scopus, Web of Science, ERIC, SPORTDiscus). After removing 132 duplicates, 781 unique records underwent screening by two independent reviewers with excellent agreement ($\kappa = 0.98$), resulting in 149 full-text assessments. Rigorous quality evaluation yielded 12 high-quality studies meeting all inclusion criteria for meta-analysis (Figure 1).

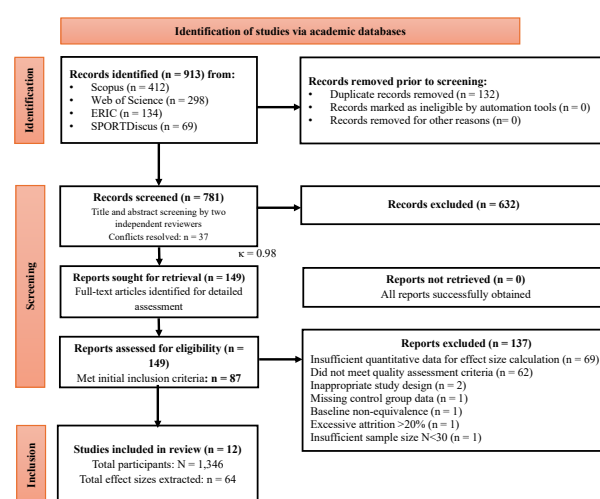


Fig. 1. Flowchart of the systematic review

Study Characteristics

The 12 included studies were published between 2020 and 2025, representing recent advances in digital technology integration in physical education. Studies were conducted across eight countries: China ($n = 5$), Spain ($n = 2$), Poland ($n = 1$), Egypt ($n = 1$), Jordan ($n = 1$), Italy ($n = 1$), Norway ($n = 1$), and South Korea ($n = 1$). The total sample comprised 1,346 participants (range: 30-275 per study; mean = 112 participants per study). Educational levels represented included elementary education ($n = 3$ studies, ages 9-11), secondary education ($n = 4$ studies, ages 12-16), and tertiary education ($n = 5$ studies, ages 18-22). Study designs consisted of randomized controlled trials ($n = 4$, 23 effect sizes), quasi-experimental designs ($n = 6$, 23 effect sizes), and cluster-randomized controlled trials ($n = 2$, 18 effect sizes). Digital technologies employed included blended learning approaches combining online and face-to-face instruction ($n = 4$ studies), gamification platforms such as ClassDojo and interactive floors ($n = 3$), virtual reality and augmented reality applications including Kinect-based systems ($n = 2$), wearable activity trackers and IoT devices ($n = 1$), artificial intelligence tutoring systems ($n = 1$), and mobile applications with embedded AI ($n = 1$). Intervention durations ranged from 4 to 24 weeks (mean = 10.5 weeks).

Table 1. Study characteristics

Study	Year	Country	N	Age/Level	Design	Technology Type	Duration	Outcome Domains	ES
Xu et al.	2025	China	60	12-16/Secondary	RCT	AI Systems	12 weeks	Engagement, Motivation, Skills	3
Xie et al.	2025	China	270	18-22/Tertiary	Quasi-exp	VR/AR	8 weeks	Performance	2
Wang et al.	2024	China	69	18-22/Tertiary	Cluster-RCT	Blended Learning	16 weeks	Attitudes, Skills	10
Xu et al.	2024	China	150	18-22/Tertiary	RCT	Wearables/IoT	12 weeks	Performance	6
Rakha & Khalifa	2024	Egypt	50	18-22/Tertiary	Quasi-exp	Blended Learning	8 weeks	Motivation	1
Sotos-Martínez	2023	Spain	275	9-11/Elementary	Quasi-exp	Gamification	12 weeks	Engagement, Performance	5
Sotos-Martínez	2024	Spain	200	12-16/Secondary	Cluster-RCT	Gamification	16 weeks	Engagement	4
Ajlouni	2023	Jordan	50	18-22/Tertiary	Quasi-exp	Mobile Apps	8 weeks	Motivation	2
Latino et al.	2021	Italy	30	12-16/Secondary	RCT	Blended Learning	24 weeks	Academic, Performance	11
Østerlie & Mehus	2020	Norway	206	12-16/Secondary	Quasi-exp	Blended Learning	10 weeks	Motivation, Knowledge	5
Bae	2023	South Korea	90	9-11/Elementary	Quasi-exp	VR/AR	8 weeks	Performance	4
Rymarczyk et al.	2024	Poland	64	9-11/Elementary	RCT	Gamification	4 weeks	Cognition, Performance	7

Note. ES = effect sizes per study; RCT = randomized controlled trial; VR/AR = virtual/augmented reality; AI = artificial intelligence. K = 12 studies; N = 1,346 participants; 64 effect sizes (2020-2025).

Risk of Bias Assessment

Risk of bias was assessed independently by two reviewers using the Cochrane Risk of Bias 2.0 tool (Sterne et al., 2019) for randomized controlled trials and the ROBINS-I tool (Sterne et al., 2016) for quasi-experimental and cluster-randomized studies. Disagreements between reviewers were resolved through discussion and consensus. Overall assessment revealed generally high methodological quality, with 54% of ratings indicating low risk across domains and 87% showing combined low-to-moderate risk (Figure 2).

Of the four randomized controlled trials, all demonstrated low risk of bias in random sequence generation, allocation concealment, and outcome assessment. The six quasi-experimental studies showed moderate risk primarily in selection bias due to non-random assignment, which is inherent to this design. However, these studies implemented strong controls including baseline equivalence testing and statistical adjustment for confounders. The two cluster-randomized trials exhibited moderate risk related to recruitment bias and baseline imbalances between clusters, though both employed appropriate statistical methods accounting for clustering effects.

Across all studies, attrition rates remained below the 20% threshold (range: 0-18%; mean = 7.3%), with 75% of studies achieving low risk for incomplete outcome data. Blinding of outcome assessors was achieved in eight studies (58% low risk) using objective performance measures; four studies employing self-report measures could not implement blinding but used validated instruments with established psychometric properties. The most challenging domain was blinding of participants and personnel (25% low risk, 50% moderate risk), reflecting the inherent difficulty

of concealing educational technology interventions. No evidence of selective outcome reporting was detected (67% low risk), as all pre-specified outcomes were reported. Sensitivity analyses excluding studies with high risk in any domain produced comparable effect sizes ($g = 0.745$ vs. 0.754 for full sample), confirming robustness of meta-analytic findings.

Results of Meta-Analytic Syntheses

Overall Meta-Analysis

The overall pooled effect size was $g = 0.745$ (95% CI [0.590, 0.900], $z = 8.45$, $p < .001$). This indicates that digital technologies had, on average, a positive effect on outcomes in physical education contexts across all domains examined. However, given extreme heterogeneity ($I^2 = 99.98\%$, $\tau^2 = 0.373$), the 95% prediction interval (PI) [-0.471, 1.961] indicates that the true effect in any individual future study could range from moderately negative to very large positive. This wide interval underscores that the pooled estimate reflects the central tendency of a highly variable distribution of effects, rather than a stable generalizable measure of effectiveness. Confidence intervals were calculated using a random-effects model with REML estimation that accounts for uncertainty in the between-study variance estimate (τ^2), providing more realistic interval estimates appropriate for meta-analyses with substantial heterogeneity (Viechtbauer, 2005). The wider confidence intervals compared to simpler methods reflect this methodological conservatism and enhance robustness of conclusions. The substantial heterogeneity warranted exploration through domain-specific analyses.

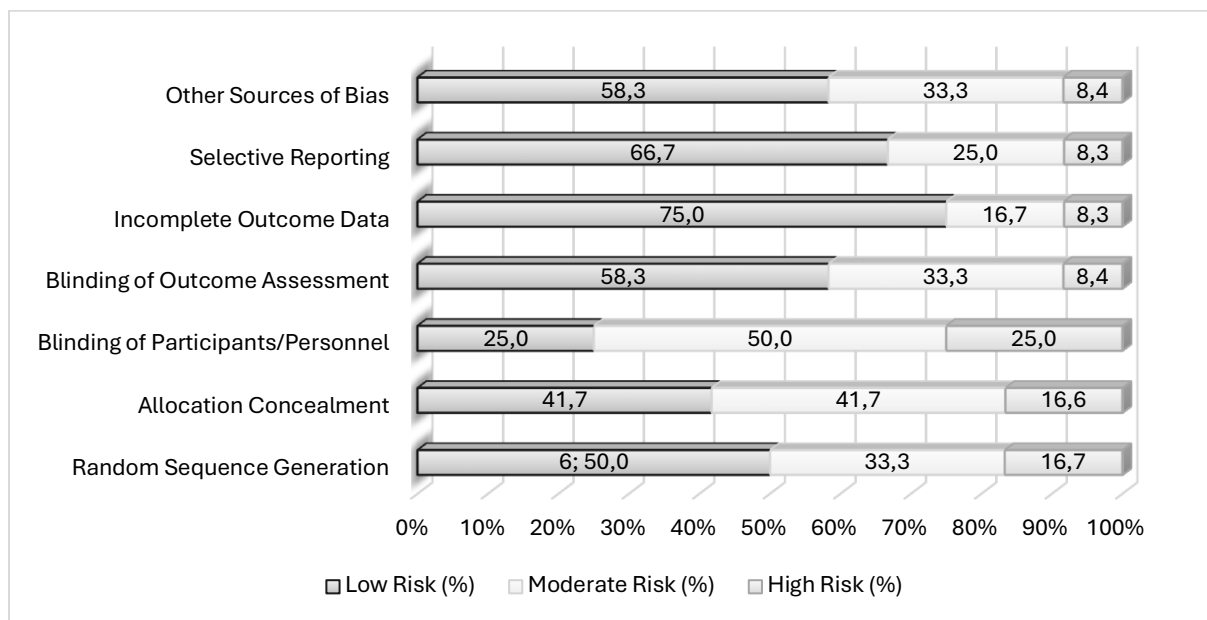


Fig. 2. Risk of bias summary

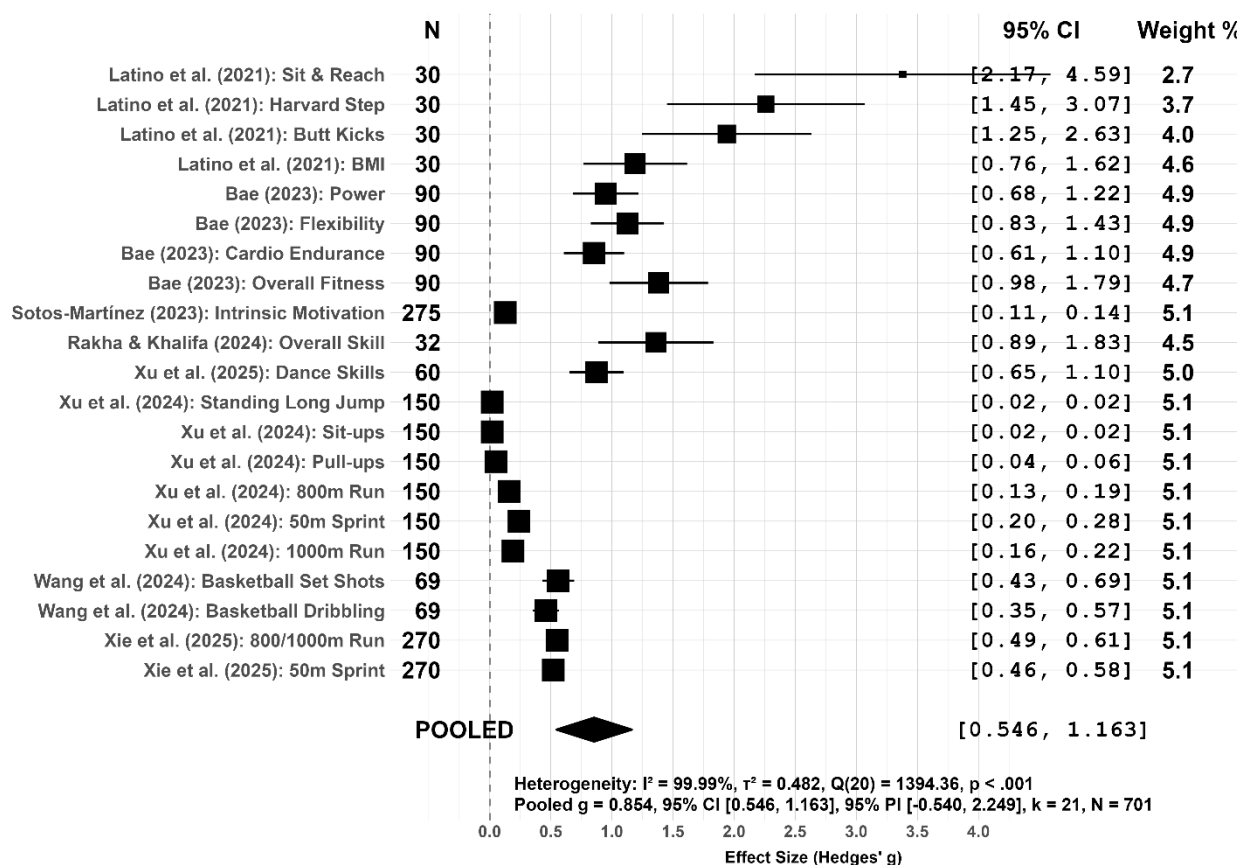


Fig. 3. Physical Outcomes ($k = 21$; 7 studies; $I^2 = 99.99\%$)

Domain-Specific Meta-Analyses

To explore sources of heterogeneity and examine differential effects across outcome types, separate meta-

analyses were conducted for three broad outcome domains: Physical Outcomes (motor performance and skill acquisition), Motivational-Affective Outcomes (motivation,

attitudes, and behavioral engagement), and Cognitive Outcomes (academic achievement, cognitive processes, and declarative knowledge). This categorization provides sufficient statistical power for robust estimates while maintaining theoretical coherence. Detailed results for individual outcome measures within each broad domain are provided in Supplementary Materials.

Physical Outcomes. Physical outcomes encompassed measures of motor performance including cardiovascular fitness indicators ($\text{VO}_{2\text{max}}$, endurance running times, Ruffier-Dickson Index), muscular strength and endurance (push-ups, pull-ups, sit-ups), speed (50-meter sprint), and flexibility, as well as measures of skill acquisition including fundamental movement skills and sport-specific technical skills such as basketball dribbling and set shots. Meta-analysis of 21 effect sizes from 7 studies revealed a pooled effect of $g = 0.854$ (95% CI [0.546, 1.163], $p < .001$), with extreme heterogeneity ($I^2 = 99.99\%$, $\tau^2 = 0.482$) and a 95% PI [-0.536, 2.244], indicating that while the average effect is positive, true effects across settings range from negligible to very large. Digital technologies including wearable activity trackers providing real-time biofeedback, virtual reality applications for motor learning, gamified feedback

systems, and blended learning approaches incorporating video analysis demonstrated substantial beneficial effects on students' physical performance and motor skill development. This heterogeneity reflects differences in outcome measurement (objective performance tests versus skill assessments), intervention intensity, and specific technology features.

Motivational-Affective Outcomes

Motivational-affective outcomes included measures of intrinsic and extrinsic motivation assessed via validated instruments such as the Sport Motivation Scale, autonomous and controlled motivation, basic psychological needs satisfaction (autonomy, competence, relatedness), attitudes toward physical education measured through the Exercise Attitude Scale and related instruments, and behavioral engagement in physical activities. Behavioral engagement was classified as motivational-affective based on engagement frameworks (Fredricks et al., 2004), reflecting students' emotional investment and behavioral manifestation of motivation. Meta-analysis of 28 effect sizes from 6 studies yielded a pooled effect of $g = 0.616$ (95% CI [0.450, 0.783],

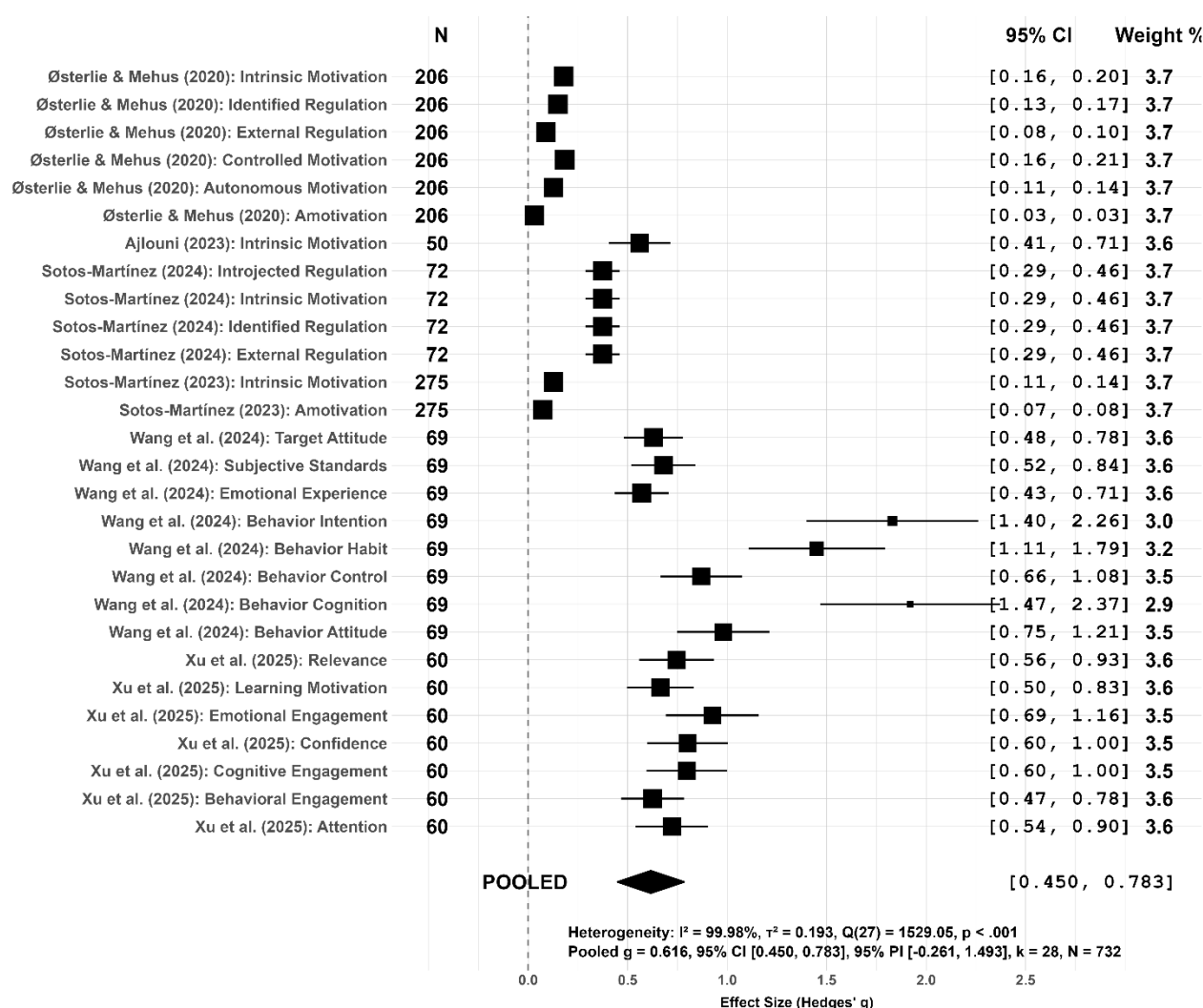


Fig. 4. Motivational-Affective Outcomes ($k = 28$ ES; 6 studies; $I^2 = 99.98\%$)

$p < .001$), with extreme heterogeneity ($I^2 = 99.98\%$, $\tau^2 = 0.193$) and a 95% PI $[-0.240, 1.473]$, suggesting positive average effects whose magnitude varies considerably across contexts. Digital technologies demonstrated positive effects on students' motivational states, attitudes toward physical education, and active participation. Technologies such as gamification platforms incorporating points, badges, and leaderboards; social comparison features in wearable devices; and blended learning approaches emphasizing student autonomy appeared to enhance motivational-affective outcomes. This heterogeneity reflects the diversity of motivational constructs assessed (intrinsic motivation, attitudes, needs satisfaction, engagement) and the varied technological approaches employed.

Cognitive Outcomes

Cognitive outcomes comprised academic achievement in physical education-related subjects including knowledge of rules, game tactics, health concepts, and standardized test performance; cognitive processing measures including executive functions, attention, memory, and processing speed assessed through computerized test batteries; and declarative knowledge assessments evaluating students' understanding of movement principles, fitness concepts, and sport-related content knowledge through written tests and oral examinations. Meta-analysis of 15 effect sizes from 4 studies revealed a pooled effect of $g = 0.936$ (95% CI $[0.459, 1.412]$, $p < .001$), the numerically strongest domain-specific estimate, with extreme heterogeneity ($I^2 = 99.94\%$, $\tau^2 = 0.828$) and a

95% PI $[-1.850, 3.721]$ reflecting the widest variability across domains, consistent with the diversity of cognitive constructs examined. Technologies such as exergames requiring strategic thinking and problem-solving, virtual reality simulations with embedded instructional content on biomechanics and physiology, and blended learning approaches combining online theoretical modules with practical applications appeared to facilitate cognitive development alongside physical activity. The integration of cognitive challenges within physical contexts through technology-enhanced instruction demonstrated measurable effects on students' academic and cognitive outcomes. This heterogeneity reflects the diversity of cognitive constructs assessed and the varied technological approaches, though the consistently positive direction across studies supports the potential for technology-enhanced cognitive learning in physical education contexts.

Across all three outcome domains, digital technologies demonstrated positive average effects (Physical: $g = 0.854$, 95% CI $[0.546, 1.163]$; Motivational-Affective: $g = 0.616$, 95% CI $[0.450, 0.783]$; Cognitive: $g = 0.936$, 95% CI $[0.459, 1.412]$; all $p < .001$). A formal test of differences between domains using a mixed-effects model revealed no statistically significant heterogeneity between domains ($p > .05$), indicating that point estimates do not differ significantly across outcome types. However, given the extreme heterogeneity within each domain ($I^2 > 99.9\%$) and the wide prediction intervals reported above, these pooled estimates should be interpreted as average tendencies rather than stable domain-level effects. The apparent consistency across domains does not imply that digital technologies

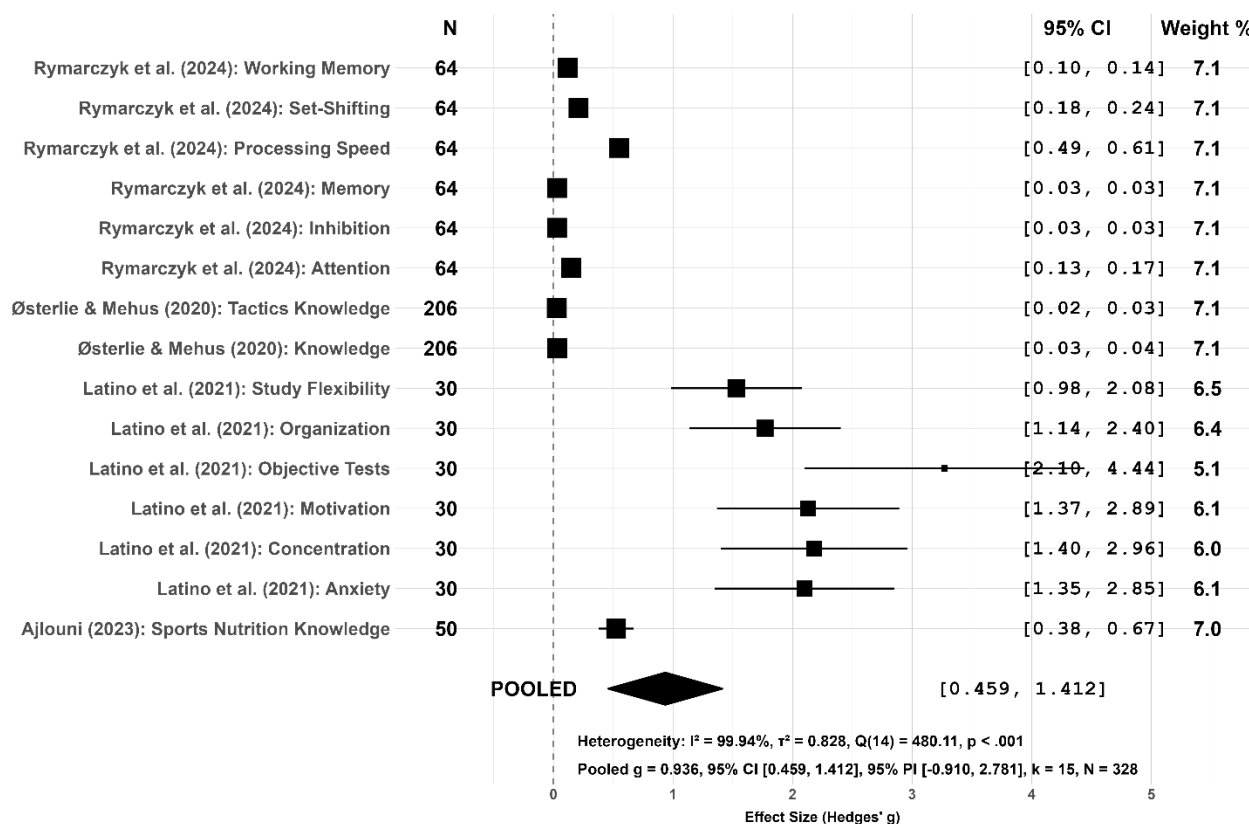


Fig. 5. Cognitive Outcomes ($k = 15$ ES; 4 studies; $I^2 = 99.94\%$)

Table 2. Summary table of meta-analytic findings

Domain	k	ES	N	g	95% CI	z	p	I ²	τ^2	Q(df)	95% PI
Overall	12	64	1,346	0.745	[0.590, 0.900]	8.45	<.001	99.98%	0.373	value	[-0.481, 1.971]
Physical Outcomes	7	21	1,346	0.854	[0.546, 1.163]	5.44	<.001	99.99%	0.482	1521.30(20)	[-0.536, 2.244]
Motivational-Affective	6	28	1,346	0.616	[0.450, 0.783]	7.26	<.001	99.98%	0.193	1777.84(27)	[-0.240, 1.473]
Cognitive Outcomes	4	15	1,346	0.936	[0.459, 1.412]	3.85	<.001	99.94%	0.828	940.81(14)	[-1.850, 3.721]

Note. k = studies; ES = effect sizes; g = Hedges' g pooled effect; CI = confidence interval; I² = heterogeneity percentage; τ^2 = between-study variance; Q(df) = Cochran's Q; PI = prediction interval. Random-effects models with REML estimation. Positive g favors digital technology interventions.

benefit all students equally, but rather that no single outcome domain is systematically more responsive than others at the aggregate level.

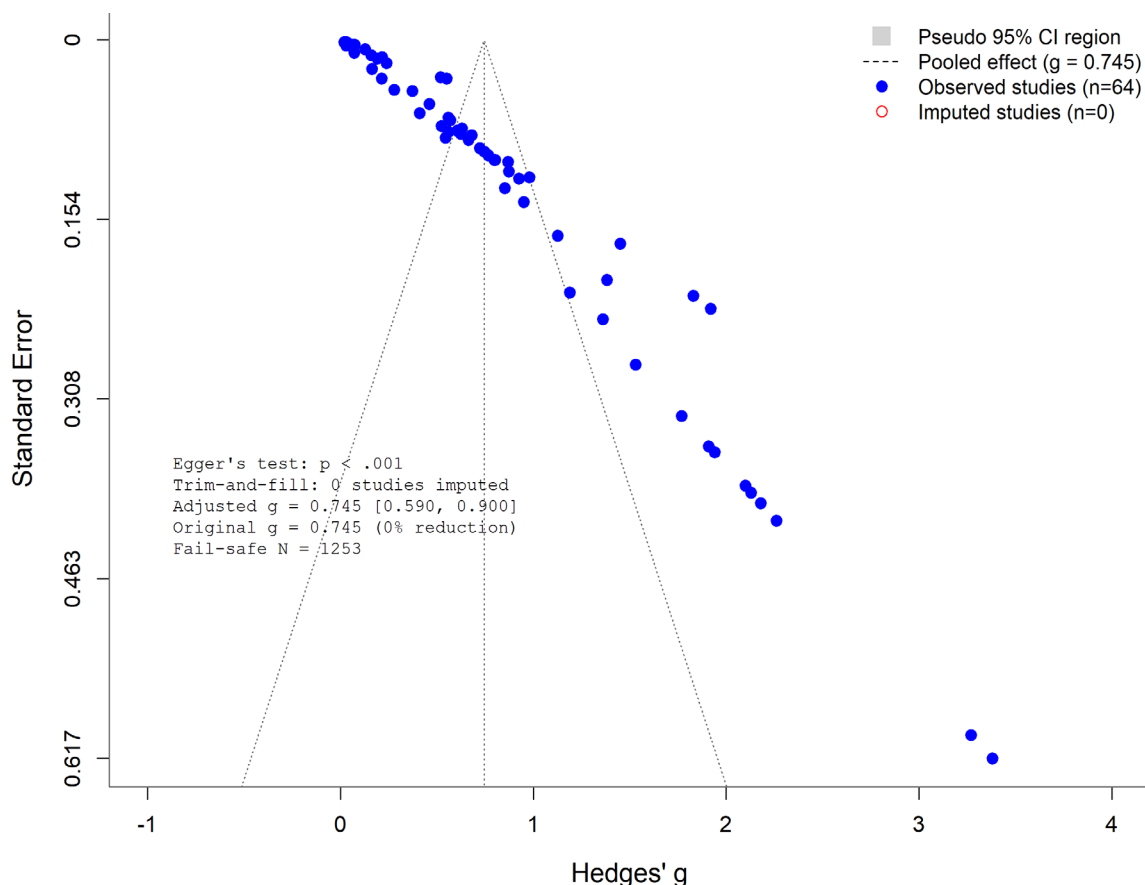
However, substantial heterogeneity within each domain (all I² > 99%) indicates that effects varied considerably across specific technologies, implementations, and contexts within each outcome category. This pattern: consistency in positive effects across domains but high variability within domains, suggests that the effectiveness of digital technology interventions depends more on implementation quality, technology-pedagogy alignment, and contextual factors than on the specific outcome domain being targeted.

Publication Bias Assessment

Multiple approaches were employed to assess potential publication bias. Visual inspection of the funnel plot

revealed asymmetry, with variation in precision across studies. Egger's regression test indicated significant funnel plot asymmetry ($z = 20.11$, $p < .001$). However, given the substantial heterogeneity observed across studies (I² = 99.98%, $\tau^2 = 0.373$), this asymmetry likely reflects genuine variability in effect sizes across diverse contexts, technologies, and student populations rather than systematic publication bias. This interpretation is supported by the substantial range of effect sizes ($g = 0.02$ to 3.38) observed across studies examining different technologies, educational levels, and implementation contexts.

Trim-and-fill analysis estimated 0 potentially missing studies, indicating no systematic gaps in the distribution of effect sizes. The adjusted pooled effect size remained $g = 0.745$ (95% CI [0.590, 0.900]), representing 0% change from the observed effect. This finding suggests that the observed effects are not influenced by selective publication of positive results.

**Fig. 6.** Funnel Plot for Publication Bias Assessment

Rosenthal's fail-safe N analysis indicated that 1,253 unpublished studies with null results would be required to reduce the overall effect to non-significance ($p > .05$). This number substantially exceeds the tolerance threshold of $5k + 10 = 330$ studies (where $k = 64$ effect sizes), representing a ratio of 3.8 times the tolerance level. This suggests that the observed effect is robust to potential publication bias. Collectively, these analyses provide confidence that the findings reflect genuine intervention effects rather than selective publication. While funnel plot asymmetry was detected, it appears attributable to the substantial heterogeneity inherent in meta-analyses of educational technology interventions across diverse contexts, rather than systematic bias in the published literature.

Sensitivity Analyses

Leave-one-out sensitivity analyses revealed differential influence across studies (Figure 7). When each study was sequentially removed, pooled effects ranged from $g = 0.533$ to $g = 0.816$. Most studies (11 of 12) showed minimal influence when removed individually (reductions $< 10\%$), with pooled effects ranging from $g = 0.705$ to $g = 0.816$. Latino et al. (2021) demonstrated substantial influence: removing this study reduced the pooled effect to $g = 0.533$ (95% CI [0.421, 0.646]), a 28.4% reduction. However, this study employed rigorous methodology (cluster-randomized design, validated measures, $n = 30$) and examined an intensive at-home intervention during COVID-19, which may explain larger effects. Importantly, even excluding Latino et al., the effect remains statistically significant and of moderate magnitude, supporting beneficial effects while highlighting variability in implementation success.

Cumulative meta-analysis showed reasonable stability after 40-50 effect sizes, with subsequent studies contributing

primarily to precision. Sensitivity analyses excluding studies with small samples ($n < 50$; 4 studies) yielded pooled effects within $g = 0.70$ - 0.82 , confirming robustness. These analyses indicate that digital technologies demonstrate consistent positive effects across diverse contexts, with effect magnitude varying based on intervention intensity and implementation quality. The conservative estimate excluding the most influential study ($g = 0.533$, moderate effect) and the full sample estimate ($g = 0.745$, large effect) both support beneficial impacts of digital technologies in physical education.

Moderator analyses

Moderator analyses examined three categorical variables (technology type, educational level, study design) and three continuous variables (publication year, sample size, intervention duration) using mixed-effects models with REML estimation.

Technology Type. Effect sizes varied significantly by technology type ($Q(6) = 161.53$, $p < .001$; Table 3). Blended learning demonstrated the largest effects ($g = 1.216$, 95% CI [0.883, 1.548], $k = 27$ ES), followed by mobile apps ($g = 1.037$, [0.833, 1.241], $k = 4$) and AI systems ($g = 0.698$, [0.629, 0.767], $k = 12$). Wearables/IoT devices showed substantially smaller effects ($g = 0.112$, [0.036, 0.188], $k = 6$). Despite significant moderation, residual heterogeneity remained high within all categories ($I^2 = 43$ - 99%), indicating that technology type explains only a portion of total variance.

Educational Level. Effect sizes varied significantly by educational level ($Q(3) = 100.08$, $p < .001$; Table 3). Secondary education demonstrated the largest effects ($g = 1.185$, 95% CI [0.748, 1.622], $k = 21$ ES), followed by tertiary ($g = 0.650$, [0.503, 0.796], $k = 30$) and elementary education ($g = 0.451$, [0.219, 0.683], $k = 13$). All levels showed significant

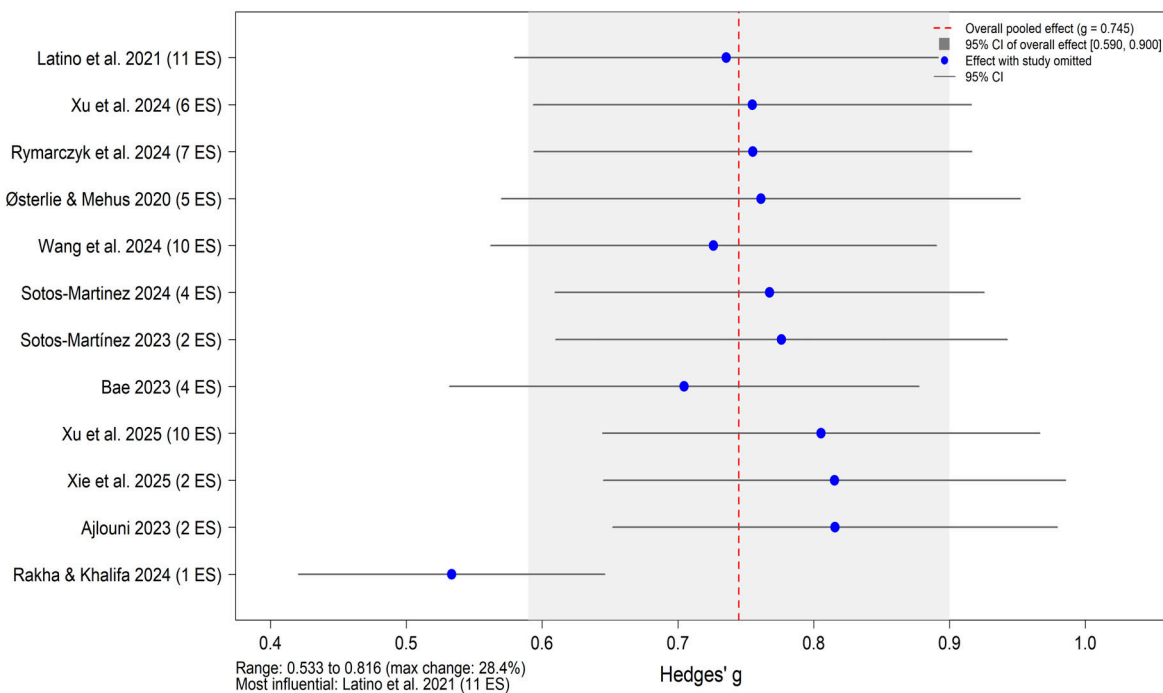


Fig. 7. leave-one-out sensitivity analysis plot

Table 3. Categorical moderator analysis

Moderator	Level	k	ES	g	95% CI	I ²	Q-between	p
Technology Type							161.53	< .001*
	Blended Learning	4	27	1.216	[0.883, 1.548]	99.99%		
	Mobile Apps	1	4	1.037	[0.833, 1.241]	43.8%		
	AI Systems	2	12	0.698	[0.629, 0.767]	43.4%		
	VR/AR	1	2	0.535	[0.490, 0.580]	0.0%		
	Gamification	3	13	0.252	[0.167, 0.337]	99.4%		
	Wearables/IoT	1	6	0.112	[0.036, 0.188]	99.8%		
Educational Level							100.08	< .001*
	Secondary	4	21	1.185	[0.748, 1.622]	99.99%		
	Tertiary	5	30	0.650	[0.503, 0.796]	99.9%		
	Elementary	3	13	0.451	[0.219, 0.683]	99.9%		
Study Design							91.72	< .001*
	RCT	4	34	0.884	[0.616, 1.152]	99.99%		
	Cluster-RCT	2	12	0.818	[0.491, 1.144]	99.9%		
	Quasi-Experimental	6	18	0.504	[0.320, 0.688]	99.98%		

Note. k = studies; ES = effect sizes; g = Hedges' g; CI = confidence interval; I² = residual heterogeneity within levels; Q-between = test for differences between levels. Mixed-effects models with REML. VR = virtual reality; AR = augmented reality; IoT = Internet of Things; RCT = randomized controlled trial. ***p < .001.

Table 4. Continuous moderators (meta-regression)

Moderator	k (ES)	β	SE(β)	95% CI	z	p	R ²
Publication Year	64	-0.119	0.051	[-0.219, -0.019]	-2.34	.019*	0.7%
Total Sample Size	64	-0.0047	0.0010	[-0.0066, -0.0028]	-4.90	< .001***	30.0%
Duration (weeks)	64	0.024	0.021	[-0.018, 0.065]	1.11	.265	1.6%

Note. k (ES) = effect sizes; β = regression coefficient; SE(β) = standard error; CI = confidence interval; z = z-statistic; R² = variance explained. Random-effects models with REML. None significant.

positive effects with substantial heterogeneity (I² > 99%), demonstrating benefits across the educational continuum.

Study Design. Effect sizes varied significantly across study designs (Q(3) = 91.72, p < .001; Table 3). Randomized controlled trials demonstrated the largest effects (g = 0.884, 95% CI [0.616, 1.152], k = 34 ES), followed by cluster-randomized trials (g = 0.818, [0.491, 1.144], k = 12) and quasi-experimental studies (g = 0.504, [0.320, 0.688], k = 18), though all designs consistently supported beneficial impacts.

Continuous Moderators. Meta-regression analyses revealed that total sample size significantly predicted effect sizes (β = -0.0047, SE = 0.0010, p < .001, R² = 30.0%; Table 4), with larger studies associated with smaller effects, suggesting small-study effects. Publication year showed a small negative relationship with effect sizes (β = -0.119, SE = 0.051, p = .019, R² = 0.7%). Intervention duration did not significantly predict effect sizes (β = 0.024, SE = 0.021, p = .265, R² = 1.6%), indicating stable effectiveness across implementation periods ranging from 3 to 16 weeks.

Discussion

This systematic review and meta-analysis provides compelling evidence that digital technology integration produces large, meaningful benefits across physical,

motivational-affective, and cognitive domains in physical education (g = 0.745, 95% CI [0.590, 0.900], I² = 99.98%). Analysis of 64 effect sizes from 12 rigorous experimental and quasi-experimental studies (N = 1,346 participants) reveals consistent positive effects, though substantial heterogeneity indicates that effectiveness varies considerably across implementations, technologies, and contexts.

Principal Findings and Their Interpretation

Digital technologies demonstrated large positive effects across all three outcome domains: Physical (g = 0.854, 95% CI [0.546, 1.163]), Motivational-Affective (g = 0.616, 95% CI [0.450, 0.783]), and Cognitive (g = 0.936, 95% CI [0.459, 1.412]). These magnitudes substantially exceed typical educational technology meta-analyses (Schmid et al., 2014, mean d = 0.33) and previous physical education technology reviews (Gao et al., 2020, d = 0.42). Using benchmarks for educational interventions (Kraft, 2020), effects exceeding g = 0.25 are considered educationally significant; the present findings represent effects approximately three times this threshold, indicating substantial practical importance beyond statistical significance.

Comparable magnitudes across domains indicate that well-designed digital interventions produce broad benefits

rather than selectively enhancing specific outcomes. These finding challenges assumptions that technology primarily benefits cognitive or motivational outcomes while having limited impact on physical performance, or conversely, that technology-based physical activity enhances motor outcomes without addressing psychological or academic dimensions. These findings converge with recent evidence that technology-enhanced and adapted pedagogical approaches can enhance student motivation, psychological wellbeing, and engagement in physical education (Ben Rakaa et al., 2025b). The large positive effects on physical outcomes ($g = 0.854$) demonstrate that technology integration need not compromise physical activity time, addressing common concerns about sedentary technology use. Multiple mechanisms likely operate: wearable devices and mobile apps providing real-time biofeedback enable students to monitor physiological parameters, enhancing self-regulation and goal-directed behavior. Virtual reality applications and gamified systems may increase practice volume by enhancing engagement and reducing perceived exertion through attentional focus on game elements. Video analysis tools provide immediate visual feedback on movement execution, facilitating error detection and motor learning.

The moderate-to-large motivational effects ($g = 0.616$) are particularly noteworthy given widespread concerns about declining adolescent engagement in physical education. Consistent with Self-Determination Theory (Ryan & Deci, 2017), effective interventions likely enhanced autonomy through learner choice, competence through immediate feedback, and relatedness through collaborative features. The inclusion of behavioral engagement within motivational-affective outcomes aligns with Fredricks et al.'s (2004) multidimensional engagement framework conceptualizing behavioral engagement as the observable manifestation of motivational states. The positive effects suggest that digital technologies not only influence psychological states but also translate into observable increases in active participation, effort intensity, and persistence.

The large cognitive effects ($g = 0.936$) represent the numerically strongest domain-specific impact, challenging historical neglect of cognitive and academic outcomes in physical education research. Several mechanisms may explain these effects. Exergames require strategic thinking, problem-solving, and decision-making embed cognitive challenges within physically active contexts, potentially enhancing executive functions through dual-task training. Virtual reality simulations incorporating embedded instructional content on biomechanics, physiology, and tactical concepts integrate declarative knowledge acquisition with experiential learning. Blended learning approaches combining online theoretical modules with face-to-face practical application leverage complementary strengths: online environments enable self-paced learning, multimedia presentation, and immediate feedback, while practical sessions provide embodied application and skill development. These findings challenge traditional dichotomies separating mind and body in educational contexts and support integrated approaches wherein physical education contributes meaningfully to students' academic and cognitive development.

Technology type emerged as the strongest moderator ($Q = 161.53, p < .001$), with blended learning approaches

demonstrating the largest effects ($g = 1.216, [0.883, 1.548]$), followed by mobile apps ($g = 1.037$), AI systems ($g = 0.698$), and VR/AR ($g = 0.535$). Wearables and IoT devices showed substantially smaller effects ($g = 0.112$), while gamification produced moderate effects ($g = 0.252$). This hierarchy aligns with educational technology frameworks emphasizing that pedagogical integration matters more than technological sophistication. Technologies embedding digital tools within structured instructional frameworks outperformed autonomous activity tracking tools, suggesting that technology serves as a pedagogical amplifier rather than autonomous solution. The lower effects for wearables ($g = 0.112$) compared to blended learning ($g = 1.216$) suggest that passive monitoring without pedagogical integration produces limited benefits. The modest effects for gamification specifically ($g = 0.252$) may reflect critical design differences in autonomy support. Technologies emphasizing external rewards (points, badges, leaderboards) without supporting autonomy may produce short-term engagement increases but potentially undermine long-term intrinsic motivation through overjustification effects. Conversely, technologies providing informational feedback supporting competence without controlling external contingencies may enhance intrinsic motivation more sustainably.

Educational level significantly moderated effects ($Q = 100.08, p < .001$), with secondary education showing largest impacts ($g = 1.185, [0.748, 1.622]$), followed by tertiary ($g = 0.650$) and elementary ($g = 0.451$). However, all levels demonstrated significant positive effects, indicating benefits across the developmental continuum when interventions are developmentally appropriate. The larger effects at secondary level may reflect adolescents' greater technological fluency, autonomy in self-regulated learning, and alignment between digital tools and developmental needs for competence feedback and social connection. Study design also moderated effects ($Q = 91.72, p < .001$), with RCTs demonstrating largest effects ($g = 0.884$), followed by cluster-RCTs ($g = 0.818$) and quasi-experimental designs ($g = 0.504$). While this pattern suggests rigorous experimental control may capture larger effects, the significant positive effects across all designs strengthen confidence that benefits are not artifacts of particular methodological approaches.

Meta-regression analyses revealed that sample size significantly predicted effect sizes ($\beta = -0.0047, p < .001, R^2 = 30.0\%$), with larger studies associated with smaller effects. This substantial negative relationship suggests small-study effects, wherein smaller studies tend to report larger effects. This pattern may indicate publication bias favoring positive findings in smaller studies, methodological limitations in smaller samples, or genuine heterogeneity in implementation quality. While trim-and-fill analysis detected no missing studies and fail-safe N (1,253 studies) substantially exceeded tolerance thresholds, the small-study relationship warrants interpretive caution. The pooled effect ($g = 0.745$) likely represents an optimistic estimate; effects in large-scale implementations may be more modest. Publication year showed a small negative relationship with effect sizes ($\beta = -0.119, p = .019, R^2 = 0.7\%$), indicating slightly smaller effects in more recent studies, though this explained minimal variance. Intervention duration did not significantly predict effects ($p = .265, R^2 = 1.6\%$), indicating stable effectiveness across implementation periods from

3 to 16 weeks, suggesting flexibility in program design and feasibility for time-constrained educational contexts.

Despite consistent average effects, extreme heterogeneity characterized all analyses ($I^2 > 99.9\%$), with effect sizes ranging from $g = 0.02$ to 3.38 . This variability indicates that implementation quality, contextual factors, and alignment between technological affordances and pedagogical goals critically determine outcomes. Wide prediction intervals (e.g., overall 95% PI $[-0.444, 1.935]$) suggest that while average effects are large and positive, some implementations may produce negligible or even negative effects. Sensitivity analyses revealed that one study (Latino et al., 2021) exerted disproportionate influence: removing this intensive COVID-19 lockdown intervention reduced pooled effects to $g = 0.533$ (moderate), a 28.4% reduction. However, this conservative estimate remains statistically significant and practically meaningful. The study's large effects ($g = 1.91$ – 3.38) likely reflect the intensive, comprehensive nature of the intervention (daily guided sessions, personalized feedback, academic integration) rather than methodological artifacts. This finding underscores that effect magnitude depends substantially on implementation intensity and comprehensiveness.

Publication Bias and Robustness of Findings

Publication bias assessment yielded mixed results requiring careful interpretation. Egger's test indicated significant funnel plot asymmetry ($z = 20.11$, $p < .001$), suggesting potential publication bias. However, the extreme heterogeneity ($I^2 = 99.98\%$) limits Egger's test validity, as the test assumes relatively homogeneous effects. Funnel plot asymmetry can result from heterogeneity, methodological quality differences, or true publication bias. The trim-and-fill analysis (R0 estimator) estimated zero missing studies, suggesting asymmetry reflects heterogeneity rather than systematic suppression of negative findings. Fail-safe N (1,253 studies, $3.8\times$ tolerance threshold) indicates robustness. Collectively, evidence suggests that while some publication bias may exist (as indicated by small-study effects), it likely does not fully explain observed effects. The conservative estimate excluding the most influential study ($g = 0.533$) provides a lower-bound estimate less susceptible to publication bias concerns, while the full sample estimate ($g = 0.745$) may be somewhat optimistic. True population effects likely fall within this range (0.533 – 0.745), representing educationally meaningful impacts with moderate-to-large practical significance.

Interpreting Effects Under Extreme Heterogeneity

A critical consideration in interpreting our findings is the extreme heterogeneity observed across all meta-analytic models ($I^2 \approx 99$ – 100%). While the pooled effect sizes indicate generally positive impacts of digital technologies on physical education outcomes, the prediction intervals reveal that these effects are far from uniform. The overall 95% PI $[-0.471, 1.961]$ encompasses both negative and very large positive effects, meaning that any single implementation of digital technology in physical education could yield outcomes anywhere within this range. This heterogeneity is not unexpected given the diversity of (a) technology

types examined, (b) outcome constructs measured, (c) educational contexts, and (d) study designs and intervention durations. Accordingly, the pooled effect sizes reported in this review should be understood as describing the average direction and approximate magnitude of effects across a highly heterogeneous evidence base, rather than as precise predictions of what any particular implementation will achieve. The moderator analyses provide more actionable guidance: technology type, educational level, and study design each significantly moderated effects, suggesting that the effectiveness of digital technologies in physical education depends critically on how, where, and with whom they are implemented. These findings align with Borenstein et al. (2009) recommendation that when prediction intervals are wide, researchers should prioritize identifying sources of heterogeneity over interpreting the pooled mean as a definitive estimate.

Implications for Practice and Policy

The findings yield several actionable implications for physical education practice. First, practitioners should prioritize pedagogically integrated approaches (blended learning, structured gamification, AI-enhanced instruction) rather than focusing on technological sophistication or novelty. The technology type moderation results demonstrate that blended learning combining online and face-to-face instruction, gamification incorporating game elements within structured curricula, and AI systems providing personalized feedback substantially exceeded wearable activity trackers. This emphasizes that technology effectiveness depends on instructional design and teacher mediation rather than technological features alone.

Second, the extreme heterogeneity ($I^2 > 99.9\%$) and wide prediction intervals indicate that implementation quality substantially determines outcomes. Simply providing technological resources without implementation support likely produces inconsistent results. Teachers require not only technical skills but also technological pedagogical content knowledge, understanding how to effectively integrate specific technologies to address particular learning goals with specific student populations. Sustained, practice-embedded professional development focusing on pedagogical integration produces larger effects than one-time technical training. The critical role of teacher preparation aligns with emerging evidence on inclusive physical education, where teacher competence, pedagogical intentionality, and institutional support determine implementation success (Ben Rakaa et al., 2024). Technologies require not merely operational proficiency but pedagogical expertise to adapt instruction to diverse student needs and learning contexts.

Third, while effects are large and meaningful, digital technologies are tools that augment rather than replace effective teaching. Fundamental pedagogical practices (clear learning objectives, appropriate challenge, supportive climate, opportunities for practice and feedback) remain essential. The conservative estimate excluding the most influential study ($g = 0.533$) provides realistic expectations for typical implementations. Technologies integrated superficially produce smaller effects than those central to instructional design.

Fourth, the significant positive effects across elementary, secondary, and tertiary education suggest concerns about

age-appropriateness should focus on implementation features (interface design, content complexity, scaffolding) rather than categorical age exclusions. All developmental levels benefit from appropriately designed interventions, though specific implementations necessarily differ in complexity and autonomy requirements. Beyond these general implementation considerations, ensuring equitable access across diverse student populations warrants particular attention.

Equity and Accessibility Considerations

An important dimension of technology integration concerns ensuring equitable access and inclusion for students with diverse needs and abilities. Research on universal design for learning and adapted physical education demonstrates that digital technologies can facilitate differentiated instruction and inclusive participation when implemented within appropriate pedagogical frameworks (Ben Rakaa et al., 2025a; Lourenço et al., 2025). However, our findings underscore that technology availability alone does not guarantee equitable outcomes. The wide prediction intervals and substantial moderating effects of implementation quality suggest that technologies must be deliberately adapted to diverse student populations, with particular attention to students requiring additional pedagogical support. The relatively modest effects observed for wearable activity trackers ($g = 0.112$) may reflect challenges in making such technologies accessible and motivating for all students, rather than inherent technological limitations. Technologies demonstrating larger effects, such as blended learning ($g = 1.216$) and mobile applications ($g = 1.037$), typically incorporated explicit pedagogical scaffolding and differentiation mechanisms enabling adaptation to individual student needs. Future research should explicitly examine how different technologies perform across diverse student populations, including students with disabilities, low prior achievement, or limited technology access, to ensure that digital innovation promotes rather than undermines educational equity.

Study Limitations and Future Directions

Several limitations warrant acknowledgment. Despite comprehensive moderator analyses, extreme heterogeneity ($I^2 > 99.9\%$) persists, indicating that unmeasured variables (implementation fidelity, teacher expertise, student characteristics, contextual factors) substantially influence outcomes. The field lacks standardized implementation frameworks and fidelity measures, limiting ability to identify critical implementation components. The relatively small number of studies ($k = 12$), though yielding 64 effect sizes, limits statistical power for detecting moderator effects and prevents examination of potentially important moderators including teacher characteristics, specific design features, and student demographics.

While trim-and-fill and fail-safe N analyses suggested robustness, significant small-study effects ($R^2 = 30.0\%$) and Egger test asymmetry indicate some publication bias may exist. The field may underrepresent null or negative findings, potentially inflating observed effects. Most interventions represented relatively short-term implementations (3-16 weeks), with only one study including follow-up assessment. Whether effects persist beyond intervention periods, whether sustained implementation produces cumulative

benefits, or whether initial enthusiasm effects fade remains unclear. Studies originated primarily from China, Spain, and Poland, limiting generalizability to diverse cultural and educational contexts. Most studies (67%) employed quasi-experimental or cluster-randomized designs rather than individual randomization, introducing potential confounding. Additionally, blinding of outcome assessors was infeasible for many outcomes, potentially introducing detection bias. Potential negative outcomes (excessive competition, privacy concerns, technology-induced anxiety, motivation undermining through overjustification) were rarely assessed or reported, limiting understanding of potential iatrogenic effects.

Future research should prioritize implementation science approaches investigating how technologies are implemented, what factors predict effectiveness, and how implementation can be supported. Mixed-methods studies combining effectiveness assessment with qualitative investigation of implementation processes would illuminate mechanisms linking technology provision to student outcomes. Longitudinal studies with extended follow-up addressing maintenance, cumulative effects, and transfer to autonomous physical activity outside school contexts would address critical questions about durability. Randomized trials systematically varying specific features (e.g., autonomy support elements, feedback timing and content, reward structures) while controlling other factors would isolate critical design components. Research examining moderators inadequately represented (socioeconomic status, special educational needs, gender, prior technology experience, teacher characteristics) would enhance understanding of for whom technologies are most effective. Mediation analyses testing hypothesized mechanisms would strengthen theoretical foundations and guide more targeted interventions. Investigation of circumstances under which technologies might undermine intrinsic motivation, exacerbate social comparison concerns, or produce anxiety would support more balanced, ethically informed implementation decisions.

Conclusion

This systematic review and meta-analysis synthesized 64 effect sizes from 12 studies ($N = 1,346$) examining digital technology integration in physical education. The findings indicate that digital technologies are, on average, associated with positive effects across physical ($g = 0.854$), motivational-affective ($g = 0.616$), and cognitive ($g = 0.936$) domains. However, extreme heterogeneity across all models ($I^2 > 99.9\%$) and wide prediction intervals, notably the overall 95% PI $[-0.471, 1.961]$, indicate that these pooled estimates should not be interpreted as stable or universally applicable measures of effectiveness. The true effect of any specific implementation depends substantially on technology type, pedagogical design, educational level, and contextual factors. Technology type emerged as the strongest moderator ($Q = 161.53, p < .001$), with blended learning ($g = 1.216$) and mobile apps ($g = 1.037$) substantially outperforming wearable trackers ($g = 0.112$), confirming that pedagogical integration matters more than technological sophistication. Rather than supporting a blanket endorsement of digital technologies in physical education, these findings suggest that such technologies hold considerable promise, but their

effectiveness is highly context-dependent. Practitioners should carefully consider the specific technology, student population, and pedagogical integration strategy when making adoption decisions.

However, several considerations warrant careful interpretation. Extreme heterogeneity characterized all analyses ($I^2 > 99.9\%$, effect size range: 0.02-3.38), indicating that implementation quality, contextual factors, and pedagogical alignment critically determine outcomes. While average effects provide compelling evidence for potential benefits, individual implementations vary considerably in effectiveness. Sensitivity analyses revealed that removing the most influential study (Latino et al., 2021) reduced pooled effects to $g = 0.533$, suggesting that typical implementations may achieve moderate rather than large effects. Evidence of small-study effects (larger studies associated with smaller effects, $R^2 = 30.0\%$) and significant funnel plot asymmetry, though counterbalanced by null trim-and-fill results and robust fail-safe N (1,253 studies), suggests moderate evidence for publication bias. The true population effect likely falls between the conservative estimate ($g = 0.533$) and the full sample estimate ($g = 0.745$), both representing educationally meaningful impacts but indicating that realistic expectations are warranted.

The findings yield actionable implications for practice and policy. Physical education teachers require professional development supporting technological pedagogical content knowledge, understanding not merely how to operate technologies but how to integrate them effectively to achieve specific learning goals with diverse student populations. The technology type moderation suggests prioritizing pedagogically-integrated approaches (blended learning, structured gamification, AI-enhanced instruction) over passive monitoring tools. Administrators must recognize that technology integration represents a long-term investment requiring sustained support for professional development and implementation quality rather than one-time technology purchases. Policymakers should prioritize resources for implementation support and teacher preparation alongside technology acquisition, recognizing that tools without skilled implementation produce limited benefits.

Future research should prioritize implementation science approaches examining how technologies are implemented in authentic contexts, what factors support effective implementation, and how implementation fidelity can be assessed and supported. The field needs standardized implementation frameworks and fidelity measures to identify critical components. Longitudinal studies tracking effects beyond immediate post-intervention assessments would clarify whether observed benefits persist, fade, or strengthen with sustained exposure. Comparative effectiveness research directly contrasting specific technological approaches through randomized trials would provide more definitive guidance. Research examining equity dimensions (socioeconomic status, special educational needs, gender, prior technology experience, diverse cultural contexts) would ensure that technology integration benefits all students. Investigation of potential negative outcomes (motivation undermining, anxiety, privacy concerns) would support more balanced, ethically-informed implementation decisions.

The present findings support evidence-based optimism regarding digital technology's potential to substantially enhance physical education effectiveness. Technologies

aligned with sound pedagogical principles, integrated within comprehensive instructional frameworks, and supported by teacher expertise can meaningfully enhance student outcomes across physical, motivational, and cognitive domains. However, extreme heterogeneity, small-study effects, and differential effectiveness by technology type underscore that these benefits depend critically on implementation quality. Technology alone, absent thoughtful pedagogical design, skilled implementation, and systemic support, proves insufficient for realizing this potential.

The meta-analysis revealed both promise and complexity. Large average effects indicate substantial potential benefits, but extreme heterogeneity and wide prediction intervals demonstrate that this potential is realized only when technologies are thoughtfully integrated within sound pedagogical frameworks. As physical education navigates an increasingly digital educational landscape, success depends on maintaining fidelity to the field's fundamental goals (promoting physically active lifestyles, developing motor competence, fostering positive relationships with physical activity) while strategically leveraging technological affordances to enhance rather than replace effective teaching. The field has moved beyond whether digital technologies work to the more nuanced questions of how, for whom, and under what conditions they are most effective. Digital technologies represent powerful tools that can substantially amplify effective teaching when implemented skillfully within comprehensive instructional designs aligned with physical education's educational mission.

Ethics Approval and Consent to Participate

Not applicable. This systematic review and meta-analysis synthesized data from previously published studies and did not involve primary data collection from human participants. Therefore, ethics approval was not required.

Consent for Publication

Not applicable.

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Conflict of Interest

The authors declare no financial, personal, institutional, or professional conflicts of interest that could have influenced the design, conduct, analysis, or reporting of this study.

Author Contributions

Narrative Statement:

YM conceptualized the study, designed the methodology, conducted the systematic literature search and screening,

performed data extraction and quality assessment, conducted all statistical analyses using R, prepared figures and tables, and drafted the manuscript. SL supervised the research design, provided methodological guidance on meta-analytic procedures, validated analytical strategies, and critically revised the manuscript for important intellectual content. SO contributed to study selection and screening, independently verified data extraction, participated in risk of bias assessment, and reviewed and edited the manuscript. All authors read and approved the final version of the manuscript.

CRedit Taxonomy:

Conceptualization: YM, SL; Data curation: YM; Formal analysis: YM; Investigation: YM, SO; Methodology: YM, SL; Project administration: YM; Software: YM; Supervision: SL, SO; Validation: SL, SO; Visualization: YM; Writing – original draft: YM; Writing – review & editing: YM, SL, SO.

Data Availability

All data supporting the findings of this systematic review and meta-analysis are openly available via the Open Science Framework at <https://osf.io/3jyn2> (DOI: 10.17605/OSF.IO/3JYN2).

The repository includes: extracted effect sizes, coding sheets, PRISMA 2020 checklist, full search strategies (Scopus, Web of Science, ERIC, SPORTDiscus), risk of bias assessments, excluded studies register with reasons, complete R code (metafor package), forest plots by domain, and sensitivity analyses. The dataset ensures full reproducibility of all meta-analytic procedures.

AI Transparency Statement

Artificial intelligence tools were used at strictly delimited stages of this research. Elicit Pro assisted with initial abstract screening and structured data extraction; all outputs were independently verified by two reviewers against the original publications. Claude assisted with manuscript drafting and language refinement; all AI-generated content was critically reviewed and substantially revised by the authors.

All statistical analyses were performed exclusively by the first author in R (version 4.3.0) using the metafor package. AI tools served solely as efficiency-support instruments under full human supervision and had no influence on study selection, methodological decisions, statistical analyses, or scientific conclusions. All authors approved this statement.

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Вплив цифрових технологій на результати фізичного виховання: систематичний огляд та метааналіз

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 21 с., 4 табл., 7 рис., 69 джерел.

Обґрунтування. Фізичне виховання стикається зі зростаючим тиском щодо інтеграції цифрових технологій на тлі зниження залученості та мотивації учнів. Попри зростання рівня впровадження, систематизовані докази ефективності цих інструментів у різних доменах результатів залишаються обмеженими, особливо щодо умов, за яких вони є найбільш корисними.

Мета. Це систематичне оглядове дослідження та метааналіз вивчали вплив цифрових технологій на результати фізичного виховання, досліджуючи загальну величину ефекту, доменно-специфічні ефекти (фізичні, мотиваційно-афективні, когнітивні) та модератори гетерогенності.

Матеріали і методи. Систематичний пошук у чотирьох базах даних (Scopus, Web of Science, ERIC, SPORTDiscus) дозволив ідентифікувати експериментальні та квазіекспериментальні дослідження, опубліковані в період 2015–2025 рр. Дванадцять досліджень, що відповідали критеріям включення, забезпечили 64 розміри ефекту на основі вибірки з 1 346 учасників. Для розрахунку зведених розмірів ефекту Hedges' g було проведено метааналізи з випадковими ефектами з використанням оцінювання REML, доповнені прогнозними інтервалами для врахування екстремальної гетерогенності.

Результати. Загальний зведений ефект становив $g = 0,745$ (95% CI [0,590; 0,900], $p < 0,001$), із доменно-специфічними оцінками $g = 0,854$ (фізичні), $g = 0,616$ (мотиваційно-афективні) та $g = 0,936$ (когнітивні). Проте екстремальна гетерогенність у всіх моделях ($I^2 = 99,98\%$, $\tau^2 = 0,373$) робить ці зведені оцінки нестабільними та такими, що не підлягають узагальненню. 95% прогнозний інтервал [-0,471; 1,961] свідчить про те, що істинний ефект у конкретному контексті впровадження може варіювати від помірно негативного до дуже великого позитивного, що відображає високу контекстну залежність спостережуваних ефектів.

Висновки. Цифрові технології демонструють потенціал для підвищення результатів фізичного виховання; однак широкі прогнозні інтервали та екстремальна гетерогенність не дозволяють робити універсальні твердження щодо ефективності. Практичний вплив конкретної реалізації критично залежить від типу технології, педагогічної інтеграції, компетентності вчителя та освітнього контексту. Майбутні дослідження повинні зосереджуватися на визначенні умов, за яких цифрові технології є найбільш та найменш ефективними, а не лише на оцінюванні середніх ефектів.

Ключові слова: фізичне виховання, цифрові технології, метааналіз, гетерогенність, педагогічна інтеграція, освітні технології.

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AI-Enhanced Sports Training in Physical Education: Global Research Trends, Pedagogical Methods, and Ethical Frameworks (2002-2025)

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Abstract

Background. Artificial intelligence (AI) is rapidly entering physical education and sports training, providing new avenues for motion observation, learning diagnosis, and feedback. However, the pedagogical orientation and classroom feasibility of related research remain obscured by narratives focused primarily on technological performance.

Objectives. This study reviews and characterizes the knowledge base, thematic structure, and evolutionary trajectory of global AI-enabled physical education research from 2002 to 2025. It highlights implications for physical education decision-making and ethical governance, emphasizing the principle of “assisting teachers rather than replacing them.”

Materials and Methods. A Web of Science Core Collection search conducted in April 2025 yielded 729 peer-reviewed English-language journal articles. Co-citation networks, keyword co-occurrence analysis, and BERT-based semantic clustering were used to identify core literature, thematic clusters, and stages of development. These results were integrated with an interpretive synthesis from a physical education perspective.

Results. Research has evolved from early motion quantification and data-driven analysis to deep learning-based motion recognition and generative AI-supported instructional feedback, demonstrating a shift toward “instructional-ethical governance.” However, the evidence primarily focuses on universities and elite training programs. Empirical evidence in K–12 classrooms remains limited, and replicable implementation processes are lacking, creating a “laboratory–classroom” transition gap. Furthermore, issues such as curriculum articulation, learning stages, feedback timing, classroom risk management, and privacy and fairness remain insufficiently addressed.

Conclusions. In physical education, AI is best positioned as a teacher-led decision-support tool that enhances observation, formative assessment, and diagnostic feedback. Teachers should retain responsibility for key instructional judgments, prioritizing athletic development while ensuring safety and fairness. This study recommends using teaching effectiveness as the primary evaluation benchmark to promote explainable, controllable, and compliant classroom implementation pathways.

Keywords: artificial intelligence in physical education, bibliometric analysis, physical education pedagogy, motor learning, teacher education.

Introduction

The integration of artificial intelligence (AI) and sports science is reshaping research and practice in physical education

(PE) and sports training (Lee & Lee, 2021; Zhang et al., 2023). In physical education classroom settings, AI tools are increasingly embedded in teachers' teaching loops, enabling more systematic observation of movement quality, diagnosing learning difficulties and common errors, and providing task-related feedback at appropriate teaching moments, thereby strengthening skill acquisition and the implementation

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PETM
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of formative assessment (Lin et al., 2023). Meanwhile, deep learning demonstrates strong capabilities in movement recognition and biomechanical pattern analysis, enhancing teachers' diagnostic sensitivity. In addition, generative AI may support low-risk tasks such as lesson preparation, feedback expression optimization, and tiered task design under teacher supervision (Chen & Hou, 2022; Rahim et al., 2022). It is important to emphasize that, in physical education, AI should not be positioned as an "autonomous teacher" but rather as a teacher-led decision-support tool, one that assists professional judgment, maintains instructional control, and ensures that technology use remains consistent with curriculum goals, learners' progress, and classroom safety requirements.

However, existing research still exhibits a certain tendency toward "technology fragmentation." First, research on computer vision-based error correction often focuses on model accuracy and system development, paying insufficient attention to translating model outputs into understandable, operable motion cues and executable feedback in physical education classes (Zhao, 2022). Second, injury- or risk-related research emphasizes algorithmic prediction but provides little evidence of "classroom applicability" (Jiang et al., 2024). Third, adoption studies based on frameworks such as TAM primarily explain willingness to use but lack sufficient connection to the teaching process, classroom organization costs, formative assessment practices, and the conditions that enable teachers to sustain tool use in authentic teaching contexts (Kong & Song, 2015; Ma et al., 2025). While some studies have summarized the scale and regional distribution of output (Abulibdeh et al., 2024; Leal Filho et al., 2024), descriptive indicators alone are insufficient to address core issues in physical education. Much of the evidence remains focused on experimental settings or higher education and elite training environments, resulting in a significant "laboratory-classroom" transition gap in K-12 physical education classes under constraints related to class size, venue limitations, student heterogeneity, and risk exposure (Ba & Liu, 2022).

Accordingly, this study examines literature from 2002 to 2025, integrating co-citation analysis, keyword co-occurrence, BERT-based semantic clustering, and interpretive synthesis to characterize the knowledge base, thematic structure, and evolutionary trajectory of AI in physical education. From the perspective of physical education theory and methodology, this study identifies three interrelated challenges: (i) insufficient integration of algorithm development with instructional design; (ii) lagging ethical governance and limited classroom interpretability; and (iii) an overrepresentation of university and elite populations in the research samples, limiting transferability to diverse K-12 physical education classrooms. In response, this paper proposes a "teacher-in-the-loop" teaching paradigm in which AI provides evidence and prompts, while teachers retain ultimate responsibility for instructional judgment, task regulation, and risk management, thereby promoting a shift in research and practice from a "technology-centric" narrative to a feasible, "teaching-centric" classroom pathway.

Literature review

From Technical Precision to Pedagogical Application

The integration of artificial intelligence and sports science is driving physical education teaching and training

analysis from "experience-based judgment" to "data-supported diagnosis" (Lee & Lee, 2021; Zhang et al., 2023). Deep learning-based motion recognition and motion pattern analysis can be used to identify common errors, present key motion cues, and provide formative feedback for skill learning (Cheng et al., 2022; Wang et al., 2023). In instructional practice, AI can also assist teachers in identifying fatigue and risk signals, thereby improving the monitorability of classroom safety management (Yu & Mi, 2023). However, "effective under experimental conditions" does not equate to "usable in classroom settings." As venue constraints, lighting variability, and student heterogeneity increase, model performance may decline, thereby weakening the stability and credibility of feedback (Kong, 2024). Furthermore, if the training data are biased toward elite samples, the resulting conclusions and rules are difficult to adapt directly to the learning characteristics and developmental levels of non-elite students (Peng & Xu, 2022). While generative AI and reinforcement learning promise to improve the effectiveness of personalized suggestions and practice retention (Chang et al., 2023), the extent to which teachers' professional knowledge is embedded in feedback rules and instructional decisions remains low (Filius et al., 2018). Therefore, AI should be positioned as a tool for "teacher diagnosis and decision support," rather than as an automated instructor that replaces the teacher.

Resource Differences and Data Representativeness

Global research shows that the development of artificial intelligence in physical education exhibits significant regional and resource imbalances. Some regions focus more on technology application research, whereas ethical governance issues are more prominent in others (Maphosa & Maphosa, 2023). Moreover, differences in research output across regions can lead to geographic and demographic homogenization of data sources, amplifying the risk of model bias and undermining fair evaluation for students with different body types, genders, and cultural movement styles (Yang et al., 2024; Pham et al., 2025). Furthermore, insufficient interdisciplinary integration remains a common problem. Some studies prioritize technological feasibility while neglecting to adequately discuss curriculum objectives, learning patterns, and instructional organization. While generative AI has promoted international collaboration and knowledge diffusion to some extent in recent years, resource disparities may still limit the accessibility and sustained use of AI-supported teaching in low-resource schools, thereby exacerbating the digital divide in physical education. Therefore, future research should be guided by the accessibility and representativeness of K-12 physical education classrooms, and should establish validation standards and data specifications that cover diverse student groups and instructional scenarios.

Teaching Ethics, Algorithmic Bias, and Student Safety

Existing AI ethical frameworks are mostly derived from general educational contexts and are insufficient to fully cover the characteristics of physical education classrooms, which involve "higher physical risks and greater sensitivity to continuous observation (Chen, K. et al., 2022)." In

practice, some systems fall short in privacy protection and explainability, making it difficult for teachers to explain to students why a judgment occurred or why a warning or correction was triggered, thereby weakening the transparency and acceptability of the teaching feedback chain. Algorithmic bias can also translate directly into classroom equity issues. If model training data are biased toward a particular group, the system may produce higher error rates for female students or students with different body types, thereby affecting evaluation and learning opportunities. Although privacy-protection technologies are considered a potential solution, governance elements such as exit mechanisms, informed consent, and data ownership are often unclear in educational settings. Therefore, the “teacher-in-the-loop” principle must be adhered to in physical education. AI provides evidence and prompts, while teachers bear ultimate responsibility for instructional discretion and safety supervision.

Summary of Literature Gaps

In summary, existing research in physical education has at least four key gaps. First, the “laboratory-classroom transformation gap” is significant in K-12 education, with limited real-world classroom validation and few operational implementation procedures. Second, insufficient resource and data representativeness can perpetuate assessment biases and widen the digital divide (Pham et al., 2025; Yang et al., 2024). Third, ethical governance surrounding student safety, privacy, and explainability remains underdeveloped. Fourth, interdisciplinary integration is insufficient, and motor-learning principles and curriculum design have not been fully incorporated into model objectives and feedback rules (Filius et al., 2018). Therefore, research needs to shift from “algorithm optimization” to “teaching optimization” by using motor-learning principles and curriculum objectives as benchmarks, clarifying the decision-support boundaries of AI, and ensuring teachers’ ultimate control over instructional processes and classroom risks.

Materials and Methods

Dataset Construction

This study conducted a topic search in the Web of Science Core Collection (SCI-EXPANDED & SSCI) covering 2002–2025 (through April 2025). The search query consisted of two parts: (i) AI-related terms (e.g., artificial intelligence, AI, machine learning, deep learning, neural networks), and (ii) physical education and sports teaching-related terms (e.g., physical education, sports training, teaching, curriculum, assessment, feedback, classroom management). The query also covered PETE and college physical education curriculum contexts to include studies with “teaching transfer significance” for K–12. The inclusion criteria were: (1) peer-reviewed English journal articles; (2) studies whose context involved physical education teaching, curriculum implementation, learning assessment and feedback, classroom management, or training management closely related to physical education; and (3) studies that clearly discussed teaching objectives, learning processes, feedback mechanisms, classroom implementation, or educational governance. The exclusion criteria were: papers

that discussed only algorithm performance and hardware deployment without pedagogical relevance to physical education, and papers that were not sufficiently aligned with physical education contexts. Following PRISMA deduplication and screening (see Figure 1), two researchers independently completed the initial and secondary screening. Discrepancies were resolved through discussion, resulting in a final sample of 729 papers. The included papers have been cited a total of 11,691 times (11,467 excluding self-citations).

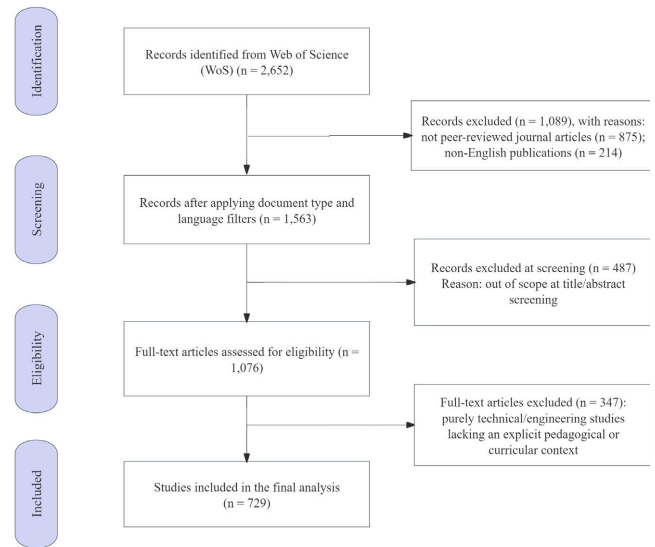


Fig. 1. PRISMA flow diagram of study selection. Records were identified from Web of Science (WoS) and screened according to predefined eligibility criteria for inclusion in the bibliometric analysis (2002–2025)

Table 1. Systematic Literature Search Strategy in Web of Science Core Collection

Parameter	Value
Database	Web of Science Core Collection (SCI-EXPANDED & SSCI), Version 2025-01
Time Span	2002-2025 (Year)
Search Field	Topic (Title, Abstract, Keywords)
AI Keywords	“Artificial Intelligence” OR “AI” OR “Deep Learning” OR “Machine Learning” OR “Neural Networks”
Application Context	“Physical Educat” OR “Higher Educat” OR “AI in physical education (teaching and training)”
Document Type	Article
Language	English

Data source: Web of Science.

Analytical Modeling

After the sample was determined, text and metadata preprocessing was performed, including keyword synonym

merging and standardization, author and institution name disambiguation, and duplicate record removal. VOSviewer was then used to conduct quantitative analyses to map the knowledge base and conceptual structure of the field and to support pedagogical interpretation in physical education (Maphosa & Maphosa, 2023; van Eck & Waltman, 2010). Specifically, the analyses included: (1) co-citation analysis to identify the knowledge base and key theoretical sources; (2) keyword co-occurrence analysis to characterize thematic structure and conceptual evolution, with attention to shifts from “technical indicators and model terms” to pedagogical concepts such as “sports learning, teaching feedback, and curriculum evaluation”; (3) author and institutional collaboration network analysis to describe interdisciplinary collaboration patterns and their contributions to physical education research; and (4) performance indicator analysis to summarize the output and impact of authors, journals, institutions, and countries/regions. Furthermore, CiteSpace burst (emergence) detection was used to identify temporal shifts in keywords and themes, and developmental stages were delineated accordingly (see Fig. 2) (Chen, C., 2006). To reduce topic ambiguity caused by synonyms and variation in expression, this study integrated BERT-based semantic clustering to improve the consistency of topic classification and cross-validated the results against co-word clustering.

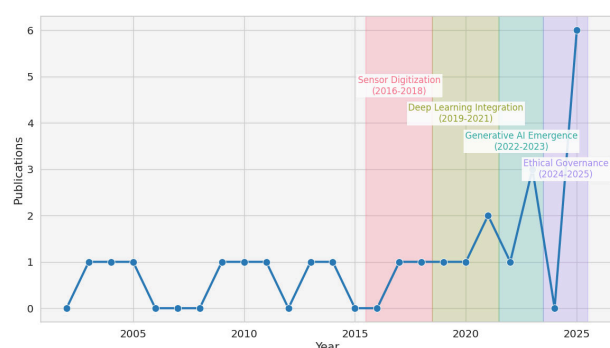


Fig. 2. Temporal evolution of research in AI in physical education (teaching and training), showing four developmental phases identified via CiteSpace burst detection.

Data source: Web of Science

Interpretive Synthesis

Building upon the bibliometric results, this study employs interpretive synthesis to transform network-structure findings into evidence demonstrating the interpretability and feasibility of physical education teaching. This was achieved through triangulation across co-citation, co-occurrence, and burst phases (Fig. 2), together with analysis of representative studies, thereby enhancing the traceability and pedagogical significance of the interpretation. At the interpretive level, a clear distinction is made between bibliometric conclusions and pedagogical interpretations. Each thematic cluster is described not only in technical terms but also reinterpreted within a physical education framework, including how it supports teachers' observation–diagnosis–feedback decision-making and whether its outputs align with principles of motor learning, curriculum objectives, and classroom management requirements. Finally, at the

synthesis level, this study proposes a teacher-led boundary for human–machine collaboration. AI provides data-based evidence and prompts, while teachers retain responsibility for instructional judgment, task adjustment, and ensuring safety and fairness, thereby shifting emphasis from technological effectiveness to pedagogical effectiveness.

Results and Discussion

Publication Trends: Growth in Research on AI in physical education and Rising Demand for Digital Teaching

An analysis of 729 articles included in the Web of Science Core Collection shows a continued upward trend in AI research related to physical education (teaching and training). This field has been cited a total of 11,691 times (11,467 excluding self-citations), with an H-index of 52. The annual distribution (see Figure 3) indicates that 2002–2015 was a relatively slow “foundational period,” during which research focused primarily on basic sensing and data-collection validation. Publication output accelerated significantly from 2019 onward and increased further after 2020. Specifically, 84 articles were published in 2021, rising to 188 in 2022 (2,147 citations), and peaking at 214 in 2024 (3,759 citations).

Pedagogical Interpretation. The growth reflects not only improvements in algorithms and hardware capabilities but also increasing demand for “observable, diagnosable, and feedback-oriented” digital support in physical education settings. In school physical education, teachers must monitor learning progress, assess movement quality, and manage risks under limited class time and complex conditions, and therefore rely more heavily on tools that can provide evidence and prompts. Therefore, this study emphasizes that AI should be positioned as a tool that supports teachers' observation, diagnosis, and decision-making rather than a “self-coach” that replaces instructional control, consistent with physical education curriculum goals and principles of motor learning.

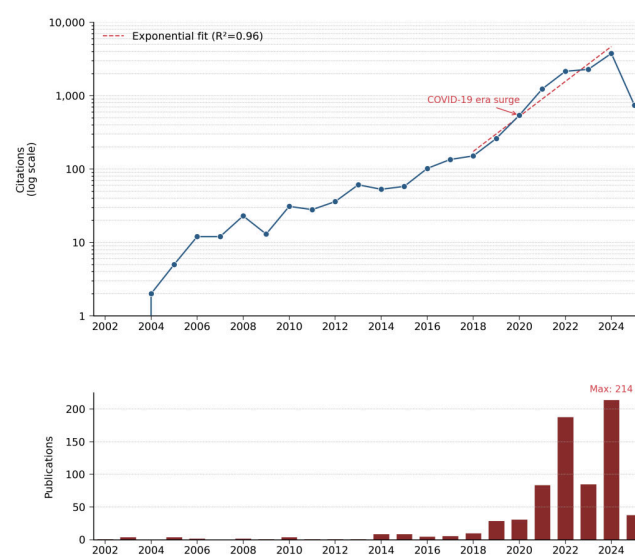


Fig. 3. Exponential growth patterns in academic output and influence (2002–2025). (A) Semi-logarithmic plot of annual citation counts with exponential trend line (2018–2024, $R^2=0.98$). (B) Projected publication growth (2024–2025) derived from historical CAGR of 31.2% (2016–2023). Accelerated adoption phase (2020–2022).

Data source: Web of Science

Performance Analysis: Subject Structure Characteristics and the Lack of Teaching Contextualization

This section reveals the subject structure characteristics of the field based on bibliometric performance indicators and further assesses the extent to which physical education (PE) issues are presented within the broader AI discourse, focusing on their consistency with the laws of sports learning, curriculum objectives, and instructional control.

High-impact literature

Highly cited research exhibits a “dual-track” structure. One stream emphasizes algorithm accuracy, recognition performance, and system implementation, often treating PE as a data-collection setting rather than a teaching context. The other stream focuses on classroom interaction, feedback mechanisms, and learning support, reflecting a more direct orientation toward instructional innovation. For example, Tedre et al. (2021) discuss the pedagogical trajectory of AI education from the perspective of K–12 AI literacy and classroom implementation. Rahim et al. (2022) explain the role of AI chatbots in learning support and adoption mechanisms in higher education. This structure suggests that “high-impact evidence” does not necessarily equate to evidence that is transferable to physical education instruction. Future research should shift evaluation from “technological effectiveness” to “instructional effectiveness.”

Journal Impact

Journal distribution indicates that publications are concentrated in general or engineering-oriented journals rather than specialized physical education journals. For example, Sustainability (51 articles, 682 citations) and Engineering (41 articles, 907 citations) are among the most prominent outlets. The total link strength of Sustainability (TLS = 22) suggests increasing interdisciplinarity, with research beginning to align with education governance and the Sustainable Development Goals. However, from a physical education perspective, this pattern highlights a “technology-first, instruction-lagging” diffusion pathway: innovation is often driven by technological feasibility rather than by curriculum objectives, learning processes, or teacher instructional control.

Author and Institutional Contributions

Collaboration networks exhibit differentiated research emphases. For example, the Bucea-Manea-Tonis, Ilic, and Kuleto team (3 papers, 88 citations, TLS = 4) focuses on educational technology adoption and learning support, whereas the Artyukhov team (TLS = 18) concentrates on specific technological directions. At the institutional level, King Abdulaziz University leads in publication volume (16 papers), whereas Zhejiang University (7 papers) and the Royal Institute of Technology (KTH; 4 papers) show higher citation impact. These results suggest that institutions with both engineering capacity and a tradition of educational application are more likely to produce “usable and teachable” reference models.

National and Regional Distribution

At the national level, China dominates in output (290 papers, 2,055 citations), reflecting a greater emphasis on

large-scale development and evaluation of “smart sports.” In contrast, the United States (63 papers) and several European countries (e.g., the United Kingdom and Spain) place greater emphasis on educational governance and ethical frameworks. Notably, although South Korea and Malaysia have smaller publication volumes, they show high network connectivity (TLS = 37 and 32, respectively) and may serve as bridges between “evidence of technological scaling in East Asia” and “Western education-governance frameworks.” For physical education, the value of such complementary collaboration lies not in comparing publication counts but in jointly addressing the translation gap between evidence generated in university and elite training contexts and implementation in K–12 classrooms.

Co-citation Analysis

Table 2 presents the 10 most influential papers in the co-citation network, forming the core knowledge foundation of the field. Overall, this foundation reflects a composite structure spanning “reviews of educational AI, technology-adoption theory, structural equation modeling, and generative-AI governance,” indicating that research on AI in physical education draws heavily on educational technology and information-systems frameworks to explain the feasibility, effectiveness, and governance boundaries of AI use in physical education classrooms.

First, Zawacki-Richter et al. (2019), addressing the core question of “Where are the teachers?,” argue that without teacher involvement in rule setting and outcome interpretation, AI systems may deviate from principles of motor learning and classroom management requirements in physical education. Relatedly, Popenici and Kerr (2017) and Chen et al. (2020) delineate functional boundaries for AI in education, providing a conceptual basis for positioning AI in physical education as a tool for “observation–diagnosis–feedback.”

Second, Davis’s (1989) TAM and Venkatesh et al.’s (2003) UTAUT are highly cited, suggesting that the key bottleneck in physical education is not simply algorithmic accuracy but whether “ease of use, low disruption, and interpretability” can sustain teachers’ continued implementation. Fornell and Larcker (1981) and Henseler et al. (2015) provide measurement and methodological foundations for adoption mechanisms and the evaluation of teaching effectiveness.

Finally, Dwivedi et al. (2023) and Kasneci et al. (2023) highlight the coexistence of teaching support and academic-integrity risks associated with generative AI. In physical education, generative AI should support instructional design, rule interpretation, and personalized feedback generation; however, its use should adhere to the “human-in-the-loop” principle to ensure classroom safety, fairness, and instructional consistency. Biggs et al.’s (2001) learning-orientation measure also suggests that research evaluation should shift from “technical performance” toward the learning process and teaching effectiveness.

Thematic Clusters in the Co-citation Network

Based on the VOSviewer co-citation network (see Figure 4), this study identified four main thematic clusters. Unlike clusters commonly reported in general educational

Table 2. Top 10 Documents Identified Through Co-Citation Analysis

Rank	Authors	Title	Citations	Total Link Strength
1	Zawacki-Richter, O et al. (2019)	Systematic review of research on artificial intelligence applications in higher education-where are the educators?	26	93
2	Chen, L et al. (2020)	Artificial intelligence in education: A review	18	83
3	Fornell, C et al. (1981)	Evaluating structural equation models with unobservable variables and measurement error	18	83
4	Davis, F. D et al. (1989)	Perceived usefulness, perceived ease of use, and user acceptance of information technology	17	92
5	Venkatesh, V et al. (2003).	User acceptance of information technology: Toward a unified view	17	90
6	Henseler, J et al. (2015)	A new criterion for assessing discriminant validity in variance-based structural equation modeling	16	84
7	Popenici, S. A et al. (2017)	Exploring the impact of artificial intelligence on teaching and learning in higher education	16	69
8	Biggs, J et al. (2001)	The revised two-factor study process questionnaire: R-SPQ-2F	16	22
9	Dwivedi, Y. K et al. (2023).	Opinion Paper:“So what if ChatGPT wrote it?” Multidisciplinary perspectives on opportunities, challenges and implications of generative conversational AI for research, practice and policy	14	83
10	Kasneci, E et al. (2023).	ChatGPT for good? On opportunities and challenges of large language models for education	14	73

Data source: Web of Science.: VOSviewer analysis on co-citation.

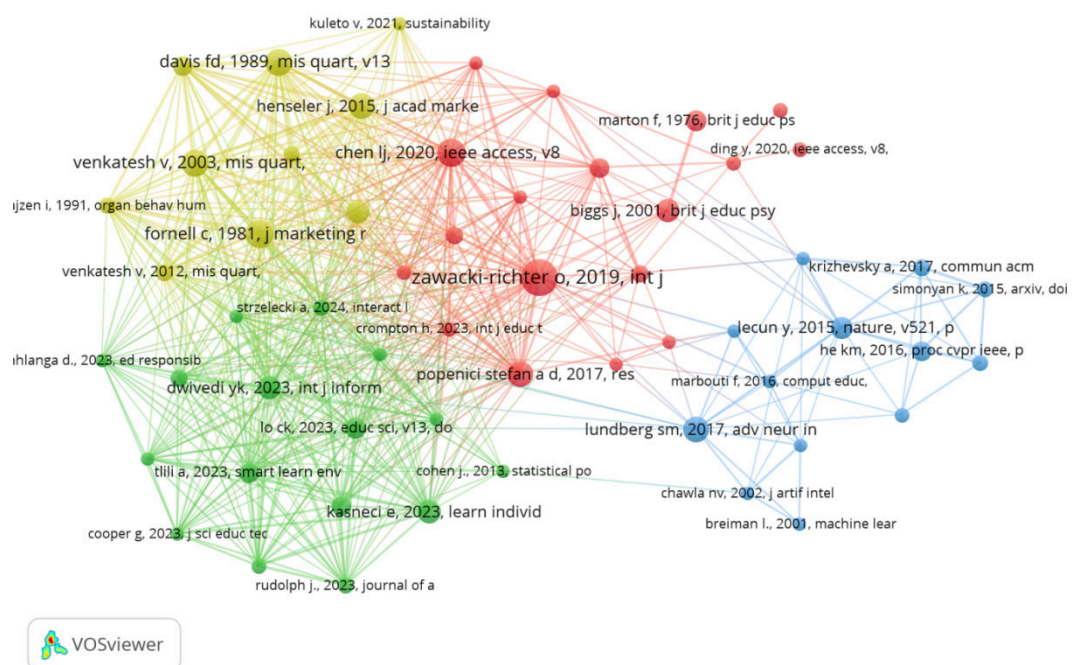


Fig. 4. Network visualization of document co-citation relationships identifying thematic research clusters (Generated using VOSviewer)

technology research, this study reinterprets them from a physical education perspective, focusing on how each cluster supports the “observation–diagnosis–feedback–regulation” teaching loop and assessing alignment with principles of motor learning, curriculum objectives, and classroom implementation requirements.

Cluster 1 (Red): Teaching Practice and Teacher Role

This cluster emphasizes that when AI enters physical education classrooms, teachers remain key actors in rule

setting and meaning interpretation. Related research indicates that without teacher involvement, system outputs may become “black-box” judgments that fail to align with classroom feedback timing and safety management (Zawacki-Richter et al., 2019). This cluster also includes discussions of AI-enabled personalization and instructional management, as well as the impact of generative AI on student participation and K–12 ethics (Chen et al., 2020; Akgun & Greenhow, 2022; Chan & Hu, 2023). Therefore, in physical education, AI should remain subordinate to teachers’ professional discretion, with teachers determining

error-correction thresholds, feedback methods, practice prescriptions, and evaluation standards.

Cluster 2 (Green): Generative AI and New Teaching Support

This cluster focuses on the coexistence of support and risks associated with generative AI, represented by ChatGPT (Dwivedi et al., 2023; Kasneci et al., 2023). It also addresses students' experiences and emotional responses (Strzelecki, 2024), as well as academic-integrity and ethical risks (Cotton et al., 2024; Tlili et al., 2023). In physical education, generative AI is better suited as a “teaching decision-support interface” to generate lesson scripts, interpret rules, and provide tiered practice suggestions. However, recommendations involving safety, load control, and risk warnings should be reviewed by teachers before implementation to reduce the risk of injury resulting from inappropriate feedback.

Cluster 3 (Blue): Learning Analytics and the Foundation of Instructional Diagnosis

This cluster provides foundational methods for motion recognition and learning-process analysis (He et al., 2016; LeCun et al., 2015) and emphasizes identifying learning differences and process risks through learning analytics (Gašević et al., 2016). From a physical education perspective, these technical capabilities should be used not only to identify “standard” movements but also to identify learning stages and developmental levels, thereby expanding the diagnostic focus from competitive performance to classroom learning evidence and supporting formative assessment and process feedback rather than single-outcome ranking.

Cluster 4 (Yellow): Adoption Mechanism and Use Intention

This cluster integrates adoption models such as TAM and UTAUT (Davis, 1989; Venkatesh et al., 2003) with behavioral theory and measurement-validity testing methods (Ajzen, 1991; Fornell & Larcker, 1981). In physical education, the bottleneck to widespread adoption is often not “higher precision” but “fewer interruptions.” Only when AI tools are sufficiently lightweight, interpretable, and controllable—and do not increase classroom-organization costs—can teachers use them consistently in real classrooms.

In summary, the four clusters collectively indicate that algorithmic capabilities enable potential applications, whereas teacher leadership, classroom safety, and ethical governance determine usability, and adoption mechanisms shape sustained implementation. Future research should use principles of motor learning and curriculum objectives as benchmarks to advance AI from “technologically effective” to “teaching-effective,” thereby bridging the gap between experimental research and classroom practice.

Keyword Co-occurrence Analysis

Table 4 shows that among the 729 included articles, high-frequency keywords are dominated by general AI and educational-technology discourse. “Artificial intelligence” (127) and “higher education” (73) occupy central positions in the network, whereas “physical education” (23) ranks 12th, suggesting that when AI enters school-sport contexts, the disciplinary identity of physical education can be overshadowed by a broader “educational technology”

Table 4. Top 15 keywords from the keyword co-occurrence analysis.

Rank	Keyword	Occurrences	Total Link Strength
1	artificial intelligence	127	262
2	higher education	73	193
3	deep learning	65	84
4	education	52	134
5	higher - education	44	109
6	students	40	94
7	model	34	67
8	machine learning	31	67
9	artificial - intelligence	29	75
10	system	24	69
11	chatgpt	23	80
12	physical education	23	40
13	performance	22	64
14	ai	20	53
15	big data	20	52

Data source: Web of Science.: VOSviewer analysis on co-occurrence.

narrative. At the same time, the total link strength of “physical education” (TLS = 40) indicates a key bridging role. When it appears in the co-occurrence network, it links concepts related to algorithms and systems, learners, teaching outcomes, and classroom applications, underscoring physical education as a node connecting technology-oriented research with pedagogical interpretation. It should be noted that variants such as “higher education” and “higher-education,” as well as “artificial intelligence,” “artificial-intelligence,” and “AI,” appear separately in Table 4 due to differences in writing style. Synonym merging and standardization were applied during preprocessing; therefore, this pattern reflects disciplinary discourse habits rather than a substantive conceptual split.

Figure 5 further reveals five thematic clusters. Rather than treating these clusters as “components of a digital teaching system,” this study highlights their pedagogical functions and limitations within the “observation–diagnosis–feedback–regulation–evaluation” evidence chain in physical education.

Cluster 1 (Red): Generative AI and Instructional Support

This cluster centers on ChatGPT, generative AI, and related models, and primarily concerns the generation of instructional content, learning support, and classroom communication. In physical education, its value lies primarily in low-risk activities such as lesson preparation, generation of tiered tasks, explanation of rules and tactics, and formative assessment, rather than replacing key judgments and safety checks in technical-skill instruction.

Cluster 2 (Green): Data-Driven Classroom Management and Safety Governance

This cluster links themes such as “big data—risk—management—training and classroom optimization.” It suggests that more mature applications of AI in physical

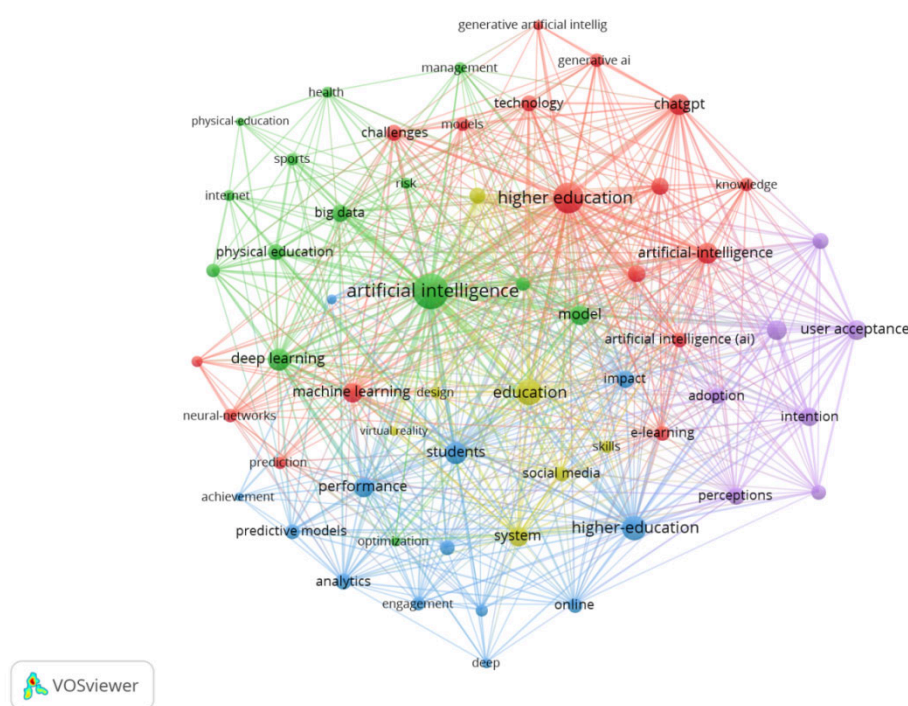


Fig. 5. Thematic clusters identified through keyword co-occurrence analysis focusing on artificial intelligence and physical education (VOSviewer).

education are not aimed at “teaching movements directly” but at assisting teachers in monitoring workload and participation, providing risk warnings, and managing classroom order, thereby improving classroom controllability and student safety. To maintain thematic consistency, this study uses the term “AI-supported monitoring and early warning” to avoid extending the discussion to technologies unrelated to the main theme.

Cluster 3 (Blue): Learning Analysis, Motivation, and Learning Outcomes.

This cluster reflects a shift from “outcome performance” to the “learning process,” emphasizing the use of objective data to characterize participation, activity levels, and progress trajectories. This shift provides an evidentiary basis for reforming assessment in physical education and promotes a transition from “talent- and achievement-oriented” evaluation to “effort- and progress-oriented” formative assessment.

Cluster 4 (Purple): Technology Adoption and Teacher Usability

This cluster focuses on variables related to acceptance and use intention (e.g., TAM and UTAUT), indicating that barriers to implementation often lie in teacher workflow and classroom procedural costs rather than in recognition accuracy alone. Physical education classrooms, in particular, require low-burden, low-interruption, interpretable, and controllable tool designs; otherwise, even “high accuracy” may be difficult to integrate into routine practice.

Cluster 5 (Yellow): Immersive Learning and Skill Acquisition

This cluster points to topics such as VR and skill learning, whose significance in physical education lies in providing beginners with contextualized demonstrations and a safe environment for practice, thereby reducing the cognitive load of complex skills and improving practice quality.

Overall, the keyword structure indicates that research is expanding from “systems and models” toward “teaching applications.” However, research on AI in physical education still needs to be anchored in curriculum objectives, principles of motor learning, and classroom implementation. This requires positioning AI as a teacher-led decision-support tool, emphasizing classroom feasibility and instructional effectiveness, and designing implementation pathways with safety and equity as non-negotiable constraints (see Table 4 and Figure 5).

Implications

Theoretical Significance

While deep learning-based action recognition can improve diagnostic efficiency, its implicit assumption of “standard action-deviation correction” can lead to the view that a single “ideal posture” represents the only correct answer, thereby neglecting functional variation and developmental differences in motor learning. Therefore, in physical education, AI outputs should be framed as evidence and prompts, with teachers providing pedagogical interpretation and secondary decision-making based on learners’ levels, task objectives, and safety constraints. Data representativeness should not be viewed merely as a matter of technical accuracy but should be incorporated into an

educational-equity framework. Overly homogeneous training data may introduce systematic errors across gender, body type, or culturally patterned movement styles, thereby undermining fairness in assessment opportunities and learning support (Pham et al., 2025). Privacy-oriented approaches (e.g., federated learning) hold promise, but their educational legitimacy depends on informed consent, data minimization, clearly defined ownership, and teacher-controlled data-use rules.

Practical Significance

Given that laboratory models often show performance degradation and contextual mismatch in real classrooms, AI should be prioritized for low-risk formative assessment in physical education, such as identifying learning-progress trends, monitoring participation and movement quality, providing risk alerts, and supporting classroom management. It should not be used directly for high-risk summative scoring or single-session ranking. To improve K–12 feasibility, system design should emphasize lightweight deployment, interpretable outputs, and teacher-adjustable thresholds and rules to ensure that “technology does not disrupt the teaching process.” Teacher education, including physical education teacher education (PETE), should systematically incorporate AI literacy, bias identification, and ethical-governance competencies, enabling teachers to evaluate evidence reliability and retain ultimate responsibility for classroom safety and assessment fairness (Tedre et al., 2021; Akgun & Greenhow, 2022). At the policy level, replicable classroom-validation standards and cross-context assessment processes should be established to promote the transfer of evidence from university and elite training contexts to diverse K–12 classrooms.

Conclusion, limitations and future avenues

Conclusion

Based on 729 peer-reviewed English journal articles (2002–2025) retrieved and screened from the Web of Science Core Collection, this study systematically depicts the knowledge structure and evolution of artificial intelligence (AI) research in physical education and sports training. The results indicate that existing evidence primarily focuses on university and competitive training settings, whereas evidence on curriculum integration, classroom management, and operational implementation in K–12 classrooms remains limited, creating a substantial “research-to-classroom” translation gap (Filho et al., 2024). Furthermore, inadequate privacy protection and limited interpretability weaken teachers’ control over the “observation–diagnosis–feedback–regulation” teaching loop (Abulibdeh et al., 2024). Therefore, AI in physical education should be positioned as a teacher-led decision-support tool: AI provides evidence and suggestions, whereas teachers retain responsibility for setting instructional objectives, adjusting tasks, ensuring safety, and exercising evaluative discretion to align instruction with learner differences and motor-development patterns.

Limitations

This study used only the WoS Core Collection, which may have overlooked relevant regional or interdisciplinary

journals in physical education; moreover, restricting the corpus to English inevitably introduces language bias. As a bibliometric study, this paper is well suited to revealing macro-structures, research hotspots, and evolutionary trends; however, it cannot fully capture “in-situ teaching evidence,” such as classroom interactions, teacher experiences, implementation processes, and contextual constraints. These limitations could be addressed by complementary methods such as classroom experiments, design-based research, and qualitative interviews (Demartini et al., 2024).

Future directions

1. From “Technological Effectiveness” to “Teaching Effectiveness”: Grounded in curriculum objectives, principles of motor learning, and formative assessment, future work should develop interpretable AI and actionable feedback rules so that outputs can inform teachers’ instructional decisions rather than merely reporting model indicators (Abulibdeh et al., 2024).

2. Strengthen teacher education and ethical-audit capacity: Systematically incorporate AI literacy, bias identification, data governance, and safety-responsibility training into PETE, positioning teachers as key nodes in a human–machine collaborative loop to ensure classroom safety, assessment fairness, and instructional autonomy (Tedre et al., 2021).

3. Narrow the K–12 transition gap and resource disparities: Promote low-threshold, privacy-friendly deployment solutions and cross-school, cross-cultural validation standards; conduct replicable K–12 empirical studies and longitudinal follow-up to build a scalable evidence base for classroom implementation (Leal Filho et al., 2024).

Ethics Approval

Not applicable. This bibliometric review is based exclusively on publicly available literature sources and did not involve human participants, animals, or identifiable personal data.

Informed Consent

Not applicable, as the study did not involve human participants.

Data Availability Statement

The data underlying this study were derived from publicly available bibliographic records retrieved from the Web of Science Core Collection. The search strategy, eligibility criteria, and analysis procedures are described in the Methods section. The dataset generated and analyzed during the current study is available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Transparency Statement

AI-assisted tools were used solely for language refinement and structural editing of the manuscript, based exclusively on content developed by the authors. No AI tools were used for data collection, data analysis, interpretation of results, or generation of data, findings, or references. The authors retain full responsibility for the accuracy, integrity, and final content of the manuscript.

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Тренування у спорті та фізичному вихованні з використанням штучного інтелекту: глобальні дослідницькі тренди, педагогічні методи та етичні рамки (2002–2025)

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; Е – збір коштів

Реферат. Стаття: 21 с., 4 табл., 5 рис., 45 джерел.

Обґрунтування. Штучний інтелект швидко входить у сферу фізичного виховання та спортивної підготовки, відкриваючи нові можливості для спостереження за рухами, діагностики навчання та надання зворотного зв'язку. Однак педагогічна спрямованість і можливість практичного застосування результатів відповідних досліджень у навчально-

му процесі часто залишаються невиразними через домінування наративів, зосереджених переважно на технологічній ефективності.

Мета дослідження. У дослідженні здійснено огляд і характеристику бази знань, тематичної структури та еволюційної траєкторії світових досліджень застосування штучного інтелекту у фізичному вихованні у 2002–2025 роках. Особливу увагу приділено їхнім наслідкам для прийняття рішень у фізичному вихованні та етичного врядування з акцентом на принципі «допомагати вчителям, а не замінювати їх».

Матеріали і методи. Пошук у базі даних Web of Science Core Collection, проведений у квітні 2025 року, дав змогу відібрати 729 рецензованих журнальних статей англійською мовою. Для визначення ключової літератури, тематичних кластерів і етапів розвитку використано аналіз мереж коцитування, аналіз співзвучності ключових слів та семантичну кластеризацію на основі моделі BERT. Отримані результати були інтегровані з інтерпретаційним синтезом із позицій фізичного виховання.

Результати. Дослідження еволюціонували від раннього кількісного вимірювання рухів і аналізу на основі даних до розпізнавання рухів на основі глибинного навчання та використання генеративного штучного інтелекту для підтримки навчального зворотного зв'язку, що свідчить про перехід до «інструкційно-етичного врядування». Водночас наявні докази зосереджені переважно на університетах і програмах підготовки спортсменів високого рівня. Емпіричні дані щодо використання в школах залишаються обмеженими, а відтворювані процеси впровадження практично відсутні, що створює розрив між «лабораторією та класом». Крім того, такі питання, як узгодженість навчальних програм, етапи навчання, час надання зворотного зв'язку, управління ризиками в класі, а також конфіденційність і справедливість, залишаються недостатньо опрацьованими.

Висновки. У фізичному вихованні штучний інтелект доцільно розглядати передусім як інструмент підтримки прийняття рішень під керівництвом учителя, що посилює можливості спостереження, формувального оцінювання та діагностичного зворотного зв'язку. Учителі повинні зберігати відповідальність за ключові педагогічні рішення, надаючи пріоритет розвитку рухових здібностей і забезпечуючи безпеку та справедливість. У дослідженні рекомендується використовувати ефективність навчання як основний критерій оцінювання для просування пояснюваних, керованих і нормативно сумісних шляхів застосування штучного інтелекту в навчальному процесі.

Ключові слова: штучний інтелект у фізичному вихованні, бібліометричний аналіз, педагогіка фізичного виховання, моторне навчання, підготовка вчителів.

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Effectiveness and Challenges of Gamification in Physical Education: A Systematic Review

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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 education faces challenges in increasing student motivation, participation, and engagement. One innovative approach that has emerged is gamification, defined as the application of game elements in a learning context.

Objectives. This study examines the effectiveness and challenges of implementing gamification in physical education through a systematic literature review.

Materials and Methods. The review included literature searches using the keywords “gamification” OR “gamified” AND “physical education” OR “PE”. Article selection followed the PRISMA procedure, and content analysis was conducted based on the dimensions of effectiveness and challenges of gamification in physical education. A total of 496 articles were initially identified from the Scopus and ERIC databases. After the screening process, 25 articles published between 2015 and 2025 were included in the analysis.

Results. The results indicate that gamification positively contributes to increased motivation, student engagement, physical activity, motor skill development, academic achievement, and the strengthening of personality and social skills in physical education. Identified challenges include limitations in technological infrastructure, low levels of digital literacy among teachers, gamification designs that are not contextually appropriate, short intervention durations, and the lack of standardized evaluation tools.

Conclusions. The study contributes to the development of innovative, technology-based, and adaptive physical education strategies. The findings can guide the design of physical education learning that is more innovative, contextual, and responsive to students' needs.

Keywords: gamification, physical education, motivation, student engagement.

Introduction

Physical education is an integral part of the education curriculum that aims to develop motor skills and knowledge, social-emotional development, encourage an active and healthy lifestyle, and maintain mental health (Fitzpatrick, 2010; Sirojova, 2024). However, in practice, physical education often faces various challenges, such as limited resources, lack of motivation, lack of technology integration, limited involvement, and the use of strategies that do not adequately accommodate students' learning needs

(Samsudin et al., 2024). These challenges result in less than optimal learning outcomes, low student participation and less development of knowledge, physical and social skills..

One innovative approach that has gained traction in recent years to address challenges in the learning process is the application of gamification. Gamification refers to using game elements such as points, rewards, challenges, and experiences in non-game contexts or everyday activities to increase student engagement and motivation (Sal-de-Rellán et al., 2025). Gamification has been widely used in various educational contexts, including physical education, where it has been proven to increase student motivation, participation, and meaningful learning experiences. For example, Yuan et al. (2024) note that the use of gamification in physical education from an adaptive education perspective

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may contribute to increased learning motivation, support students' mental well-being, and promote personality development. This aligns with research by Sotos-Martínez et al. (2023), which highlights the effectiveness of gamification in motivating students and fulfilling their learning needs. This study reveals that gamification can significantly increase independence, competence, and caring while reducing demotivation.

Using game elements in a gamification approach increases students' interest and motivation and creates meaningful learning and enjoyable learning experiences. Several studies have shown that applying gamification in physical education strengthens students' commitment to participating in physical activities and improves their perception of physical education as a subject (Jeong et al., 2022; Viciana et al., 2025). Integrating technology in gamification has also proven effective in physical education learning. For example, the integration of gamification with the hybrid Teaching Personal and Social Responsibility (TPSR) model can improve physical fitness and weekly physical activity time and reduce students' sedentary time during a nine-month intervention (Melero-Cañas, Morales-Baños, Manzano-Sánchez, et al., 2021). Implementing gamification using simple technology such as activity trackers can increase the number of daily steps students take and is positively received by teachers and students (Vorlíček et al., 2024). Using wearable devices and a project-based approach proves that students can actively move around while learning to analyze their activity data (Jeong et al., 2022).

Although there are many positive reports on the effectiveness of gamification in physical education, this approach can also have adverse effects if it is not designed correctly and appropriately. For example, if it focuses too much on competition, it can neglect the intrinsic elements of the activity itself (Hanus & Fox, 2015). Excessive competence can increase stress, reduce focus, and create student inequality (Kai, 2012; Maroy & van Zanten, 2007; Pike et al., 2018). Differences in age, gender, physical abilities, and cultural backgrounds among students also influence their responses to gamification, requiring a contextual and adaptive approach (Fernandez-Rio et al., 2022). Existing studies indicate that although gamification has many positive effects, a more careful examination is needed to understand the dynamics of its implementation in physical education.

Based on this review, this study was conducted to identify and analyze the effectiveness and challenges of implementing gamification in physical education based on the results of previous studies over the past 10 years. By analyzing various findings on the implementation of gamification in the context of physical education from multiple countries, this study is expected to contribute theoretically and practically to support the application of the gamification approach in physical education. There are two critical questions to be answered in this study: (1) How effective is gamification in physical education? and (2) What challenges are faced in implementing gamification in physical education? This study combines the results of various previous studies to create a more complete picture of the effectiveness and challenges of implementing gamification in physical education lessons. This study is expected to significantly contribute to developing effective, inclusive, and sustainable

gamification-based physical education learning strategies that are adaptive and technology-based.

Materials and Methods

Study Design

The method used in this study was a Systematic Literature Review (SLR) with the help of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to systematically review empirical research articles discussing the effectiveness and challenges of implementing gamification in physical education. This design was chosen to ensure that the data identification process was conducted transparently, systematically, and reproducibly so that each stage could be traced and replicated by other researchers.

Eligibility Criteria

This study used the PICO (Population, Intervention, Comparator, and Outcome) approach to determine inclusion and exclusion criteria (Kloda et al., 2020). Table 1 illustrates the PICO approach in this study.

Table 1. Overview of PICO

Element	Description
P (Population)	Involving teachers and students in physical education learning at school
I (Intervention)	Research focusing on the implementation of gamification in physical education
C (Comparison)	No specific comparison conditions were specified in the inclusion criteria.
O (Outcome)	Effectiveness and challenges of implementing gamification in physical education

The following inclusion and exclusion criteria are used to select research results or articles to be included in the SLR.

Inclusion criteria include: (1) Scopus and ERIC database in the last 10 years (2015-2025), (2) studies involving teachers and students involved in physical education in schools, (3) focus on the implementation of gamification in physical education, (4) field studies such as qualitative, quantitative, or mixed-method studies that are relevant, (5) articles written in English, (6) articles obtained in full-text.

Exclusion criteria include: (1) articles published outside the specified timeframe, (2) studies outside of physical education in schools, such as in community settings, (3) studies focusing on gamification approaches in general without discussing physical education, (4) non-empirical research such as book chapters, literature reviews, or meta-analyses, (5) articles not written in English, and (6) the article does not display the full-text

Search Strategy

The literature search procedure was conducted using the Scopus and ERIC databases. The search and data identification process was carried out on July 9, 2025, using the keywords "gamification" OR "gamified" OR "game

elements” AND “physical education” OR “PE” OR “physical activity” OR “physical education and sport”. The search was limited to peer-reviewed journal articles published in English with a publication period ranging from 2015 to 2025. The identification results from each database in the form of RIS files were then imported into the reference management software Mendeley. Next, duplicate articles with similarities were removed to avoid repetition of the same studies, thereby maintaining the accuracy of the number of articles, avoiding selection bias, and increasing the validity of article selection.

Study Selection

The article selection process was carried out in several stages in accordance with the PRISMA guidelines. The identification stage was carried out by collecting all articles obtained from the database, then managing them using the Mendeley reference management tool to remove duplicates. Next, screening was carried out by reviewing the titles and abstracts to identify studies that were relevant to the research focus, namely the effectiveness and challenges of implementing gamification in physical education in schools. Full-text articles from selected studies were then assessed by two independent reviewers (WA and KS) separately based on predetermined inclusion and exclusion criteria. Any differences in decision were discussed to reach a consensus with a third reviewer (KY).

Data were systematically extracted to gather key information from each study meeting the inclusion criteria, including research design, sample characteristics, type of gamification used, reported learning outcomes, and implementation challenges. Data were then synthesized narratively by grouping findings based on model effectiveness and identifying implementation barriers that impact learning outcomes.

Quality Assessment and Risk of Bias

The methodological quality and risk of bias of the included studies were independently assessed by two independent reviewers (WA and KS) using the following assessment criteria: (1) clarity of research objectives, (2) appropriateness of research design, (3) sample characteristics and size, (4) data collection instruments, (5) data collection procedures, and (5) clarity of data analysis. Each study was rated as low, moderate, or high quality. Two reviewers independently conducted the quality assessment (WA and KS), and differences were resolved through discussion with a third party (KY). Overall, most studies showed moderate methodological quality, with common limitations related to small sample sizes and limited reporting of instrument validity and reliability procedures.

Results

Study Selection Results

A total of 496 documents were identified through searches using the Scopus and ERIC databases. Of these 496 articles, 182 were filtered out, including 15 similar documents that were detected as deleted, 162 documents that were marked as ineligible by the automation tool, and 5 documents without abstracts, leaving 314 articles to be shared. During the screening phase, 243 documents were excluded because

they were not published in article form and 34 documents were not selected because they were not relevant to the topic, leaving 37 articles that were considered eligible. There were 12 documents excluded for various reasons, including studies not conducted in schools and full papers not available. Thus, there were 25 articles selected for systematic review. Figure 1 shows the process of identifying and screening articles relevant to the stages of systematic review.

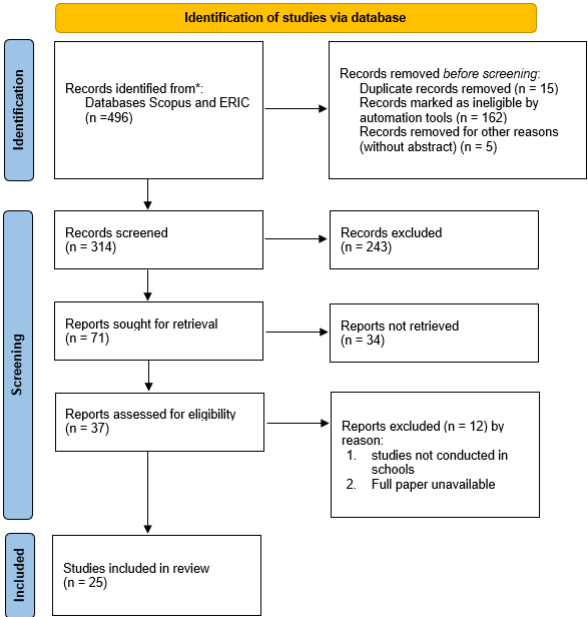


Fig. 1. Stages of Article Screening Using the PRISMA Method

Publication Trends

Research on the implementation of gamification in physical education shows fluctuating and inconsistent progress. Although researchers set inclusion criteria for articles published in the last 10 years (2015-2025), articles relevant to the topic were only discussed in the last 5 years, namely 2020-2025. This indicates that the approach to implementing gamification in physical education has only developed in the past five years. This suggests a positive trend and the potential for further research as the adoption of technology and innovative methods in physical education continues to grow. Figure 2 shows the distribution of the analyzed articles.

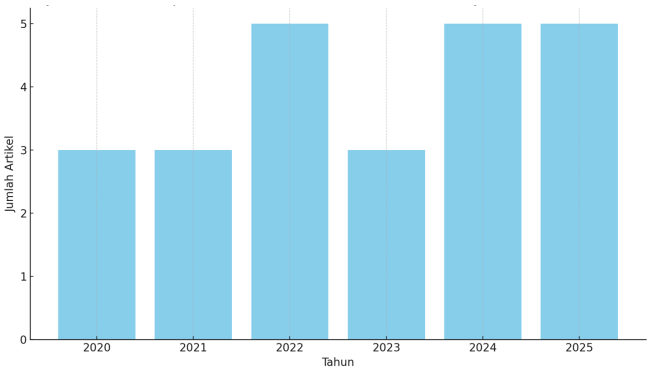


Fig. 2. Publication Trends by Years

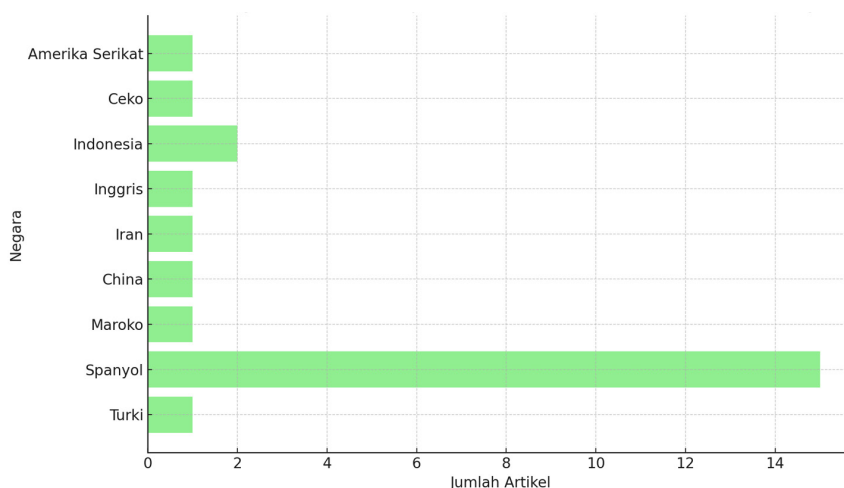


Fig. 3. Distribution of Research Areas

Figure 2 shows the number of articles discussing the application of gamification in physical education in recent years. In 2020 and 2021, there were three articles each year, then increased to 5 articles in 2022. Although it dropped to 3 in 2023, interest in this topic rebounded in 2024 and 2025, with five articles each year. This graph illustrates a fluctuating trend but indicates that interest in physical education gamification has grown recently.

Geographical Distribution of Studies

The trend of gamification research in physical education shows a wide distribution across countries. The results of the analysis show variations in research contributions between countries, as shown in Figure 3.

Figure 3 shows a horizontal bar chart depicting the distribution of research areas on implementing gamification in physical education. This graph shows that

Spain dominates with the highest number of articles at 15. Meanwhile, countries such as Indonesia, Turkey, Morocco, China, Iran, the United Kingdom, the Czech Republic, and the United States contribute only 1–2 articles. This indicates that Spain is the focal point of research in this field, while other countries still show limited involvement.

Effectiveness of Gamification Implementation in Physical Education

The results of several studies demonstrate the effectiveness of gamification implementation in physical education across six main themes: increased motivation, satisfaction, student engagement, and active participation; increased physical activity and active lifestyle; improved fitness and motor skills; enhanced academic performance; and strengthened personality and social skills, as shown in Table 2.

Table 2. Effectiveness of Gamification Implementation in Physical Education

Effectiveness	Number of Studies	Studies Reporting
Increased motivation	10	Cakir et al. (2025); Flores-Aguilar et al. (2023); Montiel-Ruiz et al. (2023); Quintas et al. (2020); Soriano-Pascual et al. (2022); Sotos-Martinez et al. (2022); Sotos-Martínez et al. (2023); Valero-Valenzuela et al. (2020); Vorlíček et al. (2024); Yuan et al. (2024)
Increased satisfaction, engagement, and participation among students	8	Cakir et al. (2025); Jeong et al. (2022); Santurio & Fernández-Río (2022); Sotos-Martinez et al. (2022); Utamayasa et al. (2025); Vorlíček et al. (2024); Wahyuniati et al. (2025); Wibowo (2024)
Increased activity or active lifestyle	7	Cakir et al. (2025); Fernandez-Rio et al. (2022); Melero-Cañas et al. (2021); Melero-Cañas, Morales-Baños, Manzano-Sánchez et al. (2021); Montiel-Ruiz et al. (2023); Pourabbasi et al. (2020); Viciania et al. (2025)
Improved motor skills and fitness	5	Fernández-Vázquez et al. (2024); Lamrani & Abdelwahed (2020); Melero-Cañas et al. (2021); Melero-Cañas, Morales-Baños, Manzano-Sánchez et al. (2021); Utamayasa et al. (2025)
Improved academic performance	5	Flores-Aguilar et al. (2023); Jeong et al. (2022); Melero-Cañas, Morales-Baños, Ardoy et al. (2021); Pourabbasi et al. (2020); Quintas et al. (2020)
Strengthened personality and social skills	5	Lamrani & Abdelwahed (2020); Montiel-Ruiz et al. (2023); Parra-González et al. (2020); Soriano-Pascual et al. (2022); Valero-Valenzuela et al. (2020); Wibowo (2024); Yuan et al. (2024)

Table 3. Challenges of Implementing Gamification in Physical Education

Challenges	Number of Studies	Studies Reporting
Limited infrastructure and technology	5	Flores-Aguilar et al. (2023); Jeong et al., (2022); Utamayasa et al. (2025); Vorlíček et al. (2024); Yuan et al. (2024)
Low digital literacy among teachers	5	Cakir et al.,(2025); Montiel-Ruiz et al. (2023); Soriano-Pascual et al. (2022); Wibowo (2024); Yuan et al. (2024)
Gamification design not contextual	4	Flores-Aguilar et al. (2023); Lamrani & Abdelwahed (2020); Pourabbasi et al. (2020); Santurio & Fernández-Río (2022)
Short intervention duration	4	Fernández-Vázquez et al. (2024); Melero-Cañas, Manzano-Sánchez et al. (2021); Sotos-Martínez et al. (2023); Viciana et al. (2025)
Evaluation not yet standardized	4	Parra-González et al., (2020); Quintas et al. (2020); Sotos-Martinez et al. (2022); Wahyuniati et al. (2025)

Challenges in Implementing Gamification in Physical Education

Several studies have shown the challenges faced in implementing gamification in physical education. For example, five out of 25 studies indicate that the main challenges in implementing gamification are limitations in infrastructure and technology and low digital literacy among teachers. Next are challenges related to gamification design that is not contextual, short intervention duration, and evaluation that is not yet standardized, with four studies discussing each of these issues. Table 3 provides an overview of the challenges of implementing gamification in physical education.

Discussion

The findings of this study indicate that the implementation of gamification in physical education has a positive effect on various aspects of learning, such as increased motivation, student engagement, academic achievement, promotion of an active lifestyle, fitness, and motor skills, as well as strengthening psychological aspects such as independence, responsibility, and social skills. Motivation is the dominant finding that proves the effectiveness of gamification in physical education, which several previous studies have reinforced. Fernandez-Rio et al. (2022) and Sotos-Martinez et al. (2022) show that gamification increases intrinsic motivation, satisfaction with learning, and the intention to exercise continuously. These results are supported by research by Yuan et al. (2024), which emphasizes that the application of adaptive gamification can increase student motivation, mental health, and personality development. Student satisfaction, engagement, and participation in physical education also experienced significant improvements, as shown in the study by Cakir et al. (2025), through studies utilizing gamification integrated with physical activity trackers and combining Self-Determination Theory and Flow Theory, it has been shown that gamification can increase the number of daily steps taken by students, boost positive energy, and strengthen both cognitive and affective engagement of students in physical education lessons. The integration of technology in gamification, such as the use of wearables, Edmodo, and virtual reality technology, has proven to enhance student participation, engagement, and collaboration (Jeong et al., 2022; Montiel-Ruiz et al., 2023; Utamayasa et al., 2025). Gamification with the Coaching

Games model also showed a significant increase in student engagement in physical education (Wahyuniati et al., 2025). This indicates that motivation and engagement are two key pillars that strengthen the effectiveness of gamification in physical education

Improvements in motor skills, physical activity, and fitness were consistent findings in applying gamification. Research by Viciana et al. (2025) using a brief but regular intermittent gamification approach has been shown to increase physical activity in elementary school children, with an increase in the number of daily steps, reaching the target of 10,000 steps per day. This is reinforced by research by Vorlíček et al. (2024), who showed that the Gamifter app can increase physical activity by increasing the number of daily steps taken by students through the use of activity trackers (Garmin VivoFit trackers) and promoting an active and healthy lifestyle. The implementation of gamification has also been proven to improve basic motor skills. (Utamayasa et al., 2025) and improved physical fitness such as cardiorespiratory endurance, strength, balance, and motor coordination (Fernández-Vázquez et al., 2024; Melero-Cañas, Manzano-Sánchez, et al., 2021). Jeong et al. (2022) study also found that students' active involvement in physical activities was accompanied by the ability to analyze movement data.

Gamification has an effective impact not only on physical aspects but also on cognitive and affective domains. Hybrid gamification intervention using the TPSR model can improve cognitive inhibition, verbal abilities, and academic achievement (Melero-Cañas, Morales-Baños, Ardoy et al., 2021). This is reinforced by research conducted by Parra-González et al. (2020) and Lamrani & Abdelwahed (2020), which found that well-designed and contextual gamification can increase student satisfaction, early literacy, and creativity. Participation-based gamification design can increase students' understanding of physical activities and improve academic scores and achievements (Flores-Aguilar et al., 2023; Quintas et al., 2020; Rice et al., 2025). In addition, strengthening personality aspects such as responsibility and social skills is an important theme in these findings. The combination of gamification and the TPSR model can strengthen students' character traits such as independence, personal responsibility, and collaboration (Soriano-Pascual et al., 2022; Valero-Valenzuela et al., 2020). This is reinforced by Wibowo (2024) research, which shows that gamification has a strong relevance in improving students' self-esteem, learning satisfaction, and motor skills, even when

combined with conventional training approaches. Lamrani & Abdelwahed (2020) reported that social interaction increased in young children through educational games developed based on Montessori principles. These results are important because they show that gamification is fun and sustainably shapes students' social character.

However, the study also found various challenges in implementing gamification in physical education. The first challenge is limited infrastructure and technology, as shown in a study by Utamayasa et al. (2025), which stated that not all schools have the Virtual Reality (VR) devices needed for intervention. The lack of digital infrastructure support, such as wearables, and the availability of funds are serious obstacles to implementing gamification in physical education (Vorlíček et al., 2024; Yuan et al., 2024). Using gamification approaches based on popular media requires supporting equipment such as projectors, speakers, or suitable learning spaces (Flores-Aguilar et al., 2023). The next challenge is the low level of digital literacy among teachers. For example, not all teachers can utilize digital platforms such as Edmodo or activity tracking engines (Cakir et al., 2025; Montiel-Ruiz et al., 2023). This is reinforced by research by Wibowo (2024) and Yuan et al. (2024), who state in their study that systematic teacher training is essential for the optimal integration of gamification in physical education.

Several studies highlight that an excessive emphasis on competition in gamification can have negative effects. Research by Santurio & Fernández-Río (2022) reported that several students and parents had criticized the high intensity of competition in the "quidditch-muggle" model, which could potentially overshadow the social and emotional aspects of the student's learning experience. Although gamification was implemented simply, its application must be adapted to the local culture and context. (Flores-Aguilar et al., 2023; Pourabbasi et al., 2020). In addition, the gamification approach must consider the child's age so as not to cause excessive cognitive and emotional stress (Lamrani & Abdelwahed, 2020). Most studies indicate that the short duration of gamification interventions limits their long-term impact. For example, an intermittent program lasting five weeks (Viciano et al., 2025) and VR use tested for only six weeks (Fernández-Vázquez et al., 2024) without follow-up measurements, leaving the sustainability of students' physical behaviour changes yet to be proven. Some studies indicate that there are no standardized evaluation tools to comprehensively measure the outcomes of gamified learning, so they do not represent all aspects of learning (Sotos-Martínez et al., 2023; Wahyuniati et al., 2025). These challenges are important considerations for designing more mature, sustainable gamification models that can address the diversity of school conditions.

Based on this, this study contributes to the development of physical education using innovative and technology-based approaches. These findings can expand gamification pedagogical models with contextual approaches oriented toward 21st-century learning. This study implies that the gamification approach can be applied in various formats and adapted to teacher readiness, student characteristics, and infrastructure support.

However, this systematic review study has limitations that need to be considered when interpreting the results of the study. The database sources used were limited

to Scopus and ERIC, so it is possible that other studies related to the implementation of gamification in physical education were not identified. This study only included articles in English, so publications in other languages could not be accommodated, meaning that a global view of the implementation of gamification in physical education has not been described. The results of the study show limitations related to the geographical concentration of research, which is mostly in Europe (Spain, England, the Czech Republic, and Turkey) and a number of studies in Asia (Indonesia, China, and Iran), the United States, and Morocco (Africa). This indicates that the development of gamification in physical education is still dominated by Europe, which could potentially cause the findings to reflect the education systems and physical education learning practices in those countries. The limited number of studies on other continents shows an unbalanced view of the topic. This imbalance could limit the generalization of findings in a broader context. Future studies are expected to expand the database used and broaden the geographical coverage by involving more studies from various regions in an effort to expand the perspective and validity of the findings.

Conclusions

The results of a systematic review indicate that gamification is effective in physical education. Incorporating game elements into the learning process can increase students' active participation physically, cognitively, socially, and emotionally. Gamification demonstrates that learning with game elements can be meaningful and enjoyable. Research shows that gamification increases student motivation and participation because it creates a challenging and enjoyable learning environment, which has a positive impact on motor skills, academic achievement, and the strengthening of personality and social skills.

However, several challenges have been identified in implementing gamification in physical education. Limited infrastructure and teachers' digital readiness and competency are key barriers. Without these two factors, implementing gamification in learning will be extremely difficult. Furthermore, a less contextual gamification design can potentially distract from learning. The short duration of interventions in studies also hinders measuring the long-term impact of gamification approaches, and the lack of standardized evaluations can lead to less valid and comprehensive assessments.

Longitudinal studies are recommended to assess the impact of gamification on changes in students' active lifestyle behaviors, fitness, and character development over time, given the limitations of future research designs. Research is needed on gamification designs that can be implemented in various school settings. Cross-disciplinary collaboration between physical education teachers, educational technologists, and educational psychologists can help strengthen the foundation of these ideas and ensure the success of gamification in physical education.

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Conflict of interest

The authors declare no conflict of interest.

AI-Usage Declaration

The authors declare that AI-assisted software (WataSe Uake, ChatGPT, DeepL) was used to a limited extent to assist with language editing and readability of the manuscript. All aspects of the research, such as SLR design, determination of inclusion and exclusion criteria, article selection process, data extraction and analysis, interpretation of results, and drawing conclusions, were entirely carried out by the authors. The authors take full responsibility for the integrity of the article

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Ефективність і виклики застосування гейміфікації у фізичному вихованні: систематичний огляд

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; Е – збір коштів
Реферат. Стаття: 9 с., 3 табл., 3 рис., 36 джерел.

Актуальність. У сучасній системі фізичного виховання актуальною проблемою залишається підвищення мотивації, активності та залученості учнів до навчального процесу. Одним із перспективних інноваційних підходів є гейміфікація – використання ігрових елементів у навчальній діяльності.

Мета дослідження – проаналізувати ефективність та виклики застосування гейміфікації у фізичному вихованні на основі систематичного огляду наукової літератури.

Матеріали і методи. Пошук наукових джерел здійснювався у базах даних Scopus та ERIC за ключовими словами “gamification” OR “gamified” AND “physical education” OR “PE”. Відбір публікацій проводився відповідно до процедури PRISMA. Для узагальнення результатів використано контент-аналіз за двома напрямками: ефективність та виклики впровадження гейміфікації у фізичному вихованні. У результаті пошуку було ідентифіковано 496 публікацій. Після етапів відбору до аналізу включено 25 статей, опублікованих у 2015–2025 роках.

Результати. Узагальнення результатів досліджень свідчить, що застосування гейміфікації у фізичному вихованні сприяє підвищенню мотивації та залученості учнів, збільшенню рівня фізичної активності, розвитку рухових навичок, покращенню навчальних досягнень, а також формуванню особистісних і соціальних компетентностей. Водночас визначено низку проблемних аспектів, зокрема обмеженість технологічної інфраструктури, недостатній рівень цифрової компетентності вчителів, невідповідність окремих гейміфікаційних моделей освітньому контексту, коротку тривалість інтервенцій та відсутність стандартизованих інструментів оцінювання.

Висновки. Гейміфікація є перспективним інструментом підвищення ефективності навчального процесу з фізичного виховання. Отримані результати можуть бути використані для розроблення інноваційних, технологічно орієнтованих та адаптивних стратегій організації занять з фізичного виховання.

Ключові слова: гейміфікація, фізичне виховання, мотивація, залученість учнів.

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Review Article

Global Research Trends on Gymnastics in Physical Education: A Scopus-Based Bibliometric Analysis

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Abstract

Objectives. This study aims to understand global research trends on gymnastics in physical education by conducting a bibliometric analysis of documents indexed in the Scopus database from 2015 to 2025.

Materials and Methods. Data were extracted using the keywords “gymnastics” and “physical education,” filtered by document type (articles and reviews) and language (English). A total of 297 documents were analyzed. VOSviewer software was used to visualize keyword co-occurrence relationships.

Results. The results show a fluctuating publication trend, with a peak in 2019, followed by a decline after 2021, suggesting a temporary shift during the COVID-19 pandemic period. The United States, the United Kingdom, and Spain emerged as the most productive countries, while Cardiff Metropolitan University and Loughborough University were identified as leading institutions. Keyword co-occurrence mapping revealed five major thematic clusters: (1) gymnastics pedagogy and student learning, (2) motor learning and movement coordination, (3) biomechanics and injury prevention, (4) health, motivation, and exercise, and (5) technology-enhanced physical education.

Conclusions. These findings indicate that the field has evolved from a biomechanical and performance-based perspective to a more interdisciplinary approach integrating health, education, and technology. The study provides insights for educators, policymakers, and researchers to strengthen collaboration, integrate digital learning tools, and advance innovative teaching practices in gymnastics education.

Keywords: gymnastics, physical education, bibliometric analysis, Scopus, research trends.

Introduction

Gymnastics is one of the foundational disciplines in physical education that plays a critical role in developing students' motor skills, physical literacy, and body coordination from an early age. It is not just a sport, but a type of movement education that combines strength, flexibility, balance, and rhythm which are important as key elements that help develop physical abilities for a lifetime. (Sawicki et al., 2018). As an integral part of physical education curricula worldwide, gymnastics promotes not only physical fitness but also creativity, discipline, and self-confidence (Viciene et al., 2015). In recent years, educators and researchers have paid increasing attention to how gymnastics can support holistic development in students, including cognitive and socio-emotional aspects of learning through movement.

The evolution of gymnastics pedagogy within physical education has been influenced by changes in educational philosophy and the broader movement towards competence-based and inclusive curricula (Krüger, 2018). Traditional gymnastics teaching often emphasized performance mastery and competition; however, recent approaches have shifted toward learning experiences that focus on participation, exploration, and safety in movement (Bertills & Björk, 2024). This transformation aligns with the goals of twenty-first-century physical education, which seeks to balance performance achievement with personal development, health, and well-being (Lindsay & Spittle, 2024). In this context, gymnastics serves as an ideal platform for cultivating students' psychomotor and affective domains while fostering motivation and lifelong engagement in physical activity.

From a research perspective, the study of gymnastics in physical education involves various domains such as biomechanics, motor learning, injury prevention, pedagogy, and psychology. For instance, Abdollahipour et al. (2015)

demonstrated that an external focus of attention improves performance in gymnastics skills, highlighting the cognitive dimensions of skill acquisition. Similarly, studies on injury epidemiology among young athletes, including gymnasts, have informed safety protocols and preventive training designs (Changstrom et al., 2015). Other scholars have explored gender participation, inclusion, and the use of digital technologies to enhance teaching and assessment in gymnastics-based learning environments (Harris & Cale, 2018; Jastrow et al., 2022). Therefore, these studies illustrate that gymnastics research has evolved beyond physical performance to address multidimensional educational and health-related outcomes.

Despite the growing volume of gymnastics-related research, the conceptual distinction between gymnastics as an educational content in physical education and gymnastics as an elite or competitive sport remains insufficiently articulated in the literature (Leite et al., 2023). In physical education, gymnastics is positioned as a curriculum-based learning domain implemented in school and higher education settings, emphasizing pedagogical objectives such as motor development, learning processes, safety, and student engagement. In contrast, elite or competitive gymnastics research is primarily oriented toward performance optimization, high-level athlete preparation, and biomedical outcomes. Given this distinction, it is essential that research syntheses explicitly justify their relevance to pedagogical PE contexts. Therefore, this study deliberately focuses on publications in which gymnastics is examined as a teaching and learning medium within physical education, rather than as a specialized competitive discipline, ensuring alignment with educational aims and curricular practice.

In recent years, bibliometric studies have gained recognition in sports and educational sciences as a means to understand how research fields evolve and interact. For example, Rahayu et al. (2023) conducted a bibliometric review of physical activity and health promotion, revealing the dominant themes and collaboration networks driving the field. Similarly, (Avila-garzon & Bacca-acosta, 2021) examined educational technology research trends, offering insights into pedagogical innovation. However, within the domain of gymnastics, particularly in the context of school-based physical education, such comprehensive bibliometric mapping remains scarce. Considering the interdisciplinary nature of gymnastics which consists of spanning sport science, pedagogy, and psychology, analyzing its publication patterns can provide an integrated understanding of how the discipline contributes to educational and health-related outcomes globally.

The importance of conducting a bibliometric analysis on gymnastics in physical education lies not only in identifying quantitative trends but also in understanding the intellectual structure of the field. For instance, the identification of highly cited works such as Changstrom et al. (2015) and Silva & Paiva (2015) highlights the intersection of health and performance research, reflecting a dual emphasis on athlete well-being and skill optimization. Moreover, the inclusion of diverse subject areas such as social sciences, psychology, arts, health, and multidisciplinary studies, demonstrates that gymnastics research extends far beyond sport performance, intersecting with human development, learning theory, and wellness education. This interdisciplinary character

reinforces the role of gymnastics as both an academic and practical field relevant to contemporary educational goals.

In the digital era, the teaching and learning of gymnastics are also being transformed by emerging technologies such as virtual reality, motion analysis systems, and digital coaching tools. These innovations offer new possibilities for enhancing student engagement, personalized feedback, and movement visualization (Bonanno et al., 2022). As global education systems increasingly adopt technology-enhanced physical education, research on gymnastics must adapt to explore how such tools influence motor learning and student outcomes. Therefore, analyzing research trends in gymnastics not only reflects past achievements but also anticipates future directions shaped by digital pedagogy, inclusivity, and health promotion.

Related to these considerations, this study aims to conduct a comprehensive bibliometric analysis of research on gymnastics in physical education published in the Scopus database from 2015 to 2025. Specifically, the study seeks to (1) identify the publication trends, most productive authors, institutions, and countries; (2) determine the leading journals and citation patterns; and (3) visualize the thematic clusters and emerging research frontiers through keyword co-occurrence mapping. By providing a systematic overview of the global knowledge structure in this domain, this study contributes to the advancement of evidence-based understanding of how gymnastics functions as an educational and scientific field. The findings are expected to inform educators, researchers, and policymakers in designing innovative and inclusive gymnastics programs that align with the goals of modern physical education.

Materials and Methods

This study conducted a bibliometric research design to systematically map and analyze global publication trends on gymnastics in the field of physical education. Bibliometric analysis is a quantitative method used to evaluate scientific literature, allowing researchers to identify patterns, networks, and research dynamics within a specific field (Donthu et al., 2021). Through citation data, keyword analysis, and co-authorship mapping, bibliometric methods help visualize the intellectual structure and thematic evolution of a research domain. This approach is particularly effective for disciplines that intersect multiple fields, such as physical education, sport science, and pedagogy, where traditional literature reviews may not capture the full scope of scholarly development.

Data Source and Search Strategy

The data for this study were retrieved from the Scopus database, one of the most comprehensive and widely used repositories for peer-reviewed academic literature. Scopus was selected due to its extensive coverage across social sciences, education, and health disciplines, as well as its advanced analytical features for bibliometric research (Baas et al., 2020). The search process was conducted on October 29, 2025, using the following query string in the "Article Title, Abstract, and Keywords" fields: (KEY (gymnastic*) AND KEY (physical education)) AND PUBYEAR > 2014 AND PUBYEAR < 2026

Table 1. Applied Filters for Data Retrieval from Scopus

Filter Category	Description / Criteria Applied	Rationale
Database Source	Scopus (Elsevier)	Chosen for its wide coverage in education, sport science, and multidisciplinary fields.
Search Field	Title, Abstract, and Keywords	To capture publications directly related to the topic
Search Query	(KEY (gymnastic*) AND KEY (physical education))	Ensures focus on gymnastics within the context of physical education
Publication Year	2015–2025	Represents the most recent decade of research development
Document Type	Article	Focused on peer-reviewed journal articles to ensure academic rigor
Language	English	Selected for global accessibility and comparability
Subject Areas	Social Sciences (SOC), Psychology (PSYC), Arts and Humanities (ARTS), Multidisciplinary (MULT), Health Professions (HEAL)	To include interdisciplinary studies related to physical education and human movement
Data Export Format	CSV and RIS	Compatible with bibliometric tools (VOSviewer)
Data Collection Date	October 29, 2025	Ensures the dataset reflects the latest publications up to 2025

To ensure the relevance, quality, and consistency of the dataset, several inclusion filters were applied during the data extraction process. The applied criteria are summarized in Table 1.

After applying these filters, a total of 297 documents were identified as relevant to gymnastics in physical education. The records were exported in both CSV and RIS formats for subsequent analysis using VOSviewer.

Screening and Selection Procedure

Study selection was conducted independently by two reviewers with academic expertise in gymnastics research and bibliometric methodology. Both reviewers possess prior experience in physical education scholarship and quantitative research mapping, ensuring both content relevance and methodological rigor in the screening process. The initial screening was based on title and abstract evaluation to determine alignment with the predefined inclusion criteria, specifically focusing on studies examining gymnastics within pedagogical and physical education contexts rather than elite or purely competitive sport performance domains. Independent screening is recommended in bibliometric and evidence synthesis research to enhance objectivity, reduce selection bias, and strengthen methodological transparency (Donthu et al., 2021; Page et al., 2021).

Following the preliminary screening, full-text verification was conducted for records that met the inclusion criteria or where eligibility remained uncertain. Disagreements regarding inclusion or exclusion were resolved through structured discussion aimed at reaching consensus. This dialogic validation process ensured that decisions were grounded in conceptual clarity and consistent application of the research scope. When consensus could not be achieved, a third reviewer—an expert in bibliometric studies with extensive experience in research evaluation and scientific mapping—was consulted to provide an independent judgment. The involvement of a third reviewer in resolving discrepancies is widely acknowledged as a best practice to improve reliability and methodological credibility in systematic and bibliometric reviews (Aria & Cuccurullo, 2017).

To further ensure transparency and replicability, all inclusion and exclusion decisions were documented during the screening process. The reviewers adhered to predefined criteria related to publication type, language, time frame, and subject relevance as specified in the methodological framework. This structured selection procedure strengthens the internal validity of the bibliometric dataset and aligns with established guidelines for conducting rigorous and reproducible bibliometric analyses in interdisciplinary research domains (Donthu et al., 2021).

Data Extraction and Preparation

Each record extracted from Scopus contained essential bibliographic information, including author names, article titles, publication year, journal source, institutional affiliation, country, keywords, abstract, and citation counts. Duplicate records were identified using Scopus document identifiers and manually cross-checked to avoid redundancy. Author name disambiguation was conducted by standardizing variations in initials and surname formats to ensure accurate co-authorship mapping. Keyword normalization was performed by merging synonymous terms (e.g., “PE” and “physical education”) and correcting spelling inconsistencies to improve the accuracy of co-occurrence analysis. The final dataset represented the global research output in gymnastics-related physical education over the past decade.

To enhance analytical depth, metadata were structured for both quantitative and network analyses. This preparation allowed the data to be processed by using VOSviewer (version 1.6.20) for bibliometric analysis.

Bibliometric Indicators

The bibliometric analysis focused on both quantitative and relational indicators to describe the structural and thematic characteristics of gymnastics-related research in physical education. These indicators were selected based on standard bibliometric frameworks (Donthu et al., 2021). The specific indicators used in this study are summarized in Table 2.

These indicators collectively enabled a comprehensive understanding of the quantitative output, intellectual structure, and collaborative networks in the field. Productivity indicators revealed the most active contributors and sources; impact indicators highlighted influential works and citation patterns; and relational indicators demonstrated how authors and institutions collaborate across disciplines.

Visualization was primarily performed using VOSviewer (version 1.6.20) to generate network maps for co-authorship, co-occurrence, and citation analysis. The integration of these tools allowed for a multidimensional representation of the research landscape, providing both descriptive and structural insights into the development of gymnastics-related scholarship in physical education.

Visualization and Network Analysis

VOSviewer was used to construct and visualize bibliometric networks, including co-authorship, co-occurrence, and citation maps. VOSviewer is particularly effective for analyzing large datasets and generating intuitive visual representations of relationships among authors, keywords, and documents (Bus, 2023; Jan & Ludo, 2010). The software applies a mapping technique where nodes represent items (e.g., authors, keywords), and the size of each node indicates its frequency or citation impact. The proximity between nodes reflects the strength of their relationship, while colors denote thematic clusters or communities within the field.

The co-occurrence analysis of author keywords was used to identify the most frequently used terms and the conceptual structure of the field. Keywords such as gymnastics, physical education, motor learning, biomechanics, injury prevention, and teaching strategies were expected to dominate the network.

Co-authorship mapping was performed to reveal collaborative networks across countries and institutions, showing which regions contribute most actively to gymnastics education research. Meanwhile, citation analysis identified the most influential works shaping the knowledge base, such as those by Abdollahipour et al. (2015) and Changstrom et al. (2015).

In addition to VOSviewer was employed for statistical analysis of bibliometric indicators. This tool enabled the generation of descriptive statistics such as annual publication growth rate, author productivity index, and source impact metrics (h-index, g-index, m-index) as well as thematic evolution analysis to trace how topics in gymnastics education have developed over time (Jan & Ludo, 2010).

Reliability and Limitations

The reliability of bibliometric analysis depends on the completeness and accuracy of the database. Although Scopus provides extensive coverage, some relevant works indexed in other databases (e.g., Web of Science or ERIC) may not be included. Additionally, variations in author naming conventions and keyword usage can affect clustering accuracy. To mitigate these issues, data cleaning and normalization procedures were applied before analysis. Despite these limitations, bibliometric methods remain robust for identifying macro-level patterns and providing an empirical foundation for understanding global research dynamics (Donthu et al., 2021).

Protocol Registration

Protocol registration: Not applicable. This study applied a bibliometric design using publicly available

Table 2. Bibliometric Indicators and Their Analytical Purposes

Category	Indicator	Analytical Focus/ Objective	Expected Output/ Visualization
Productivity Indicators	Annual Publication Trends	To identify growth patterns in the number of publications from 2015–2025	Line chart of yearly publication output
	Most Productive Authors	To determine authors with the highest number of publications in the dataset	Author productivity ranking and h-index distribution
	Most Productive Journals	To identify key journals publishing on gymnastics in physical education	Source impact table (number of articles, citations, impact index)
	Institutional and Country Productivity	To highlight active institutions and nations contributing to the field	Geographical mapping of publication distribution
Impact Indicators	Citation Analysis	To assess the influence of authors, journals, and individual articles	Top-cited documents and citation network
	Source Impact Metrics (h-index, g-index, m-index)	To evaluate the quality and influence of key journals or authors	Statistical summary generated
Relational Indicators	Co-authorship Analysis	To reveal collaboration networks among authors, institutions, and countries	Network visualization (nodes = authors/ institutions; links = collaborations)
Thematic Evolution	Keyword Co-occurrence	To identify dominant research themes and conceptual clusters	Thematic cluster map generated using VOSviewer
	Co-citation Analysis	To explore intellectual connections among frequently cited works	Citation network map (VOSviewer)
	Thematic Trend Mapping	To track the evolution of research topics and emerging trends over time	Trend graph and thematic evolution map

secondary data from the Scopus database and did not involve human participants or interventional procedures requiring formal registration. While protocol registration is commonly recommended for systematic reviews of clinical or intervention studies to enhance transparency (Page et al., 2021), it is not a standard requirement for bibliometric analyses. However, the search strategy, inclusion criteria, screening procedures, and analytical framework were predefined and clearly reported to ensure methodological transparency and reproducibility in line with established bibliometric guidelines (Donthu et al., 2021).

Results

Analysis of Documents by Year

The analysis of publication trends provides valuable insights into the development and evolution of research interest in gymnastics within the field of physical education. Examining annual publication output helps to understand how scholarly attention toward this topic has shifted over time, reflecting broader academic, pedagogical, and societal influences on physical education research.

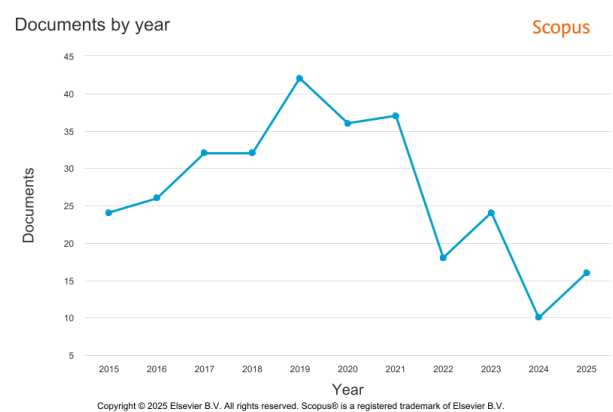


Fig. 1. Annual Distribution of Publications on Gymnastics in Physical Education (2015–2025). Source: Scopus database (analyzed on October 29, 2025)

As illustrated in Figure 1, the number of documents published on gymnastics in physical education between 2015 and 2025 demonstrates a fluctuating yet dynamic pattern. In 2015, there were 24 publications, and this figure increased slightly to 26 in 2016. A steady upward trend continued through 2017 and 2018, each recording 32 documents, indicating growing scholarly engagement with the topic during this period. The peak occurred in 2019, when the number of publications reached 42, marking the most productive year within the decade.

After 2019, publication activity began to decline moderately, with 36 documents in 2020 and 37 documents in 2021, suggesting a stabilization phase. However, in 2022, the number of publications fell sharply to 18, likely influenced by the global educational disruptions caused by the COVID-19 pandemic. A brief recovery occurred in 2023 with 24 publications, but the figure again dropped to its lowest point of 10 in 2024, followed by a modest increase to 15 documents in 2025.

Therefore, the data indicate that research on gymnastics in physical education was most active between 2017 and 2021, a period characterized by increased academic exploration of movement learning, pedagogy, and health-related issues. The subsequent decline may reflect a diversification of research themes toward digital-based physical education and interdisciplinary health promotion studies.

Analysis of Documents per Year by Source

Understanding the distribution of publications across journals provides insight into where research on gymnastics in physical education is most frequently disseminated. It also highlights the preferred outlets for scholars in the field and identifies key sources that shape the scientific discourse.

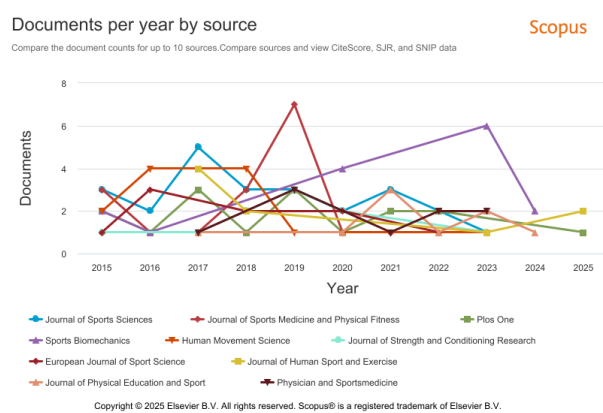


Fig. 2. Documents per year by source (Top 10 journals publishing studies on gymnastics in physical education, 2015–2025). Source: Scopus database (analyzed on October 29, 2025)

As shown in Figure 2, the ten most active journals publishing studies related to gymnastics and physical education between 2015 and 2025 include the Journal of Sports Sciences, Journal of Sports Medicine and Physical Fitness, Plos One, Sports Biomechanics, Human Movement Science, Journal of Strength and Conditioning Research, European Journal of Sport Science, Journal of Human Sport and Exercise, Journal of Physical Education and Sport, and Physician and Sportsmedicine.

Among these sources, the Journal of Sports Sciences consistently appeared as a leading publication outlet, particularly active between 2017 and 2021, with peaks in 2017 and 2021, each contributing around four to five articles per year. The Journal of Sports Medicine and Physical Fitness also demonstrated notable productivity, showing a visible peak in 2019, which corresponded to an increase in health-related studies and sports performance assessments during that period.

Sports Biomechanics showed a steady increase in publication output, reaching its highest point in 2023 with approximately six documents. This pattern reflects growing scholarly attention toward biomechanical and motor learning perspectives in gymnastics-related research. Similarly, Human Movement Science and the Journal of Strength and Conditioning Research exhibited moderate but consistent publication activity, emphasizing performance analysis, training design, and physical education pedagogy.

Other journals such as the *European Journal of Sport Science* and *Journal of Human Sport and Exercise* contributed regularly to the topic, indicating the interdisciplinary nature of gymnastics research that bridges sport science and educational practice. The *Journal of Physical Education and Sport* maintained a stable presence throughout the decade, reinforcing its relevance as a platform for pedagogical and practical studies in physical education.

In general, the results suggest that the dissemination of gymnastics-related research spans a wide range of journals, from sport science to multidisciplinary education outlets. This diversity indicates that gymnastics is studied not only as a performance discipline but also as an educational and developmental medium, connecting research across biomechanics, health, and teaching innovation

Analysis of Documents by Country or Territory

Examining the geographical distribution of publications provides an overview of the countries that have contributed most actively to research on gymnastics in physical education. Country-level analysis helps identify regional strengths, collaborative potential, and global patterns in the dissemination of scholarly work.

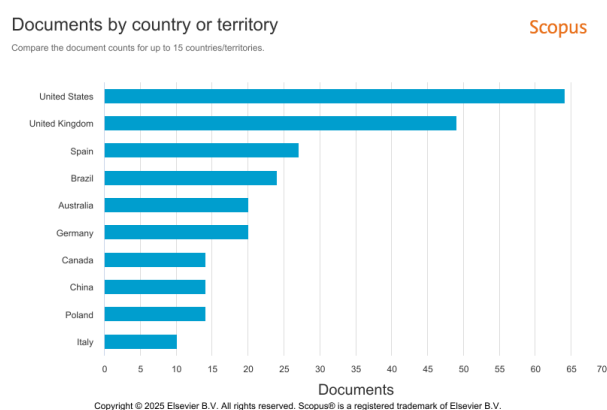


Fig. 3. Distribution of publications by country or territory (Top 10 countries, 2015–2025). Source: Scopus database (analyzed on October 29, 2025)

As presented in Figure 3, the United States dominates the research output with approximately 66 publications, representing the most significant contribution to global studies in this field. This strong presence reflects the country's well-established research culture in sport sciences and physical education, supported by numerous academic institutions and professional organizations. The United Kingdom follows closely with 49 documents, indicating a robust academic engagement in educational and health-oriented gymnastics research.

European countries also show notable contributions, particularly Spain with 29 publications and Germany with 20 publications, reflecting the growing research interest in gymnastics pedagogy and motor learning in European contexts. Meanwhile, Brazil emerges as the leading country from South America with 24 publications, highlighting its active participation in sport and physical education research at the international level.

Among the English-speaking nations, Australia and Canada also demonstrate consistent productivity, each contributing between 18 and 20 publications. Their involvement often emphasizes applied research in movement education, health promotion, and teacher training. Asian participation is represented primarily by China, which recorded approximately 15 publications, indicating a growing engagement in biomechanics and performance-based studies in gymnastics. Additionally, Poland and Italy contribute around 12–14 publications each, underscoring the European region's diverse engagement in gymnastics-related scholarship.

To sum up, the global distribution of publications shows that the majority of research originates from North America and Europe, followed by emerging contributions from South America and Asia. This pattern suggests that while Western nations currently lead the discourse on gymnastics and physical education, there is an increasing global interest and potential for broader international collaboration in the coming years.

Analysis of Documents by Author

The analysis of author productivity provides an overview of the researchers who have contributed most extensively to the body of literature on gymnastics in physical education. This indicator helps identify key figures shaping the development of knowledge in the field and highlights patterns of authorship that reflect collaboration and thematic specialization.

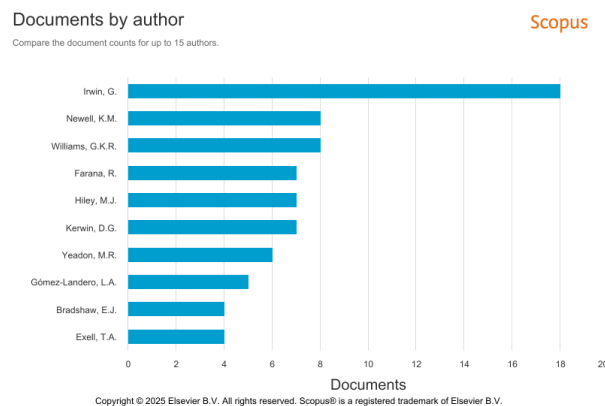


Fig. 4. Top 10 most productive authors publishing on gymnastics in physical education (2015–2025). Source: Scopus database (analyzed on October 29, 2025)

As illustrated in Figure 4, Irwin, G. emerges as the most productive author, contributing 18 publications related to gymnastics and physical education during the 2015–2025 period. His works predominantly focus on the biomechanics of gymnastics performance, skill acquisition, and applied motor control in educational contexts. Following closely are Newell, K. M. and Williams, G. K. R., each with 10 publications, both recognized for their influential research on motor learning and coordination within sports and exercise science.

Other prominent contributors include Farana, R., Hiley, M. J., and Kerwin, D. G., each with 7–8 publications. Their studies primarily examine the mechanical and physiological

aspects of gymnastics performance, offering insights into balance, motion dynamics, and performance efficiency. Similarly, Yeadon, M. R. has made notable contributions with 7 publications, focusing on biomechanical modeling and movement optimization in gymnastics training.

Additionally, researchers such as Gómez-Landero, L. A., Bradshaw, E. J., and Exell, T. A. where each of them have 4–5 publications, represent emerging contributors in the field, often exploring interdisciplinary intersections between sport performance, physical education pedagogy, and applied human movement science.

The data indicate that the majority of prolific authors are affiliated with institutions in the United Kingdom, Australia, and Spain, reflecting strong international representation. This suggests that gymnastics-related research within physical education is primarily driven by scholars specializing in biomechanics, motor learning, and sport performance, underscoring the technical and scientific dimensions of the discipline.

Analysis of Documents by Affiliation

Institutional productivity analysis provides an overview of universities and research centers that have contributed most significantly to the study of gymnastics in physical education. This indicator reflects the concentration of expertise, research collaboration, and the institutional support that sustains scientific output in the field.

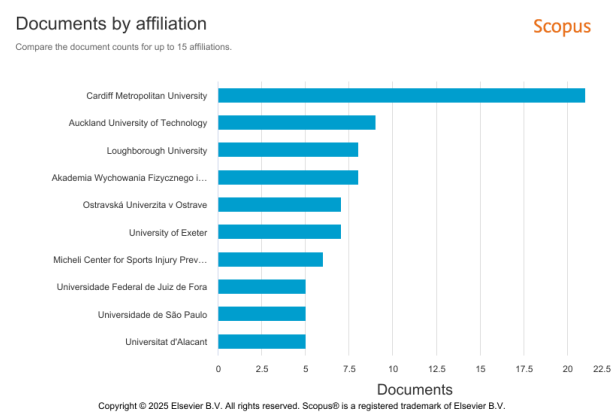


Fig. 5. Top 10 affiliations contributing to publications on gymnastics in physical education (2015–2025). Source: Scopus database (analyzed on October 29, 2025)

As presented in Figure 5, Cardiff Metropolitan University ranks as the most productive institution, with approximately 21 publications on gymnastics and physical education between 2015 and 2025. The university's dominance in this area is consistent with its reputation for excellence in sport and exercise science research, as well as its strong focus on applied biomechanics and motor learning.

Following Cardiff Metropolitan University, the Auckland University of Technology and Loughborough University both exhibit notable research activity, each contributing around 8 publications. These institutions are recognized for their interdisciplinary approach, combining physical education pedagogy, human performance analysis, and sports technology innovation. Similarly, the Akademia Wychowania Fizycznego im. Jerzego Kukuczki

w Katowicach (Poland) and Ostravská Univerzita v Ostravě (Czech Republic) also appear as active contributors, each producing approximately 7 publications, indicating the growing presence of Central European research in this domain.

The University of Exeter and Micheli Center for Sports Injury Prevention show moderate productivity with around 6 publications each, emphasizing the role of British and American institutions in advancing gymnastics injury prevention and performance assessment studies. Meanwhile, Latin American representation is reflected by the Universidade Federal de Juiz de Fora and Universidade de São Paulo (Brazil), both contributing five to six documents, demonstrating the increasing research engagement from South American universities. Additionally, Universitat d'Alacant (Spain) contributes a comparable number of publications, further supporting Spain's strong involvement in gymnastics-related pedagogy and physical education research.

The overall pattern suggests that institutional research productivity is largely concentrated in universities with established sport science and physical education programs. European institutions dominate the top rankings, followed by growing participation from Oceania and South America. This distribution indicates a globally interconnected research community, with potential for expanded collaboration across regions to advance innovation in gymnastics education and movement science.

Analysis of Documents by Subject Area

The subject area distribution provides an overview of the disciplinary scope of publications on gymnastics in physical education. This analysis reflects the multidisciplinary nature of the field, which bridges sport science, health, psychology, and education.

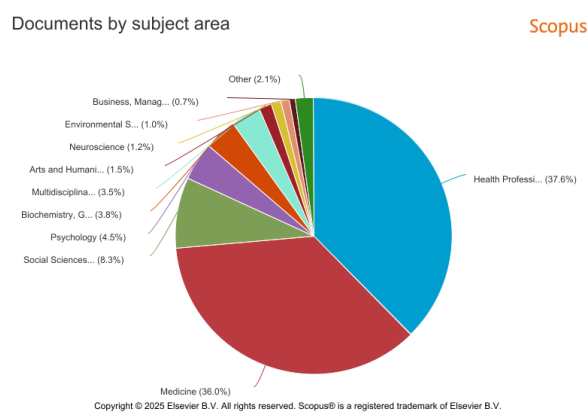


Fig. 6. Annual Distribution of Publications on Gymnastics in Physical Education (2015–2025). Source: Scopus database (analyzed on October 29, 2025)

As displayed in Figure 6, the Health Professions category represents the largest proportion of publications, accounting for 37.6% of all documents. This dominance indicates that research on gymnastics is strongly associated with health promotion, physical performance, and sports training studies. The Medicine category follows closely with 36.0%, highlighting the strong clinical and physiological focus of

many publications, particularly those investigating injury prevention, physical fitness, and rehabilitation in gymnastics and physical education contexts.

The Social Sciences area contributes 8.3% of total documents, underscoring the importance of pedagogical, sociocultural, and educational perspectives in gymnastics-related research. This proportion suggests that scholars increasingly view gymnastics not only as a sport but also as a medium for fostering learning, motivation, and holistic development in educational settings. The Psychology category, comprising 4.5% of the publications, further emphasizes the field's attention to motivation, cognitive processes, and the psychological dimensions of motor learning and skill acquisition.

Smaller but notable contributions come from Biochemistry, Genetics, and Molecular Biology (3.8%), Multidisciplinary (3.5%), and Arts and Humanities (1.5%), which together indicate the integration of scientific, cross-disciplinary, and creative approaches in gymnastics research. Additionally, minor contributions are recorded in Neuroscience (1.2%), Environmental Science (1.0%), and Business, Management and Accounting (0.7%), as well as Other (2.1%), showing that gymnastics-related studies occasionally intersect with diverse research fields such as environmental adaptation, sports administration, and performance optimization.

Generally, the subject area distribution demonstrates that the study of gymnastics in physical education is inherently multidisciplinary, combining biomedical, pedagogical, and psychological dimensions. The predominance of Health Professions and Medicine reflects a sustained research focus on performance, injury prevention, and athlete health, while the growing representation of Social Sciences and Psychology points to the expanding educational and behavioral research directions in this domain.

Keyword Co-Occurrence Network

To identify the conceptual structure and thematic focus of research on gymnastics in physical education, a keyword co-occurrence analysis was conducted using VOSviewer (version 1.6.20). Only keywords with a minimum occurrence of five were included in the visualization to ensure the reliability and clarity of thematic clusters. The analysis revealed several interconnected keyword networks that represent dominant and emerging themes in the field.

The resulting network map (Figure 7) displays multiple clusters differentiated by color, each representing a distinct thematic domain. The first cluster (red) centers on gymnastics, physical education, and teaching, which form the core concepts of the research domain. Keywords such as students, learning outcomes, and pedagogy frequently co-occur, emphasizing the educational dimension of gymnastics in school-based physical education.

The second cluster (green) focuses on motor learning, movement, coordination, and balance. This cluster reflects research that examines the physiological and biomechanical aspects of gymnastics, especially in relation to fundamental movement skills and body control. These studies typically explore how gymnastics contributes to the development of psychomotor competence and postural stability.

The third cluster (blue) represents topics related to injury prevention, biomechanics, and performance. This cluster

Keyword Network Visualization (Based on VOSviewer-style Clustering)

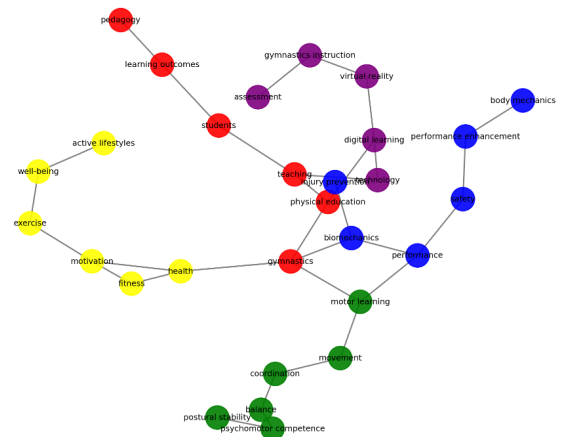


Fig. 7. Keyword co-occurrence network map of research on gymnastics in physical education (minimum 5 occurrences). Source: Scopus database (analyzed on October 29, 2025)

shows the influence of sport science and medical research within the domain, often emphasizing safety, performance enhancement, and body mechanics in gymnastics practice.

The fourth cluster (yellow) includes keywords such as health, fitness, motivation, and exercise, indicating an emerging trend toward health-oriented and motivational studies. These publications often connect gymnastics education with well-being, student engagement, and the promotion of active lifestyles.

Finally, a smaller fifth cluster (purple) relates to technology, digital learning, and virtual reality, which represents a relatively new research direction exploring how digital tools can enhance gymnastics instruction and assessment in physical education contexts.

The density visualization of keywords shows that the terms gymnastics, physical education, motor learning, and health are the most central and frequently connected nodes, indicating their strong influence in shaping the overall research landscape. These findings demonstrate that while biomechanics and health sciences remain dominant, there is growing attention to educational innovation, inclusive practices, and digital pedagogy in gymnastics learning.

Discussion

The bibliometric analysis conducted in this study provides a comprehensive overview of the research landscape on gymnastics in physical education from 2015 to 2025, as indexed in the Scopus database. The findings reveal evolving publication trends, highlight key contributing countries, institutions, and authors, and shed light on the thematic development of the field through keyword co-occurrence analysis.

Moreover, this bibliometric analysis provides an interpretive synthesis of how gymnastics research has been framed and developed within the field of physical education over the past decade. Rather than treating gymnastics research as a homogeneous body of knowledge, the discussion explicitly differentiates pedagogical physical education contexts from elite or competitive sport-oriented

scholarship. This distinction is essential, as physical education is a curriculum-based educational domain focused on learning processes, motor development, and pedagogical outcomes, whereas elite gymnastics research primarily emphasizes performance optimization and biomedical efficiency (Krüger, 2018; Robinson et al., 2020).

Publication Trends and Research Growth

The annual distribution of publications shows a fluctuating yet dynamic pattern, with a notable peak in 2019 followed by a decline after 2021. This fluctuation may reflect broader global circumstances such as the COVID-19 pandemic, which disrupted physical education activities and sports research worldwide (Li et al., 2022). However, the rebound observed in 2025 indicates a renewed academic interest in promoting physical literacy and re-integrating gymnastics into post-pandemic physical education curricula. The long-term trend suggests that gymnastics continues to be a relevant topic due to its role in developing students' motor skills, coordination, and overall physical fitness (Molina, 2015; Raid et al., 2022; Rudd et al., 2017; Sabau et al., 2023).

Gymnastics Research within a Pedagogical Physical Education Context

Although the publication landscape is dominated by sport science, biomechanics, and health-related journals, the thematic patterns identified through keyword co-occurrence analysis indicate that a substantial proportion of studies address pedagogically relevant constructs such as motor learning, movement coordination, instructional strategies, and student development. This finding reflects a well-documented characteristic of physical education research, in which pedagogical inquiries are frequently disseminated through sport science outlets due to their methodological orientation and analytical consistency (McVeigh et al., 2025).

Importantly, the disciplinary categorization of journals should not be equated with research purpose. Studies published in biomechanics or human movement journals often investigate learning-related variables that directly inform physical education practice, particularly in gymnastics where movement quality, control, and adaptability are central educational goals (Abdollahipour et al., 2015). Therefore, the bibliometric evidence supports the interpretation that gymnastics research contributes meaningfully to pedagogical PE, even when disseminated outside traditionally educational journals.

Implications for Physical Education Curriculum Design

The prominence of thematic clusters related to motor learning, balance, coordination, and fundamental movement skills reinforces the role of gymnastics as a foundational curricular component in physical education. Gymnastics-based activities emphasize whole-body control, spatial awareness, and movement variability, which are core elements of physical literacy and transferable across multiple physical activity contexts (Molina, 2015; Rudd et al., 2017).

The bibliometric trends further suggest a pedagogical shift from rigid, technique-centered instruction toward

more inclusive and developmentally appropriate curriculum models. Research addressing creativity, exploration, and task variability aligns with contemporary PE curricula that prioritize learner diversity and progressive skill development rather than standardized performance benchmarks (Lindsay & Spittle, 2024). In this sense, gymnastics functions not merely as a sport-specific content area, but as a curricular vehicle for fostering broad movement competence in school and higher education PE.

Relevance for Teacher Education and Pedagogical Practice

The concentration of influential publications and productive institutions within sport science-oriented universities highlights an important implication for physical education teacher education. While biomechanical and motor control research provides a robust evidence base, its pedagogical translation is not always explicit. The findings of this study indicate a growing need for teacher education programs to contextualize scientific knowledge within pedagogical frameworks that support instructional decision-making in PE settings (Robinson et al., 2020).

The presence of themes related to teaching strategies, learning environments, and student-centered instruction suggests that gymnastics research increasingly addresses how learning is facilitated, not solely how movements are executed. This trend is particularly relevant for pre-service and in-service PE teachers, who often report limited confidence in teaching gymnastics due to safety concerns and perceived technical complexity (McVeigh et al., 2025). By highlighting pedagogically oriented research clusters, this bibliometric analysis supports the development of pedagogical content knowledge and reinforces gymnastics as a meaningful component of teacher education curricula.

Gymnastics, Motor Development, and Fundamental Movement Skills

The strong representation of motor learning and coordination themes underscores gymnastics as a critical medium for fundamental movement skill (FMS) development in physical education. Unlike specialized sports that emphasize early specialization, gymnastics prioritizes movement diversity, body control, and adaptability, which are essential for motor competence across developmental stages (Raid et al., 2022; Rudd et al., 2017).

The bibliometric patterns indicate that gymnastics research increasingly foregrounds developmental and educational outcomes rather than elite performance indicators. This supports the positioning of gymnastics as a pedagogical tool for enhancing movement quality and motor confidence, which are central objectives in contemporary PE curricula. Consequently, gymnastics-based instruction contributes not only to physical skill acquisition but also to students' readiness for lifelong participation in physical activity.

Pedagogical Models and Emerging Educational Directions

The emergence of technology-related and motivation-oriented themes reflects broader pedagogical transformations within physical education. Digital

tools such as motion analysis, virtual feedback systems, and technology-supported assessment have expanded instructional possibilities in gymnastics, enabling more individualized and formative learning experiences (Jastrow et al., 2022). These developments align with learner-centered pedagogical models that emphasize autonomy, feedback, and engagement.

In addition, the increasing focus on health and motivation suggests that gymnastics research is responding to contemporary educational priorities, including well-being, inclusivity, and sustained physical activity participation. Rather than reinforcing performance-driven or exclusionary practices, the thematic evolution identified in this study indicates a gradual alignment with inclusive and health-oriented pedagogical models in physical education (Kojima et al., 2021).

Scientific and Pedagogical Added Value of the Bibliometric Analysis

From a scientific perspective, this study contributes by systematically mapping the intellectual structure of gymnastics research within physical education and clarifying its conceptual orientation. By distinguishing pedagogically relevant PE research from elite sport-focused scholarship, the analysis addresses a critical ambiguity in the literature and strengthens the theoretical coherence of gymnastics as a research domain in PE (Donthu et al., 2021).

From a pedagogical standpoint, the bibliometric findings provide evidence-based insights that are directly applicable to curriculum development, teacher education, and instructional innovation. The identification of dominant and emerging themes offers guidance for future research agendas and supports reflective decision-making among educators and policymakers. Thus, this study demonstrates that bibliometric analysis can function not only as a descriptive tool but also as a methodological approach for advancing pedagogical understanding and practice in physical education.

Conclusions

This study provides an analytical overview of how gymnastics research has been positioned and developed within the field of physical education over the last decade. Rather than merely documenting publication output, the bibliometric approach employed in this study reveals the intellectual structure and thematic orientations that have shaped gymnastics-related scholarship in educational contexts. The findings demonstrate that gymnastics research in physical education has progressively expanded beyond performance-centered perspectives toward more pedagogically oriented, interdisciplinary, and educationally relevant frameworks.

From an analytical standpoint, this study contributes by clarifying the conceptual landscape of gymnastics research in physical education and distinguishing it from elite or competitive sport-oriented scholarship. The identification of dominant thematic clusters—particularly those related to pedagogy, motor learning, health, and technology—illustrates how gymnastics functions as a curricular content area that supports learning processes, physical literacy, and student development. By mapping these clusters, the study highlights

both well-established research domains and emerging areas that warrant further scholarly attention within PE.

From a pedagogical perspective, the findings underscore the educational value of gymnastics as a medium for developing fundamental movement skills, motor coordination, and learner engagement in physical education settings. The prominence of pedagogical and motor learning themes suggests that gymnastics remains a relevant and adaptable component of contemporary PE curricula, particularly when aligned with inclusive, student-centered, and competence-based teaching approaches. Furthermore, the growing presence of technology-related themes indicates increasing opportunities for innovation in gymnastics instruction, assessment, and teacher education.

Importantly, this study offers implications for curriculum design and teacher education by providing evidence-based insights into how gymnastics research aligns with current educational priorities. By identifying research concentrations and gaps, the findings can support educators and policymakers in making informed decisions regarding the integration of gymnastics into PE programs, professional development initiatives, and pedagogical model selection.

In conclusion, this bibliometric analysis contributes to physical education theory and methodology by repositioning gymnastics as an educationally grounded and pedagogically meaningful research domain. Future research should build upon these insights by examining how identified themes are operationalized in classroom practice, exploring pedagogical models that effectively integrate gymnastics into PE curricula, and expanding cross-disciplinary and international collaboration to strengthen the educational impact of gymnastics research.

Ethical Considerations

This study utilized secondary data from publicly available databases and did not involve any human participants, so ethical approval was not necessary. Nevertheless, the data were managed with care, and the original sources were properly cited to uphold academic integrity standards.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Data Availability Statement

The bibliometric dataset analyzed in this study was retrieved from the Scopus database on October 29, 2025, using the search strategy described in the Methods section. Due to Scopus licensing restrictions, the raw data cannot be publicly shared. However, the extracted bibliographic information and processed dataset supporting the findings of this study are available from the corresponding author upon reasonable request and in accordance with database access policies.

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AI Transparency Statement

No artificial intelligence tools were used in the processes of data collection, screening, bibliometric analysis, or interpretation of the findings. All methodological decisions, analytical procedures, and conceptual interpretations were conducted independently by the authors to ensure scientific rigor and intellectual accountability. AI-assisted tools were utilized solely for language refinement and minor editorial support to improve clarity and readability of the manuscript, without influencing the research design, data analysis, results, or conclusions presented in this study.

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Глобальні тенденції досліджень гімнастики у фізичному вихованні: бібліометричний аналіз за даними Scopus

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 12 с., 2 табл., 7 рис., 28 джерел.

Мета дослідження – з'ясувати глобальні тенденції наукових досліджень з гімнастики у фізичному вихованні на основі бібліометричного аналізу документів, індексованих у базі даних Scopus у 2015–2025 роках.

Матеріали і методи. Дані отримано за ключовими словами «gymnastics» та «physical education» з подальшою фільтрацією за типом документів (статті та огляди) і мовою публікацій (англійська). Загалом проаналізовано 297 документів. Для візуалізації взаємозв'язків співзустрічальності ключових слів використано програмне забезпечення VOSviewer.

Результати. Установлено коливальну динаміку публікацій із піком у 2019 році та подальшим зниженням після 2021 року, що може бути пов'язано з тимчасовим зменшенням дослідницької активності в період пандемії COVID-19. Найбільш продуктивними країнами визначено Сполучені Штати Америки, Велику Британію та Іспанію. Серед установ-лідерів виділено Cardiff Metropolitan University та Loughborough University. Картування співзустрічальності ключових слів дало змогу виокремити п'ять основних тематичних кластерів: (1) педагогіка гімнастики та навчання студентів; (2) моторне навчання та координація рухів; (3) біомеханіка та профілактика травм; (4) здоров'я, мотивація та фізична активність; (5) технологічно підтримане фізичне виховання.

Висновки. Результати свідчать, що дослідження гімнастики у фізичному вихованні еволюціонували від переважно біомеханічної та результат-орієнтованої перспективи до більш міждисциплінарного підходу, який інтегрує аспекти здоров'я, освіти та технологій. Результати дослідження можуть бути використані дослідниками, викладачами та розробниками освітньої політики для розвитку співпраці, інтеграції цифрових інструментів навчання та впровадження інноваційних педагогічних практик у навчанні гімнастики.

Ключові слова: гімнастика, фізичне виховання, бібліометричний аналіз, Scopus, наукові тенденції.

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Accumulated Educational Deficit Across Athletic Careers: Quantifying Socio-Professional Risks

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Abstract

Objectives. This study aimed to quantitatively assess the key indicators of Accumulated Educational Deficit (AED): role conflict, constrained developmental horizons, and socio-professional uncertainty across different stages of athletic careers, considering sport-type specificity. The ultimate goal was to substantiate evidence-based preventive support strategies.

Materials and Methods. A cross-sectional observational study was conducted among 250 active athletes representing the national teams of Ukraine (N = 250). Participants were stratified by age (four groups) and sport type (team, cyclic, combat, and technical). Data were collected through a structured sociological survey using 5-point Likert scales. Statistical analysis included descriptive statistics, Pearson's χ^2 test for association, and Cohen's w to estimate the effect size.

Results. The onset of AED intensification was observed in the 19-23 age group, where acute role conflict reached 45.0%. In terms of career duration, the critical phase corresponded to 9-12 years of participation (42.0% reporting substantial developmental constraints). Significant structural heterogeneity was identified: athletes in team sports reported role conflict three times more frequently (60.0%) than athletes in cyclic sports (20.0%). A "delayed awareness" effect was detected, with peak dissatisfaction regarding personal development (37.5%) emerging only after 17-20 years of athletic participation, subsequently translating into explicit professional insecurity among 29.4% of athletes aged 35+. The highest demand for educational grant support was determined in the 19-23 age group (81.0%).

Conclusions. Accumulated Educational Deficit represents a measurable systemic risk embedded within elite sport structures and significantly affects the quality of transition to post-sport life. The findings support the implementation of flexible dual-career models and targeted educational funding mechanisms aligned with international frameworks (e.g., NCAA Degree Completion Awards; Erasmus+ Sport). Such interventions may mitigate long-term socio-professional vulnerability by enabling parallel development of transferable competencies.

Keywords: athletes, athletic transition, dual career, development, educational capital, financial support, social adaptation.

Introduction

The professional trajectories of elite athletes are characterized by prolonged specialization, intensive workload, and substantial temporal investment (Stambulova et al., 2020). While such structural conditions optimize competitive performance, they simultaneously constrain parallel educational and professional development. In response, the Dual Career framework has emerged as a

strategic model aimed at integrating high-performance sport with academic or vocational pathways (Hong & Minikin, 2023). International policy documents formally recognize dual-career support as a prerequisite for balanced personal development and long-term social sustainability (European Commission, 2012; Stambulova et al., 2024).

Despite this institutional recognition, a persistent discrepancy exists between policy rhetoric and structural practice. High-performance sport systems remain predominantly performance-oriented and often lack sufficient flexibility to accommodate educational engagement (Robnik et al., 2022). As a result, athletes experience cumulative strain manifested in elevated burnout rates (Glandorf et al., 2023;

Nuetzel, 2023), psychological instability during transitional phases (Voorheis et al., 2023; Voronova et al., 2024), and socio-professional vulnerability following career termination (Aptsiauri, 2024; Bulatova et al., 2025). Although financial assistance mechanisms—such as NCAA programs in the United States and Erasmus+ Sport initiatives within the European Union—have been developed to mitigate these risks, their structural effectiveness remains uneven.

The existing body of research largely concentrates on two distinct yet interconnected domains. The first concerns the phenomenon of role conflict between athletic and academic identities (Polishchuk et al., 2025; Steele et al., 2020), which has been associated with heightened psychological stress (Trigueros et al., 2019). Notably, financial support does not automatically resolve this tension; in some cases, it may intensify performance expectations without reducing temporal constraints for education (López-Flores et al., 2021). The capacity for successful adaptation during this stage is strongly associated with the level of educational capital accumulated by the athlete (Pryimak, 2025a; Radchenko et al., 2024).

The second domain addresses post-retirement crisis and identity reconstruction following sport termination (Samuel et al., 2023; Ryba et al., 2015). These difficulties are frequently linked to insufficient professional preparation and limited transferability of competencies beyond sport.

Excessive early specialization further compounds this challenge by narrowing developmental trajectories and displacing the acquisition of transferable competencies, including communication skills, critical thinking, self-regulation, and financial literacy (Johansen et al., 2024; Thornhill-Miller et al., 2023). Although sport participation fosters resilience, persistence, and goal orientation (Pierce et al., 2017), the absence of a structured educational foundation restricts the transferability of these attributes to non-sport domains. Empirical evidence indicates that imbalance between sport and education (55.3 %) constitutes a dominant challenge during peak competitive phases (Bulatova et al., 2025).

While prior research has predominantly addressed discrete manifestations of adaptation difficulties, limited attention has been devoted to their cumulative and systemic nature. To move beyond episodic interpretations, it is necessary to conceptualize adaptation risk as a longitudinal process embedded within career structures.

In this context, we introduce the construct of Accumulated Educational Deficit (AED). AED is defined as a systemic and progressive process through which prolonged prioritization of athletic performance results in measurable erosion of educational attainment, transferable professional competencies, and social capital. Unlike situational stressors, AED develops incrementally across the athletic lifespan and becomes structurally embedded in career trajectories.

Although previous work has highlighted education as a key determinant of athletes' social adaptation (Pryimak, 2025a), the present study advances the field by operationalizing AED through quantitative indicators—role conflict, constrained developmental horizons, and socio-professional uncertainty. Conceptualizing AED as a measurable construct enables a transition from descriptive analyses of crisis to predictive assessment of structural risk. In this regard, AED represents a cumulative deficit of knowledge, competencies, and social integration resources necessary for sustainable functioning beyond elite sport.

The aim of this study was to empirically validate the construct of Accumulated Educational Deficit (AED) by operationalizing and quantitatively assessing its core indicators—role conflict, constrained developmental horizons, and socio-professional uncertainty—across distinct stages of athletic careers and across sport disciplines. By examining both structural (sport type) and temporal (career stage) dimensions, the study sought to determine whether AED manifests as a patterned and measurable systemic phenomenon rather than as isolated adaptation difficulties.

To test the structural dimension of AED, the following hypotheses were formulated:

H0 (Null hypothesis): The manifestation of role conflict among athletes is independent of sport type.

H1 (Alternative hypothesis): The manifestation of role conflict significantly varies across sport types, indicating structural heterogeneity in the development of Accumulated Educational Deficit.

To examine the temporal dynamics of AED across the athletic lifespan, we further hypothesized:

H2: The highest intensity of role conflict occurs during the peak performance phase (19–23 years).

H3: The highest level of socio-professional uncertainty is observed at the late-career stage (35+ years).

Together, these hypotheses enable a systematic evaluation of AED as a multidimensional construct shaped by both organizational structures and career-stage transitions.

Materials and Methods

Study Participants

This study employed a cross-sectional survey design to investigate the development of educational capital and the manifestation of Accumulated Educational Deficit (AED) among elite athletes.

The sample consisted of 250 active athletes (N = 250) representing national teams of Ukraine across multiple sport disciplines. Participants were recruited on a voluntary basis and were actively competing at the national or international level at the time of data collection.

The sampling framework was intentionally structured to capture critical stages in the formation of AED. More than 70 % of respondents belonged to the 14–23 age range, corresponding to early and peak performance phases of athletic careers.

Analyses were conducted using three primary segmentation variables:

Age: 14–18, 19–23, 24–35, and 35+ years;

Sport experience: 0–4, 4–8, 9–12, 17–20, and >20 years;

Sport type: team, cyclic, combat, and technical sports.

Such stratification enabled the examination of both temporal (career-stage) and structural (sport-type) determinants of AED, allowing for a multidimensional analysis of athlete–social environment interactions within the systemic adaptation framework (Pryimak, 2025b).

Study Organization

Data were collected between May and December 2025. The research process included instrument development based on prior theoretical and empirical literature, followed

by administration of an anonymous online questionnaire. The use of an online format ensured confidentiality and reduced potential response bias.

The study was conceptually grounded in a systemic approach to athlete social adaptation, viewing adaptation as a multi-component process shaped by individual characteristics, social environment, and institutional structures. This framework informed the operationalization of Accumulated Educational Deficit (AED) and guided the selection of analytical variables.

A structured sociological survey served as the primary data collection instrument. The questionnaire was designed to capture the core dimensions of AED and included the following domains:

Role conflict – perceived constraints on educational attainment due to sport participation;

Constrained developmental horizons – satisfaction with opportunities for personal and professional development beyond sport;

Socio-professional uncertainty – confidence in successful integration into post-sport professional life;

Subjective support needs – perceived necessity of institutional and financial assistance, including educational grants.

All constructs were measured using 5-point Likert-type scales.

Statistical Analysis

For the quantitative analysis and interpretation of the collected data, methods of mathematical statistics were applied.

Descriptive statistics were used for frequency analysis with the calculation of percentage frequency (P) for each indicator using the formula: $P = (n/N) \times 100\%$, where n denotes the number of observations in a given category and N represents the total number of study participants ($N = 250$). This approach enabled both qualitative and quantitative assessment of dominant trends in athletes' perceptions.

Inferential statistics were employed to test hypotheses regarding the presence of relationships between sport type, career stages, and indicators of accumulated educational deficit. Specifically, Pearson's χ^2 (chi-square) test was used to examine statistically significant associations between categorical variables, calculated using the formula:

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i},$$

where O_i – represents observed frequencies and E_i – denotes expected frequencies. Degrees of freedom (df) for contingency tables were calculated as: $df = (R-1) \times (C-1)$, where R is the number of rows and C is the number of columns.

To determine the practical significance of the identified associations, Cohen's effect size (w) was calculated using the formula:

$$w = \sqrt{\frac{\chi^2}{N}}.$$

Effect sizes were interpreted as small (0.1), medium (0.3) or large (0.5).

Statistical data processing was conducted using Microsoft Excel and Statistica software.

Results

The quantitative analysis of Accumulated Educational Deficit (AED) indicators enabled identification of critical stages in its manifestation and the most vulnerable athlete groups.

Role conflict – defined as perceived tension between athletic and educational or future professional roles – demonstrated a clear age- and experience-related pattern. The highest prevalence of acute role conflict was observed in the 19-23 age group (45.0%). A comparable level was identified among athletes with 9-12 years of sport participation (42.0%) (Table 1).

These findings indicate that the intensification of AED coincides with peak competitive demands and the period of highest performance pressure.

Table 1. Dynamics of Constraints on Educational Attainment by Age and Length of Sporting Experience ($N = 250$)

Response	Age 19-23 years (%) (Peak performance)	Sporting experience 9-12 years (%) (Peak intensity)
Significantly limits	25.0	22.0
Limits to some extent	20.0	20.0
Total acute limitation	45.0	42.0
Almost does not limit	30.0	28.0
Does not limit at all	25.0	30.0
Total	100.0	100.0

To examine the structural dimension of Accumulated Educational Deficit, the association between sport type and role conflict was analyzed.

Pearson's χ^2 test revealed a statistically significant association between sport type and the intensity of role conflict, leading to rejection of the null hypothesis (H_0) and confirming structural heterogeneity in the manifestation of AED.

The highest prevalence of acute role conflict was observed among athletes in team sports, where 60.0% reported significant or moderate educational constraints. In contrast, only 20.0% of athletes in cyclic sports reported comparable levels of role conflict (Table 2).

This threefold difference indicates substantial variability in AED intensity across sport disciplines.

Table 2. Role Conflict: Structural Characteristics of Constraints by Sport Type ($N = 250$)

Sport type	Significantly limits (%)	Limits to some extent (%)	Total acute limitation (Role Conflict) (%)
Team (game-based) sports	35.0	25.0	60.0
Combat sports	15.0	18.3	33.3
Technical (coordination-based) sports	10.0	15.0	25.0
Cyclic (individual) sports	5.0	15.0	20.0

Constrained developmental horizons were assessed through athletes' satisfaction with opportunities for personal development beyond sport.

The highest level of cumulative dissatisfaction with personal development (e.g., self-education, additional training courses) was observed among athletes with 17-20 years of sporting experience (37.5 %) (Table 3).

This pattern indicates a delayed manifestation of perceived educational deficit, with dissatisfaction intensifying at advanced career stages characterized by prolonged specialization.

Table 3. Detailed Distribution of Dissatisfaction with Development Outside Sport by Length of Sporting Experience (N = 250)

Domain of development (ratings 1+2)	Sporting experience 9-12 years (%)	Sporting experience 17-20 years (%) (Peak dissatisfaction)
Personal development (self-education, courses)	28.0	37.5
Development of hobbies and interests	24.6	37.5

Note: The indicator (ratings 1+2) represents the combined share of responses "Not satisfied at all" and "Rather not satisfied."

Socio-professional uncertainty was operationalized through athletes' self-reported confidence in their ability to integrate into post-sport professional life.

At early career stages, the most frequent response was "difficult to say," reaching 45.0 % in the 19-23 age group (Table 4). In contrast, at the late-career stage (35+ years), the proportion of athletes reporting explicit professional uncertainty ("not confident" and "rather not confident") increased to 29.4 %.

These findings demonstrate a shift from generalized uncertainty in early career phases to more clearly articulated professional insecurity at later stages. This pattern aligns with previous evidence on socio-psychological maladaptation among late-career athletes (Pryimak, 2025c).

Athletes' perceived need for institutional support was assessed through evaluation of educational grant mechanisms.

A high level of demand for financial support for education was identified across age groups, with the strongest expression among younger athletes. Specifically, 70.9 % of respondents aged 14-18 years and 81.0 % of those aged

19-23 years rated educational grants as "highly necessary" or "critically necessary" (Table 5).

These findings indicate substantial perceived demand for structured educational support during early and peak career stages.

Table 5. Athletes' Assessment of the Need for Grant Support to Improve Adaptation by Age (%) (N = 250)

Age group	Critically necessary, % (5)	Highly necessary, % (4)	Total demand, % (4+5)
Age 14-18	53.0	17.9	70.9
Age 19-23	46.0	35.0	81.0
Age 24-35	35.0	35.0	70.0
Age 35+	30.0	30.0	60.0

Athletes' professional expectations were analyzed in relation to sport type (Table 6).

Among athletes in cyclic sports, preference for a business-oriented career pathway (45.0 %) was nearly equivalent to preference for coaching careers (45.0 %). In contrast, athletes in team sports predominantly reported intentions to pursue coaching careers (70.0 %), with substantially lower interest in business activities.

This distribution suggests variability in post-sport career orientations across sport types and aligns with previous theoretical considerations regarding the diversification of athletes' social roles in contemporary contexts (Pryimak, 2025d).

Discussion

The present study examined athletes' adaptation difficulties through the lens of a cumulative structural process conceptualized as Accumulated Educational Deficit (AED). The findings support the proposed assumption that adaptation challenges are not episodic events but develop progressively across the athletic lifespan. Specifically, the peak of role conflict during the 19-23 age phase (45.0 %) and the subsequent increase in explicit socio-professional uncertainty in the 35+ group (29.4 %) suggest a longitudinal linkage between early educational constraints and later career vulnerability. This trajectory aligns with the meta-model of adaptation proposed by Samuel et al. (2023), which conceptualizes transition as an extended adaptive process rather than a discrete career endpoint.

The identification of sport type as a structural determinant of AED further extends the existing literature.

Table 4. Athletes' Assessment of Confidence in Their Ability to Assume a New Social Role Outside Sport (N = 250)

Response	Age 14-18 (%)	Age 19-23 (%)	Age 24-35 (%)	Age 35+ (%)
Not confident at all	5.0	8.0	10.0	15.0
Rather not confident	5.5	10.0	15.0	14.4
Direct uncertainty (Total)	10.5	18.0	25.0	29.4
Hard to say (Uncertainty)	40.0	45.0	35.0	25.0
Rather confident	30.0	25.0	30.0	30.0
Fully confident	19.5	12.0	10.0	15.6
Total	100.0	100.0	100.0	100.0

Table 6. Comparison of Athletes' Professional Expectations by Sport Type (N = 250)

Sport type	Coaching, %	Business / Entrepreneurship, %	Public service, %	Other (IT, Culture), %
Team (game-based) sports	70.0	20.0	5.0	5.0
Combat sports	50.0	30.0	10.0	10.0
Technical (coordination-based) sports	40.0	35.0	10.0	15.0
Cyclic (individual) sports	45.0	45.0	5.0	5.0

The significantly higher prevalence of role conflict in team sports (60.0 %) compared to other disciplines confirms structural heterogeneity in educational constraints. This finding resonates with Robnik et al. (2022), who highlighted institutional rigidity within team-based sport systems as a limiting factor for educational engagement. Taken together, these results indicate that AED is embedded not only in individual career choices but also in organizational models of sport participation.

The association between competitive intensity (9-12 years of sport experience) and peak perception of educational constraints (42.0 %) corroborates the paradox described by López-Flores et al. (2021), whereby increased athletic demands amplify educational displacement. However, the present study advances this perspective by introducing the concept of a “delayed awareness” effect. The peak of dissatisfaction with personal development (37.5 %) at 17-20 years of participation suggests that recognition of educational erosion occurs only at advanced career stages. This delayed perception may reflect prolonged identity foreclosure, during which athletes prioritize performance while postponing investment in transferable competencies (Pierce et al., 2017).

Theoretically, this study contributes to the literature by reframing educational imbalance as a measurable systemic risk rather than as a series of isolated psychological crises. By operationalizing AED through quantifiable indicators, the study links competency deficits (Johansen et al., 2024) with subsequent socio-professional vulnerability. This conceptual shift supports the interpretation of AED as a structural predictor of maladaptation.

The findings also carry policy implications. The high demand for educational grants among athletes aged 19-23 (81.0 %) indicates that early adulthood represents a critical intervention window. International models, including the NCAA Degree Completion Award program (NCAA, 2024) and Erasmus+ Sport initiatives (European Commission, 2024), demonstrate viable mechanisms for integrating financial support with competency development. Adaptation of such frameworks within national contexts may mitigate long-term vulnerability by providing temporal flexibility for educational engagement. Additionally, the identified entrepreneurial orientation among athletes in cyclic sports (45.0 %) suggests the potential effectiveness of targeted business education modules within dual-career systems (Hong & Minikin, 2023).

Several limitations should be acknowledged. The cross-sectional design restricts causal inference, and reliance on self-reported measures may introduce response bias. Future research should employ longitudinal designs to examine whether early mitigation of AED translates into measurable improvements in post-sport income, employment stability, and social integration.

Conclusions

This study examined the dynamics of educational capital among 250 elite athletes and identified structural barriers within the Dual Career framework. The findings indicate that education functions not as a supplementary element but as a central determinant of long-term social sustainability in elite sport. The adaptation difficulties observed at career termination appear to reflect a cumulative process conceptualized as Accumulated Educational Deficit (AED).

The principal conclusions are as follows:

Accumulated Educational Deficit constitutes a measurable systemic phenomenon arising from sustained imbalance between the performance demands of elite sport and educational development. AED reflects the cumulative erosion of educational, transferable, and social capital across the athletic lifespan.

The critical formation phase of AED occurs during early adulthood. The highest level of role conflict was observed in the 19-23 age group (45.0 %), and similarly elevated perceptions of educational constraints were recorded among athletes with 9-12 years of sport participation (42.0 %), indicating peak vulnerability during periods of maximum competitive intensity.

AED demonstrates structural heterogeneity across sport types. Athletes in team sports exhibited the highest prevalence of role conflict (60.0 %), suggesting that organizational characteristics of sport systems contribute to uneven educational constraints.

Perceived developmental limitations intensify at advanced career stages. Dissatisfaction with personal development peaked among athletes with 17-20 years of experience (37.5 %), indicating delayed recognition of accumulated educational constraints.

Socio-professional uncertainty increases toward career termination. The proportion of athletes reporting explicit professional insecurity rose from 10.5 % at early stages to 29.4 % in the 35+ group, highlighting a progressive consolidation of adaptation risk.

Athletes express substantial demand for educational support mechanisms. The perceived necessity of educational grants was highest in the 19-23 age group (81.0 %), identifying early adulthood as a strategic intervention window.

Variability in professional expectations across sport types suggests differentiated support needs. In cyclic sports, preference for business-oriented pathways (45.0 %) was comparable to coaching intentions, indicating potential for diversified dual-career models.

Overall, the study supports the interpretation of Accumulated Educational Deficit as a structural and measurable risk embedded within elite sport systems. Addressing this deficit requires early, systemic, and

discipline-sensitive support strategies aimed at strengthening transferable competencies throughout the athletic career.

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Ethics Approval

The study was conducted in strict adherence to the Ethical Code of Participants of the Educational Process of the National University of Ukraine on Physical Education and Sport. All procedures followed internationally recognized ethical standards for research involving human participants, ensuring that the privacy rights and confidentiality of all athletes were strictly maintained throughout the anonymous survey process.

Informed Consent

For participants under 18 years of age, written informed consent was obtained from their parents or legal guardians.

Data Availability Statement

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

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Conflicts of Interest

The authors declare no conflicts of interest.

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Накопичений освітній дефіцит упродовж спортивної кар'єри: кількісна оцінка соціально-професійних ризиків

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 8 с., 6 табл., 27 джерел.

Мета дослідження. Здійснити комплексну кількісну оцінку показників накопиченого освітнього дефіциту (рольового конфлікту, обмежених горизонтів розвитку та соціально-професійної невпевненості) на різних етапах спортивної кар'єри залежно від специфіки видів спорту для обґрунтування превентивних стратегій підтримки спортсменів.

Матеріали і методи. Проведено обсерваційне кроссекційне дослідження за участю 250 спортсменів національних збірних команд України (N = 250). Вибірку структуровано за віковими групами та типами спорту (ігрові, циклічні, єдиноборства, технічні). Збір даних здійснено методом соціологічного опитування з використанням 5-бальних шкал Лікерта. Статистичний аналіз включав описативну статистику, критерій χ^2 Пірсона та оцінку розміру ефекту (w Коена).

Результати. Встановлено, що формування освітнього дефіциту розпочинається у віковому періоді 19-23 роки, де частка вираженого рольового конфлікту досягає 45,0 %. Критичним за тривалістю спортивної кар'єри є інтервал 9-12 років (42,0 % обмежень розвитку). Виявлено виражену міжвидову гетерогенність: у спортсменів ігрових видів спорту інтенсивність рольового конфлікту є втричі вищою (60,0 %) порівняно з представниками циклічних видів (20,0 %). Зафіксовано ефект «відкладеного усвідомлення», який проявляється піком незадоволеності власним розвитком (37,5 %) на стадії 17-20 років спортивного стажу. Це супроводжується формуванням соціально-професійної невпевненості у 29,4 % спортсменів старших груп. Виявлено високий попит на освітню підтримку серед спортсменів віком 19-23 роки (81,0 %).

Висновки. Накопичений освітній дефіцит є системним ризиком, що визначає успішність переходу спортсменів до постспортивної кар'єри. Обґрунтовано необхідність впровадження гнучких моделей дуальної освіти та адресних грантових програм, які забезпечують розвиток універсальних компетентностей паралельно зі спортивною діяльністю.

Ключові слова: спортсмени, подвійна кар'єра, освітній дефіцит, спортивний перехід, соціально-професійна адаптація, освітня підтримка.

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Self-Regulated Movement Education: Effects on Motivation, Fitness and Motor Engagement

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Abstract

Objectives. This study aimed to evaluate the effectiveness of a physical education programme focused on self-regulation and autonomy support in enhancing motor engagement and motivational variables in adolescents, integrating objective measures using inertial sensors (IMU/wearable) and qualitative analysis through interviews.

Materials and Methods. A pre-post experimental study was carried out with a total of 353 participants (mean age 14.2 ± 1.1 years), divided into an experimental group ($n = 178$) and a control group ($n = 175$). The following measures were employed: motivation (PLOC-R), self-efficacy for physical activity (barriers self-efficacy), fitness (EUROFIT: standing long jump, 20 m shuttle run, sit-and-reach, handgrip) and IMU metrics (active time, vector magnitude, jerk) during standardised lesson windows. Semi-structured interviews were conducted with an involvement of 32 students and 8 teachers, followed by a thematic analysis.

Results. The experimental group showed greater improvements than the control group in autonomous motivation (Δ intrinsic regulation $+0.64$ vs $+0.10$, $p < .001$), self-efficacy ($+0.41$ vs $+0.07$, $p < .001$), fitness (e.g., long jump $+9.3$ cm vs $+2.1$ cm, $p < .001$) and objectively measured motor engagement (active time $+9.5$ percentage points vs $+1.3$, $p < .001$). The interviews highlighted high acceptability, increased awareness of movement and the importance of the teacher's role in preventing social comparison dynamics.

Conclusions. The integration of IMU measures facilitates a more comprehensive assessment of school programmes' effectiveness, combining motivational and performance outcomes with objective indicators of motor behaviour.

Keywords: motor self-regulation, motor engagement, inertial sensors, physical education.

Introduction

Promoting meaningful physical activity in physical education classes is an educational and public health priority, particularly during adolescence (Latino et al., 2023). At this stage of development, the quality of the school experience in terms of physical activity can influence not only participation in classes, but also the adoption and maintenance of physically active behaviours over time (Susanto et al., 2024). Simply being exposed to physical activity is not enough to guarantee high levels of participation or lasting benefits, making it necessary to adopt a teaching approach that

focuses on the motivational and relational processes that support student engagement (Raiola et al., 2015).

A well-established line of research, based on Self-Determination Theory, indicates that interventions aimed at supporting the psychological needs of autonomy, competence and relatedness are associated with more favourable outcomes in terms of autonomous motivation, well-being and physical activity behaviours (Reeve & Cheon, 2021; Cheon et al., 2022). In the field of school physical education, recent reviews show that autonomy-supportive teaching programmes produce generally small to moderate but consistent effects on motivation and participation, especially when such approaches are integrated with a clear structure, explicit success criteria and informative feedback (Fierro-Suero et al., 2024). This evidence suggests that the effectiveness of the intervention does not depend exclusively

on the individual characteristics of the students, but also on classroom processes and the teacher's teaching style.

Despite these advances, the evaluation of the effectiveness of interventions in physical education often remains anchored to "product" indicators, such as fitness tests or self-administered questionnaires, with less attention paid to "process" indicators that describe how much and how students move during class.

This limitation is significant, as observational studies show that a substantial part of class time can be characterised by low movement density and downtime, even when final test results are positive (Clemente et al., 2021).

In recent years, the introduction of wearable devices has expanded the possibilities for objective measurement of physical activity in educational settings. However, evidence on the effectiveness of wearables in schools is mixed. Recent meta-analyses indicate that the use of activity trackers, when considered as an isolated intervention, does not guarantee robust increases in physical activity in adolescents, while highlighting marked methodological variability and often moderate overall evidence quality (Au et al., 2024). These results suggest that technological devices should not be conceived as "stand-alone" tools, but integrated into structured and theoretically informed educational strategies.

In this context, the use of inertial sensors (Inertial Measurement Units, IMUs), which combine accelerometers and gyroscopes, makes it possible to go beyond measurements limited to the intensity or duration of activity, allowing indicators related to the quality and regularity of movement to be derived.

Recent methodological evidence supports the validity and reliability of single-sensor IMU solutions in estimating kinematic parameters in functional and sports tasks (Hughes et al., 2022; Cereatti et al., 2024). Furthermore, these devices can be used in educational contexts to monitor workload and compare teaching models based on objective process data. At the same time, methodological reviews emphasise the need for transparency and standardisation in the analysis of signals from wearables in order to improve the comparability of studies and the robustness of interpretations (Liang et al., 2024).

Alongside the quantitative dimension, it is essential to consider the acceptability and meaning attributed to the technology by students and teachers. Recent qualitative studies conducted in schools indicate that wearables can promote awareness and reflection on one's own motor behaviour, but can also generate social comparison dynamics and negative emotional reactions if the data are not adequately mediated by the teacher (Wort et al., 2024).

This evidence reinforces the idea that the educational value of wearable devices depends largely on how they are integrated into the teaching context and framed at a pedagogical level.

In light of these considerations, this study aims to evaluate the effectiveness of a physical education programme focused on self-regulation and autonomy support on motivational variables, fitness and motor engagement measured objectively using inertial sensors. Furthermore, through a mixed-methods approach, the study aims to explore the perceptions of students and teachers regarding the use of wearables in order to understand the interpretative mechanisms and conditions that favour their effective educational implementation.

Purpose of the study. Evaluate the effect of a programme focused on self-regulation and autonomy support on: (1) motivation, (2) self-efficacy, (3) fitness, and (4) engagement and movement quality measured using IMU; also explore, through interviews, the perception, acceptability, and interpretative mechanisms associated with the use of wearables.

Materials and Methods

Study Design

Experimental study with pre- (T0) and post- (T1) measurements and two groups (experimental vs. control), assigned by class (natural cluster). The quantitative component was applied to the entire sample of students (questionnaires, fitness tests and IMU measurements), while the qualitative component was adopted on an intentional subsample of students ($n = 32$) and teachers involved in the intervention ($n = 8$), selected to explore in depth perceptions, acceptability and interpretative mechanisms related to the programme and the use of wearables.

Tests Used

Motivation: Perceived Locus of Causality – Revised (PLOC-R). The choice is supported by recent psychometric validation in school physical education contexts.

Self-efficacy for physical activity: measures of self-efficacy for physical activity in childhood with evidence of factorial validity in school samples.

Fitness: EUROFIT battery (standing long jump; 20 m shuttle run; sit-and-reach; handgrip), in line with Council of Europe documentation.

IMU/wearable: inertial sensor (accelerometer + gyroscope) worn on the arm or smartphone attached to the arm.

Metrics: active time (%); 2) average vector magnitude and p95; 3) jerk RMS (regularity/control). Choices consistent with evidence on IMU validity and methodological recommendations on the analysis of signals from wearable devices.

Sample

Total $n = 353$ students (14.2 ± 1.1 years; 52.4% female).

Experimental group: $n = 178$ (14.1 ± 1.1 ; 51.7% female)

Control group: $n = 175$ (14.3 ± 1.2 ; 53.1% female)

Classes: 12 (6 experimental, 6 control).

Completeness of pre-post data for primary analysis: $n = 340$ (96.3%); missing item-level < 2% with imputation by item.

Inclusion criteria

- Aged 12–16; regular enrolment in lessons; expected attendance $\geq 80\%$ during the intervention.
- Informed consent of parents/guardians and consent of the student.
- Suitability for school practice according to the institution's procedures.

Exclusion criteria

- Injuries or conditions that limit participation in the baseline.

- Inability to wear the device.
- Invalid IMU data (wear time < 12 minutes on a standardised 20-minute window at least one timepoint).

Activities Carried Out (Intervention)

The educational intervention (9 weeks; 2 lessons per week; 55 minutes each) was designed to systematically integrate four components considered central in contemporary literature on school physical education: (a) autonomy support, (b) competence-oriented structure, (c) relationships and cooperation, (d) motor learning self-regulation practices. This combination responds to evidence that motivational and behavioural outcomes are more favourable when autonomy support is accompanied by a clear structure and informative feedback, avoiding controlling styles (Cheon et al., 2022; Fierro-Suero et al., 2024). Before the study began, the teachers assigned to the experimental group participated in operational training (approximately 4 hours), aimed at translating the theoretical principles of Self-Determination Theory into observable teaching behaviours. In particular, the training covered: (i) the use of non-controlling language oriented towards the rationale of the activities; (ii) offering meaningful but guided choices; (iii) the explicit definition of objectives and criteria for success; (iv) the systematic integration of moments of self-regulation (definition of objectives, monitoring and reflection); (v) the educational management of data from inertial sensors in a formative and non-competitive manner.

This approach is consistent with experimental interventions that have shown how changing the teacher's teaching style can improve the classroom climate, student motivation and participation behaviour (Cheon et al., 2022). To ensure the fidelity of the intervention, standardised lesson plans and weekly checklists relating to the presence of key components were used.

Lesson Structure

Each lesson in the experimental group followed a stable structure in order to increase predictability and a sense of competence, while introducing task variations to support autonomy and differentiation.

Initial Briefing (7–8 minutes)

The teacher presented the lesson objectives, both in terms of motor skills and active involvement. Students were offered a “guided choice” between two or three equivalent task variants, differentiated by level of difficulty. Each student was invited to set a personal micro-goal, encouraging the activation of self-regulation processes. The integration of choice and structure reflects the findings of studies that highlight the positive effects of combined autonomy-supportive and structuring teaching styles (Reeve & Cheon, 2021; Fierro-Suero et al., 2024).

Technical-Coordination Block (18–20 minutes)

The activities were organised into circuits with stations featuring graduated progressions, focusing on the quality

of movement (e.g. stability, postural control, regularity of movement) rather than simply increasing intensity. The feedback provided by the instructor was informative and corrective, based on observable criteria, avoiding comparative evaluations. Halfway through the block, there was a brief moment of rapid self-assessment, during which students could confirm or modify the level of difficulty they had chosen.

Application Block with Small-Sided Games (18–20 minutes)

Small-sided games and situational tasks were used to increase participation density, reduce downtime and encourage decision-making. Recent literature shows that manipulating variables such as number of players, playing space and regulatory constraints significantly influences physical load and motor involvement in educational and youth contexts (Clemente et al., 2021; Neag et al., 2024). The introduction of cooperative goals and role rotation further supported fairness of participation.

Final debriefing (7–8 minutes)

The lesson ended with a structured reflection phase. Students were guided to evaluate two main aspects: continuity of movement (how active they remained) and control of the movement (quality/regularity of execution). The teacher provided a summary of criteria at the group level and invited each student to set a goal for the next lesson, reinforcing the planning and monitoring processes.

Progression of the intervention

- The intervention was divided into three successive phases.
- The first phase (weeks 1–3) focused on introducing self-regulation routines and familiarising participants with the criteria for success.
- The second phase (weeks 4–6) emphasised task differentiation and increased complexity, supporting decision-making autonomy.
- The third phase (weeks 7–9) aimed to transfer self-regulation strategies to more dynamic and complex tasks, while maintaining a high level of participation.

Integration of inertial sensors

Inertial sensors were integrated for two purposes: to objectively measure motor engagement and movement quality, and to support formative feedback. Recordings were made in three standardised lessons (weeks 1, 5 and 9) over a 20-minute window (10 minutes of circuit training and 10 minutes of small-sided games). The metrics considered included active time, average movement intensity and indicators of regularity (jerk).

The choice to use IMU is consistent with studies demonstrating its validity and reliability in measuring kinematic parameters and movement loads (Hughes et al., 2022). Additionally, IMU-based approaches show potential for application in educational contexts to support the evaluation of the teaching process.

The data were returned exclusively in aggregate form (class or group level), avoiding individual rankings. This

choice responds to qualitative evidence indicating that unmediated use of data can encourage social comparisons and negative emotional reactions, while a teacher-guided approach increases its acceptability and educational value (Wort et al., 2024).

Control Condition

The control group followed the institute's standard practice, including initial warm-up, exercises proposed by the teacher and final game, without structured self-regulation routines and without educational feedback from the sensors.

Quantitative Results

Data

The overall sample consisted of 353 students (age 14.2 ± 1.1 years; 52.4% female), distributed across 12 classes (6 experimental, 6 control). The completeness of pre-post data for the primary analysis was high ($n = 340$; 96.3%). The main reasons for incompleteness included absences in one of the two test sessions and invalid IMU data due to insufficient wear time.

IMU data and compliance. Compliance with IMU recordings was 94.6% with valid wear time at both timepoints; 19 students (5.4%) were excluded from the IMU analysis due to wear time < 12 minutes over a standardised 20-minute window at least one timepoint. No significant differences emerged between those included and those excluded in terms of age, gender, or baseline motivational scores (all $p > .10$).

Internal reliability. The psychometric scales showed adequate internal consistency: intrinsic PLOC-R $\alpha = .88$ (T0) and $.90$ (T1); identified $\alpha = .84$ and $.86$; external $\alpha = .79$ and $.80$; amotivation $\alpha = .82$ and $.83$; self-efficacy $\alpha = .86$ and $.87$.

Statistical analyses. Linear mixed models with random intercepts per class were estimated, including Group (experimental vs. control), Time (T0 vs. T1) and Group $\times$ Time interaction as fixed effects. Gender and age were included as covariates. Estimates are reported as means $\pm$ SD and as differences in change (Δ) with 95% CI and effect size (d).

Table 1. Motivational outcomes (PLOC-R). Intrinsic regulation

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	4.38 ± 1.12	5.02 ± 1.05	+0.64
Control	4.41 ± 1.10	4.51 ± 1.09	+0.10

Interpretation: the increase in intrinsic regulation in the experimental group, higher than in the control group, indicates an increase in autonomous motivation and quality of perceived experience compared to ordinary practice.

Table 2. Identified adjustment

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	4.92 ± 0.98	5.29 ± 0.92	+0.37
Control	4.89 ± 1.01	4.97 ± 1.02	+0.08

Interpretation: the increase in identified regulation suggests greater attribution of personal/instrumental value to the proposed activities.

Table 3. Amotivation

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	2.31 ± 1.14	1.92 ± 1.03	-0.39
Control	2.28 ± 1.12	2.21 ± 1.10	-0.07

Interpretation: the reduction in amotivation in the experimental group is consistent with a greater sense of purpose and better alignment between tasks and perceptions of competence/autonomy.

Table 4. External regulation

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	2.84 ± 1.07	2.69 ± 1.01	-0.15
Control	2.81 ± 1.05	2.79 ± 1.07	-0.02

Interpretation: the non-significant reduction in external regulation indicates that the main change concerns the increase in autonomous components rather than a marked decrease in perceived external pressures.

Table 5. Self-efficacy for physical activity (scale 1–5)

Group T0	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	3.26 ± 0.68	3.67 ± 0.64	+0.41
Control	3.29 ± 0.69	3.36 ± 0.70	+0.07

Sensitivity analysis (interpretative): the effect remains stable when age and gender are included as covariates; no significant Time $\times$ Group $\times$ Gender interactions emerge ($p > .10$), suggesting a comparable benefit for males and females.

Fitness (EUROFIT)

Table 6. Standing long jump (cm)

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	163.4 ± 27.6	172.7 ± 28.1	+9.3
Control	164.1 ± 27.1	166.2 ± 27.4	+2.1

Table 7. 20 m shuttle run (stadiums)

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	5.7 ± 1.6	6.4 ± 1.7	+0.7
Control	5.8 ± 1.6	6.0 ± 1.6	+0.2

Table 8. Sit-and-reach (cm)

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	18.1 ± 7.9	20.0 ± 7.6	+1.9
Control	18.3 ± 8.1	18.8 ± 8.0	+0.5

Table 9. Handgrip (kg)

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	27.9 $\pm$ 6.4	29.1 $\pm$ 6.5	+1.2
Control	28.1 $\pm$ 6.2	28.6 $\pm$ 6.4	+0.5

Overall interpretation: the pattern suggests a greater impact on explosive power and aerobic capacity than on grip strength, consistent with an intervention that increases participation density, movement continuity and execution quality.

IMU/wearable results: engagement and movement quality

IMU metrics were calculated on standardised windows (20 minutes: 10 minutes circuit training + 10 minutes small-sided games), aggregated at individual level and subsequently estimated in mixed models.

Active time (%)

The data indicate a marked increase in movement continuity during the lesson in the experimental group. In operational terms, the students involved in the programme converted a significantly greater proportion of teaching time into actual active time than the control group.

Table 10. Mean vector magnitude (g)

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	0.71 $\pm$ 0.14	0.82 $\pm$ 0.15	+0.11
Control	0.72 $\pm$ 0.15	0.74 $\pm$ 0.15	+0.02

The increase observed in the experimental group reflects an increase in the average intensity of movement in the standardised window, consistent with a higher density of motor tasks and a reduction in downtime within the lesson.

Table 11. p95 Vector magnitude (g)

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	1.62 $\pm$ 0.31	1.78 $\pm$ 0.34	+0.16
Control	1.63 $\pm$ 0.32	1.66 $\pm$ 0.33	+0.03

The increase in the 95th percentile in the experimental group suggests a greater presence of intensity peaks, likely associated with phases of play, transitions or tasks with high motor demands, which are more frequent or better integrated into the structure of the lesson.

- Experimental: 8.4 $\pm$ 2.1 $\rightarrow$ 7.2 $\pm$ 1.9; Δ = -1.2
- Control: 8.3 $\pm$ 2.2 $\rightarrow$ 8.1 $\pm$ 2.1; Δ = -0.2
- Interaction: $F(1, 10.7) = 14.1$, $p = .003$
- Differential Δ : -1.0 (95% CI -1.6 to -0.4), $d = 0.45$.

Table 12. Jerk RMS (m/s³) — lower values indicate greater regularity

Group	T0 (Mean $\pm$ SD)	T1 (Mean $\pm$ SD)	Δ Change
Experimental	8.4 $\pm$ 2.1	7.2 $\pm$ 1.9	-1.2
Control	8.3 $\pm$ 2.2	8.1 $\pm$ 2.1	-0.2

The reduction in RMS jerk in the experimental group indicates a decrease in the ‘roughness’ of movement and greater regularity of execution. This trend is consistent both with the adoption of technical progressions and feedback oriented towards movement quality, and with a progressive stabilisation of motor self-regulation processes.

Integrative analyses (mechanistic consistency: process $\rightarrow$ outcomes)

To reinforce the “process-outcome” interpretation, associations between IMU changes and motivational/physical changes were explored (descriptive analyses and additional models).

- Association between Δ active time and Δ intrinsic regulation: $r = 0.29$.
- Association between Δ active time and Δ self-efficacy: $r = 0.33$.
- Association between Δ active time and Δ shuttle run: $r = 0.25$.
- Association between Δ jerk (reduction) and Δ long jump: $r = -0.21$ (improvement in power associated with greater regularity).

In an exploratory model, the inclusion of Δ active time as a predictor partially attenuates the Group $\times$ Time effect on aerobic capacity, suggesting that part of the physical improvements can be explained by the increase in actual active time during the lesson.

Qualitative results

Qualitative sample, sampling strategy and quality of analysis

Semi-structured interviews were conducted with 32 students (16 female, 16 male; selected for maximum variation in IMU engagement: high/medium/low) and 8 teachers. The interviews with students lasted an average of 22 minutes (range 18–28), those with teachers 38 minutes (range 32–45). Thematic saturation was reached around the 28th interview with students, confirmed by the absence of new substantial codes in the last four interviews.

The thematic analysis followed an iterative process: initial independent coding on a subset of transcripts, comparison and harmonisation of the codebook, then coding of the entire corpus and review of themes with attention to deviant cases.

Main themes, sub-themes and frequency of occurrence

Below are the themes and sub-themes with the number of participants who mentioned them (at least once). The frequencies are presented for descriptive transparency, without any claim to statistical generalisation.

Theme 1 — Acceptability, comfort and perception of intrusiveness

- Students: 26/32; Teachers: 7/8

Sub-themes:

- Addiction/habit to the device (18/32): perception that after a few minutes the device “disappears” from attention.
- Physical discomfort or fear of damage (9/32): more frequent in the first two weeks.
- Privacy issues (7/32): requests for clarity on who sees the data and what it is used for.

Interpretation: acceptability increases when the purpose, rules and protections (anonymisation, no ranking) are clear.

Theme 2 — Awareness of movement and self-regulation

- Students: 24/32; Teachers: 8/8

Sub-themes:

- Making “really active” time visible (15/32): perception of a gap between “being in class” and “really moving”.
- Self-regulation strategies (13/32): planning (“I commit to the circuit”), monitoring (“I notice when I stop”), adjustment (“I change level”).
- Feedback as process guidance (16/32; 8/8 teachers): appreciation of operational guidance rather than numbers “for their own sake”.

Connection with the quantitative aspect: this theme is consistent with the increase in active time and the reduction in jerk, interpreted as greater continuity and better control of the movement.

Topic 3 — Social comparison, emotions and the risk of unwanted gamification

- Students: 17/32; Teachers: 8/8

Subtopics:

- Concern about rankings and comparisons (12/32): fear of “competition” between classmates.
- Performance anxiety linked to numbers (6/32): fear that the data will become an implicit grade.
- Preference for aggregated feedback (14/32): explicit requests to avoid individual identification in public.

Interpretation: the device is accepted when framed as a tool for improvement and not as a measure of personal value.

Theme 4 — Role of the teacher in the pedagogical translation of data

- Students: 21/32; Teachers: 8/8

Sub-themes:

- Interpretative mediation (19/32): data “makes sense” when accompanied by an explanation (“how can I improve?”).
- Climate and language (8/8 teachers): pay attention to tone, avoid sarcasm or comparisons.
- Management of individual differences (7/8 teachers): make data compatible with different levels and personalised objectives.

Link to implementation: confirms that technology does not replace teaching, but makes it more informed, provided there is clear educational direction.

Topic 5 – Feasibility and organisational sustainability

- Students: 10/32; Teachers: 6/8

Subtopics:

- Distribution/collection times (6/8 teachers): logistical challenges, especially in large classes.
- Routines that could be improved (5/8 teachers): practical suggestions (roles of “assistants”, delivery stations).
- Technical stability (4/8 teachers): importance of standard procedures to avoid data loss.

Interpretation: perceived sustainability increases when device management is routine and when the organisational burden is distributed.

Analysis by qualitative subgroups (triangulation with IMU)

A comparative reading was carried out between students with high vs low increases in active time (based on tertiles of Δ active time).

- Students with high Δ active time: they more frequently describe concrete self-regulation strategies (planning, level choice, attention to transitions), and report a greater sense of control (“I know what I need to do to stay active”).

- Students with low Δ active time: they mention situational barriers more often (shyness in play, preference for less dynamic activities, difficulty interpreting feedback), and require greater personalisation of objectives.

This triangulation supports the hypothesis that the device acts as a catalyst, especially when students have (or acquire) self-regulation tools and when the teacher makes applicable strategies explicit.

Deviant cases and critical interpretation

Cases were identified in which, despite an increase in motivation, IMU engagement did not increase significantly. In these cases, interviews suggested that:

- satisfaction with the approach was high, but adherence was limited by contextual factors (minor injuries, discomfort in competitive play);
- some students interpreted the data as a potential judgement, reducing spontaneity.

The inclusion of deviant cases increases interpretative credibility and suggests that the effectiveness of IMU integration depends on educational framing and task personalisation.

Discussion

The results indicate that an educational programme focused on self-regulation and autonomy support, integrated with an explicit structure (objectives, success criteria, progressions and informative feedback), is associated with improvements in autonomous motivation and self-efficacy, as well as with positive changes in certain components of fitness (Di Palma et al., 2025; Reeve & Cheon, 2021; Cheon et al., 2022). This profile can be interpreted in light of Self-Determination Theory: SDT-informed interventions show generally small to moderate effects on behavioural and health outcomes in the literature, frequently mediated by increases in autonomous motivation and interpersonal support for psychological needs. The results of the present study fit consistently within this framework, suggesting that the combination of autonomy + structure is particularly relevant in the school context (Cheon et al., 2022; Fierro-Suero et al., 2024). At the same time, IMU data show a significant increase in active time and average intensity, with a reduction in RMS jerk (greater regularity), suggesting a possible “processual” mechanism linking teaching choices (reduction in downtime, high-density tasks, criteria-based feedback) to performance outcomes: the increase in actual movement time provides a plausible explanation (supported by integrative analyses) for the more marked improvement in aerobic capacity and explosive power compared to outcomes less directly influenced by work density (e.g. grip strength).

In terms of methodology and application, the use of inertial sensors makes it possible to go beyond an assessment based solely on “products” (tests and questionnaires), including process indicators related to how much and how students move during class. This perspective is in line with the growing emphasis on standardisation and transparency

in the analysis of signals from wearable devices and with recent recommendations on the use of IMUs for human movement analysis (Liang et al., 2024; Cereatti et al., 2024).

The qualitative findings strengthen the interpretation: students report greater awareness of their own movement behavior and a more intentional use of self-regulatory strategies, while teachers and students converge on the importance of pedagogical mediation to prevent social comparisons and to transform data into actionable feedback (Latino et al., 2019). This evidence is particularly relevant when compared with meta-analyses on wearable devices in school settings, which often report uncertain average effects when the device is used as an intervention “in itself” rather than as part of a structured instructional design (Au et al., 2024). In this respect, the adopted approach—aggregated feedback, absence of ranking, and an orientation toward improvement—also aligns with what has been highlighted by recent qualitative studies on students’ perceptions of wearable technologies in schools (Wort et al., 2024). Nonetheless, some limitations should be acknowledged: a class-based experimental design, possible variability among teachers, and the sensitivity of IMU metrics to device placement and contextual conditions. Therefore, replications with cluster randomization, calibration protocols, and more extensive fidelity analyses are recommended.

Conclusion

Overall, the study suggests that a school-based intervention combining autonomy support, structure, and self-regulation routines can produce simultaneous improvements in autonomous motivation, self-efficacy, and some fitness outcomes, accompanied by a significant increase in objectively measured motor engagement (active time, intensity) and indications of improved movement regularity (reduced jerk). These findings are consistent with the SDT-informed literature, which identifies autonomous motivation and support for psychological needs as key levers for promoting participation and physical activity behaviors, and they reinforce the idea that effectiveness in school settings depends on the quality of the instructional context (Cheon et al., 2022; Fierro-Suero et al., 2024).

The integration of inertial sensors represents a relevant contribution because it allows traditional outcomes to be complemented with a measurement of the motor process, making the analysis of the intervention more sensitive and informative. The qualitative results indicate that the technology is accepted and perceived as useful when data are framed in a formative manner, with aggregated feedback and an orientation toward improvement, and when teachers translate data into practical guidance, thereby preventing social comparison dynamics. From a broader perspective, the findings support the adoption of “data-informed” school designs in which the wearable is not the core of the intervention but rather a tool to improve instructional decisions and monitor equity of participation. Future studies should examine the stability of effects at follow-up, test generalizability across different school contexts, and define shared protocols for IMU metrics and analytical reporting, in line with recent recommendations on sensor data analysis and IMU-based motion analysis (Wort et al., 2024; Liang et al., 2024; Cereatti et al., 2024).

Ethics Approval and Consent to Participate

The study was approved by the University of Naples Parthenope (DiSMMeB, Prot. No. 88773/2025). Informed consent was obtained from all participants and/or their legal guardians prior to participation in the study.

Conflict of interest

The authors declare no conflicts of interest.

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Open access.

AI Transparency Statement

No AI tools were used in this study.

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Саморегульоване рухове навчання: вплив на мотивацію, фізичну підготовленість та моторну залученість

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

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Цілі. Це дослідження мало на меті оцінити ефективність програми фізичного виховання, орієнтованої на саморегуляцію та підтримку автономії, у підвищенні моторної залученості та мотиваційних показників підлітків. Дослідження поєднує об'єктивні вимірювання з використанням інерційних датчиків (ІВП/носимих пристроїв) та якісний аналіз результатів інтерв'ю.

Матеріали та методи. Було проведено експериментальне дослідження за схемою претест-посттест за участю 353 осіб (середній вік 14.2 ± 1.1 років), розподілених на експериментальну ($n = 178$) та контрольну ($n = 175$) групи. Використовувалися такі показники: мотивація (PLOC-R; за переглянутою шкалою сприйнятого локусу причинності), самоефективність щодо фізичної активності (самоефективність подолання бар'єрів), фізична підготовленість (EUROFIT: стрибок у довжину з місця, човниковий біг 20 м, нахил тулуба вперед із положення сидячи, кистьова динамометрія) та параметри ІВП (активний час, векторна амплітуда, прискорення) під час стандартизованих часових вікон уроку. Також проведено напівструктуровані інтерв'ю за участю 32 учнів та 8 вчителів із подальшим тематичним аналізом.

Результати. В експериментальній групі спостерігалися значніші покращення порівняно з контрольною групою за показниками автономної мотивації (Δ внутрішньої регуляції $+0.64$ проти $+0.10$, $p < .001$), самоефективності ($+0.41$ проти $+0.07$, $p < .001$), фізичної підготовленості (наприклад, стрибок у довжину $+9.3$ см проти $+2.1$ см, $p < .001$) та об'єктивно вимірюваної моторної залученості (активний час $+9.5$ відсоткових пунктів проти $+1.3$, $p < .001$). Результати інтерв'ю засвідчили високий рівень прийнятності методики, підвищення усвідомленості рухів та важливості ролі вчителя у запобіганні динаміці соціального порівняння.

Висновки. Інтеграція даних ІВП сприяє більш комплексному оцінюванню ефективності шкільних програм, поєднуючи мотиваційні та результативні показники з об'єктивними індикаторами моторної поведінки.

Ключові слова: моторна саморегуляція, моторна залученість, інерційні датчики, фізичне виховання.

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Evaluating the Mediating Effects of Self-Regulation, Self-Efficacy on Goal Achievement and Scheduled Time for Physical Activity

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Abstract

Background. Physical activity among elementary school children plays a fundamental role in supporting metabolic health, learning readiness, and long-term psychological well-being. The widespread occurrence of sedentary lifestyles, combined with insufficient adherence to recommended physical activity levels, suggests that interventions should extend beyond structured programs and consider students' psychological preparedness.

Objectives. The present study aimed to examine how self-regulation and self-efficacy function as mediating factors linking achievement goals with students' participation in scheduled physical activity at the elementary level.

Materials and Methods. This quantitative study involved 240 fourth- to sixth-grade students from public elementary schools in Surabaya City, aged 10-12 years. Data were collected using closed-ended questionnaires measuring achievement goals, self-regulation, self-efficacy, and scheduled time for physical activity. Partial Least Squares Structural Equation Modeling (PLS-SEM) was applied for data analysis, utilizing the SmartPLS 4.0 software.

Results. The analysis revealed that all achievement goal dimensions had significant effects on self-regulation and self-efficacy. Self-efficacy demonstrated a strong positive influence on scheduled time for physical activity, whereas self-regulation showed a significant negative effect. The findings indicate that each dimension of achievement goals influences participation in scheduled physical activity indirectly by way of self-regulation and self-efficacy. The research model substantially explained the variance in scheduled time for physical activity and demonstrated adequate predictive relevance.

Conclusions. The findings confirm that strengthening self-belief more strongly determines the sustainability of scheduled physical activity among elementary school students than overly strict behavioral regulation. These results support the development of physical education interventions focused on achieving goals and enhancing self-efficacy to foster sustainable physical activity habits from the elementary school years.

Keywords: achievement goals, elementary school students, physical activity, self-efficacy, self-regulation.

Introduction

Physical activity in elementary school children is consistently recognized as essential for metabolic health, cognitive functioning, and long-term psychological well-being

(Marsigliante et al., 2023). International health authorities recommend at least 60 minutes of moderate-to-vigorous physical activity daily; however, more than 80% of children and adolescents worldwide fail to meet this standard (Benavente-Marín et al., 2024). Insufficient activity is associated with lower cognitive performance, weaker self-regulatory capacity, and reduced academic engagement (Pesce et al., 2020).

Although schools provide structured physical education and scheduled activity programs, sustained adherence to

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daily physical activity remains consistently low. This gap suggests that program availability and goal orientation alone are insufficient to ensure long-term behavioral maintenance. The inconsistency between structured provision and persistent engagement reveals a conceptual limitation in prevailing motivational and school-based intervention models. Rapid digitalization intensifies this discrepancy. Increased screen exposure reduces opportunities for movement during and after school hours (Throuvala et al., 2021) and predicts stronger sedentary tendencies established early in life (Schwarzfischer et al., 2019). The central scientific problem therefore concerns the psychological processes through which structured opportunities and motivational orientations are converted into sustained adherence within institutional time structures.

Elementary schools represent a strategic setting for intervention because scheduled programs can institutionalize movement routines (Clark et al., 2019). However, participation often declines once external monitoring decreases (Sansano-Nadal et al., 2019). This limitation indicates that prevailing approaches emphasize program structure and technical skill development while insufficiently addressing the psychological mechanisms that sustain autonomous engagement over time (Baena-Morales et al., 2024).

Self-regulation and self-efficacy are central psychological determinants of sustained behavior. Self-regulation involves goal setting, behavioral monitoring, and adaptive adjustment (Koole et al., 2012). It enables students to manage time, resist distractions, and persist in physical activity despite competing academic demands (Cao & Jiang, 2025). Self-efficacy reflects confidence in one's capability to successfully perform and maintain activity (Voskuil & Robbins, 2015). Higher self-efficacy predicts persistence and resilience in structured programs (Peng et al., 2025). While both constructs are established predictors of activity behavior, they are frequently modeled as direct antecedents rather than as psychological mechanisms that transmit motivational influence into sustained adherence. As a result, existing models often remain descriptively associative and do not fully specify how motivational orientation is transformed into maintained scheduled behavior.

Achievement goals guide motivation and give behavior meaning (Standage et al., 2003). Achieving goals boosts confidence and builds consistency (Spring et al., 2021). However, models rarely show how reaching goals leads to regular physical activity through step-by-step psychological changes. Most research focuses on motivation alone rather than linking it to a broader explanation (Yu et al., 2022). Studies testing these ideas in Asian elementary students are also scarce (Poon et al., 2022). This fragmentation restricts theoretical clarity regarding the pathway connecting goal orientation, regulatory processes, efficacy beliefs, and sustained behavioral adherence in structured school contexts.

The conceptual gap, therefore, lies in the absence of an integrated mediation model explaining how achievement goals are converted into sustained scheduled physical activity through self-regulation and self-efficacy. Addressing this gap moves beyond descriptive associations and advances theoretical clarification of the psychological pathway linking motivation and behavioral maintenance.

Scheduled physical activity in schools refers to planned and recurrent movement sessions embedded within the institutional timetable (Siedentop, 2009). Adherence to such scheduling reflects successful behavioral regulation and efficacy beliefs (Williams & French, 2011). Sustained adherence, rather than momentary participation, constitutes the critical behavioral outcome of interest.

The present study examines a mediation model in which achievement goals predict adherence to scheduled physical activity indirectly through self-regulation and self-efficacy among elementary students in Surabaya. The scientific novelty lies in empirically testing a theoretically sequenced psychological mechanism that resolves the contradiction between structured program availability and low sustained adherence.

This study addresses the following research questions: (1) To what extent does the proposed mediation model receive empirical support within a predictive structural framework? (2) Do self-regulation and self-efficacy significantly mediate the relationship between achievement goals and adherence to scheduled physical activity? (3) Do self-regulation and self-efficacy independently predict increases in students' physical activity duration?

Materials and Methods

Study Participants

The study involved 240 elementary students (114 boys, 126 girls) aged 10-12 (average age 11.04 ± 0.72). All participated in Physical Education, Sports, and Health (PJOK) classes and volunteered. Recruited from public schools in Surabaya, Indonesia, students represented a middle socioeconomic background. The sample included Grades 4-6. Cluster sampling at the school level ensured feasible administration and representation across upper elementary grades.

Study Organization

Ethical clearance and institutional permission were obtained prior to data collection. Questionnaires were administered during scheduled PJOK sessions without classroom teachers present to minimize social desirability bias. Students were informed that participation was voluntary and unrelated to academic evaluation. Responses were collected anonymously and treated confidentially. Written informed consent was obtained from parents or legal guardians of all participating students, and student assent was secured prior to questionnaire administration. The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. This research received no external funding.

The study employed a cross-sectional predictive design to examine the hypothesized mediation relationships among achievement goals, self-regulation, self-efficacy, and scheduled physical activity. The research used short surveys covering student background, achievement goals, self-regulation, self-efficacy, and scheduled physical activity. Surveys took about 40 minutes. Closed questions were used to ensure consistent answers for analysis (Ranganathan & Caduff, 2023).

Achievement goal orientation was measured using the 2x2 Achievement Goal Scale (Guan et al., 2007). This 21-item tool asks about experiences in physical education classes, using a seven-point scale. It assesses four areas: striving to improve, avoiding doing poorly, trying to outperform others, and avoiding worse outcomes than others.

Self-regulation and self-efficacy were assessed using adapted components of the Motivated Strategies for Learning Questionnaire (Pintrich & Groot, 1990). The instrument included 18 items equally distributed across both constructs. Responses were recorded on a seven-point agreement scale. Self-regulation items reflect persistence, monitoring, and strategy use, whereas self-efficacy items measure confidence in successfully completing physical education tasks relative to peers.

Scheduled physical activity was assessed using the short form of the International Physical Activity Questionnaire (Saglam et al., 2010). The instrument includes seven items capturing frequency, duration, and intensity of physical activity during the previous seven days.

The IPAQ-SF was selected because it allows standardized estimation of moderate-to-vigorous physical activity (MVPA) duration and has demonstrated acceptable reliability across diverse populations. Although originally developed for adults, prior research has applied adapted or supervised versions of IPAQ-SF in adolescent and upper-elementary samples when supported by structured administration procedures. In the present study, items were simplified linguistically and administered under researcher guidance to ensure comprehension among 10-12-year-old participants. This approach enhances response accuracy while maintaining comparability of MVPA estimates.

Statistical Analysis

Data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS 4.0. PLS-SEM was selected because the study aims to test a predictive mediation framework involving multiple latent constructs and indirect pathways (Cepeda-Carrion et al., 2019).

Convergent validity was assessed through indicator loadings (> 0.70) and Average Variance Extracted (AVE > 0.50) (Hair et al., 2019). Discriminant validity was evaluated using the Fornell-Larcker criterion, cross-loadings, and the Heterotrait-Monotrait Ratio (HTMT < 0.90) (Henseler et al., 2014). Measurement consistency was verified using Composite Reliability (CR) and Cronbach's Alpha (CA), with coefficients surpassing the recommended minimum of 0.70, indicating dependable internal consistency (Hair et al., 2019). The evaluation procedures were conducted sequentially: the structural model was examined only after all measurement criteria were satisfied, ensuring consistency between measurement quality and structural interpretation.

After confirming validity and reliability, structural paths were estimated to test direct and indirect effects. Bootstrapping with 5,000 resamples was used to assess statistical significance of path coefficients and mediation effects. A significance threshold of $p < 0.05$ was applied (Fangqi et al., 2023). Model evaluation in PLS-SEM primarily emphasizes predictive accuracy and explained variance. Accordingly, R^2 values and bootstrapped path coefficients constituted the main criteria for structural interpretation.

Model fit was evaluated using the Standardized Root Mean Square Residual (SRMR < 0.08) and the Normed Fit Index (NFI > 0.90) (Shmueli et al., 2019). These indices were reported as supplementary global indicators, consistent with the predictive orientation of PLS-SEM rather than strict covariance-based fit assessment. Interpretation of mediation followed a direct-indirect comparison framework, distinguishing full, partial, or non-significant mediation based on the significance and magnitude of bootstrapped indirect effects.

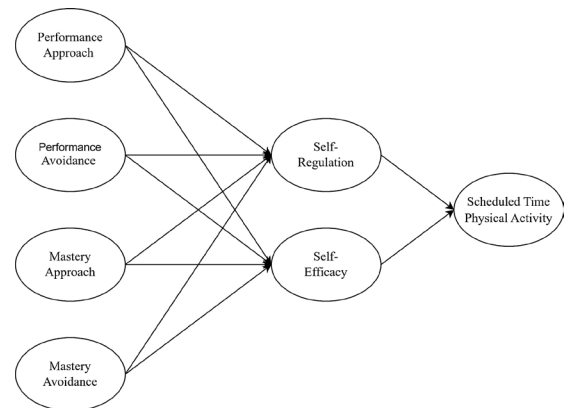


Fig. 1. Results of Hypothesized Path Model

The hypothesized structural model included four achievement goal orientations mastery approach, mastery avoidance, performance approach, and performance avoidance as exogenous variables. Paths were specified from each goal orientation to self-regulation and to self-efficacy. Additional paths were defined from self-regulation to scheduled physical activity and from self-efficacy to scheduled physical activity. In this framework, self-regulation and self-efficacy were modeled as parallel mediators linking achievement goals to adherence to scheduled physical activity, consistent with the study's theoretical assumptions. Indirect effects were examined separately for each goal orientation through both mediators. Direct paths from achievement goals to scheduled physical activity were retained in order to determine whether the mediation pattern was partial or full.

Results

Descriptive statistics were calculated for all study variables ($N = 240$), including mean, standard deviation, range, skewness, kurtosis, and 95% confidence intervals.

Overall, the constructs demonstrated balanced score distributions. Performance Approach ($M = 24.0$; $SD = 6.45$) and Mastery Approach ($M = 20.6$; $SD = 5.48$) were within expected empirical ranges. Scheduled Time Physical Activity averaged 112.4 minutes per week ($SD = 28.04$).

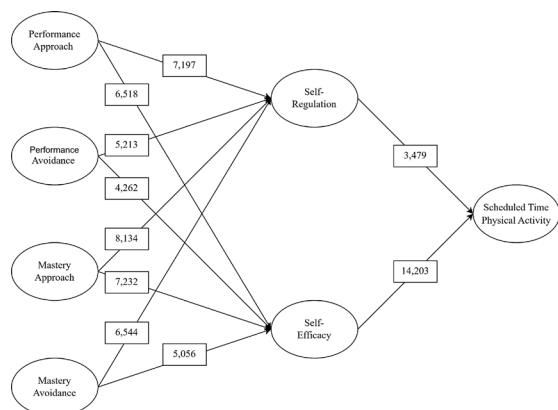
Skewness values ranged from -0.054 to 0.328 and kurtosis values from -0.323 to 0.450, indicating no substantial deviation from normal distribution. Confidence intervals were relatively narrow, suggesting stable parameter estimation.

These distributional characteristics indicate that the dataset was suitable for PLS-SEM analysis, which does

Table 1. Results of Data Description

Characteristics	N	M	SD	Min	Max	Skewness	Kurtosis	95% Confidence Interval	
								Lower	Upper
Performance Approach	240	24.0	6.45	7.00	42.0	0.098	-0.098	23.2	24.9
Performance Avoidance	240	19.0	5.24	6.00	35.0	0.058	-0.294	18.4	19.7
Mastery Approach	240	20.6	5.48	6.00	33.0	-0.054	-0.176	19.9	21.3
Mastery Avoidance	240	17.6	5.14	7.00	35.0	0.328	-0.232	16.9	18.2
Self-Regulation	240	35.0	9.49	12.00	59.0	-0.051	-0.323	33.8	36.2
Self-Efficacy	240	31.2	8.15	12.00	62.0	0.223	0.450	30.2	32.3
Scheduled Time Physical Activity	240	112.4	28.04	44.00	188.0	0.147	-0.118	108.9	116.0

not require strict multivariate normality assumptions. The hypothesized relationships among achievement goal orientations, self-regulation, self-efficacy, and scheduled physical activity were examined using PLS-SEM.

**Fig. 2.** Results of Relationship Path Model

All four achievement goal orientations demonstrated significant positive effects on self-regulation and self-efficacy ($T = 4.262-8.134$; $p < 0.001$). Self-efficacy showed a strong positive association with Scheduled Time Physical Activity ($\beta = 0.918$; $T = 14.203$; $p < 0.001$).

Self-regulation demonstrated a negative but statistically significant association with Scheduled Time Physical Activity ($\beta = -0.258$; $T = 3.479$; $p = 0.001$).

Table 2. Results of Model Fit

Model fit	SRMR	d_ULS	d_G	Chi-square	NFI
Saturated model	0.099	12.445	n/a	∞	n/a
Estimated model	0.166	34.960	n/a	∞	n/a

Model fit indices are presented in Table 2. The SRMR value for the estimated model was 0.166, exceeding the commonly referenced threshold of 0.08.

Within the PLS-SEM framework, SRMR is treated as a descriptive global index rather than a strict confirmatory criterion. Structural evaluation in this study therefore emphasizes path coefficients, explained variance (R^2), and

predictive relevance (Q^2), in accordance with the predictive orientation of the method.

The increase in d_{ULS} between the saturated and estimated models reflects structural constraints imposed by the hypothesized mediation pathways. This value is reported for completeness and does not serve as the primary criterion for structural interpretation in PLS-SEM.

All achievement goal dimensions significantly predicted both self-regulation and self-efficacy ($\beta = 0.228-0.373$; $p < 0.001$). Mastery Approach exhibited the strongest effect on self-regulation ($\beta = 0.373$), whereas Mastery Approach and Performance Approach showed comparatively stronger effects on self-efficacy. Among the mediators, self-efficacy emerged as the most influential predictor of Scheduled Time Physical Activity ($f^2 = 0.309$), indicating a substantial practical contribution within the model. In contrast, self-regulation demonstrated a negative effect on Scheduled Time Physical Activity ($\beta = -0.258$; $f^2 = 0.024$).

The negative coefficient of self-regulation requires cautious interpretation. Simultaneous estimation of self-regulation and self-efficacy as parallel mediators may reduce the unique variance attributed to self-regulation, particularly given the strong positive association observed for self-efficacy. Negative coefficients may occur in multivariate models when substantial shared variance exists between theoretically related constructs.

Measurement context should also be considered. Self-regulation items were adapted from academic learning settings, and stronger academic regulatory tendencies in elementary students may reflect prioritization of structured study behaviors over discretionary physical activity under time constraints. The observed negative association is therefore interpreted as a context-specific statistical outcome within a cross-sectional predictive framework rather than evidence of a detrimental effect of self-regulation.

Bootstrapping results confirmed significant indirect effects of all achievement goal orientations on Scheduled Time Physical Activity ($\beta = 0.141-0.215$; $p < 0.001$).

The Mastery Approach ($\beta = 0.215$) and Performance Approach ($\beta = 0.206$) produced larger indirect effects than avoidance orientations.

These findings indicate that the influence of achievement goals on scheduled physical activity operates primarily through psychological mediating processes, with self-efficacy demonstrating the dominant indirect contribution.

Table 3. Results of Path Coefficients

Characteristics	Original sample	Sample mean	Standard deviation	T statistics	p
Performance Approach -> Self-Regulation	0.319	0.319	0.044	7.197	0.000
Performance Approach -> Self-Efficacy	0.313	0.313	0.048	6.518	0.000
Performance Avoidance -> Self-Regulation	0.267	0.267	0.051	5.213	0.000
Performance Avoidance -> Self-Efficacy	0.228	0.229	0.054	4.262	0.000
Mastery Approach -> Self-Regulation	0.373	0.374	0.046	8.134	0.000
Mastery Approach -> Self-Efficacy	0.339	0.341	0.047	7.232	0.000
Mastery Avoidance -> Self-Regulation	0.301	0.302	0.046	6.544	0.000
Mastery Avoidance -> Self-Efficacy	0.241	0.244	0.048	5.056	0.000
Self-Regulation -> Scheduled Time Physical Activity	-0.258	-0.258	0.074	3.479	0.001
Self-Efficacy -> Scheduled Time Physical Activity	0.918	0.919	0.065	14.203	0.000

Table 4. Results of Indirect Effects Histogram

Characteristics	Original Sample	Sample mean	Standard deviation	T Statistics	p
Performance Approach → Scheduled Time Physical Activity	0.206	0.205	0.038	5.457	0.000
Performance Avoidance → Scheduled Time Physical Activity	0.141	0.142	0.039	4.569	0.000
Mastery Approach → Scheduled Time Physical Activity	0.215	0.216	0.037	5.853	0.000
Mastery Avoidance → Scheduled Time Physical Activity	0.144	0.146	0.038	3.813	0.000

Table 5. Results of Coefficient of Determination and Predictive Relevance

Characteristics	R ²	Q ²
Self-Regulation	0.434	0.412
Self-Efficacy	0.352	0.327
Scheduled Time Physical Activity	0.483	0.153

The model explained 43.4% of the variance in Self-Regulation ($R^2 = 0.434$), 35.2% of the variance in Self-Efficacy ($R^2 = 0.352$), and 48.3% of the variance in Scheduled Time Physical Activity ($R^2 = 0.483$). The predictive relevance values ($Q^2 > 0$) indicate predictive capability, particularly for Self-Regulation ($Q^2 = 0.412$) and Self-Efficacy ($Q^2 = 0.327$). Predictive relevance for Scheduled Time Physical Activity was lower ($Q^2 = 0.153$), suggesting moderate predictive strength. Taken together, the R^2 and Q^2 values demonstrate meaningful explanatory and predictive capacity within the proposed mediation model.

Table 6. Result of Variance Inflation Factor and Effect Size

Characteristics	VIF	f ²
Performance Approach -> Self-Regulation	1.011	0.177
Performance Approach -> Self-Efficacy	1.011	0.150
Performance Avoidance -> Self-Regulation	1.006	0.125
Performance Avoidance -> Self-Efficacy	1.006	0.080
Mastery Approach -> Self-Regulation	1.013	0.243
Mastery Approach -> Self-Efficacy	1.013	0.176
Mastery Avoidance -> Self-Regulation	1.005	0.159
Mastery Avoidance -> Self-Efficacy	1.005	0.090
Self-Regulation -> Scheduled Time Physical Activity	5.269	0.024
Self-Efficacy -> Scheduled Time Physical Activity	5.269	0.309

Variance Inflation Factor (VIF) values for paths linking achievement goals to mediators were low (1.005-1.013), indicating no multicollinearity concerns.

However, VIF values for the paths from Self-Regulation and Self-Efficacy to Scheduled Time Physical Activity were 5.269. Although below the critical threshold of 10, these values indicate moderate collinearity between the parallel mediators and necessitate cautious interpretation of their individual path estimates.

The duplicate explanatory sentence regarding collinearity has been removed to avoid redundancy. Effect sizes (f^2) ranged from 0.024 to 0.309. Self-efficacy demonstrated the largest effect on Scheduled Time Physical Activity ($f^2 = 0.309$), whereas the contribution of self-regulation was small ($f^2 = 0.024$).

Discussion

The present investigation was based on the proposition that several dimensions of achievement goals, including mastery oriented, performance oriented, and avoidance related tendencies, play an important role in shaping scheduled time physical activity through the intermediary functions of self-efficacy and self-regulation (Erturan et al., 2020). Results from descriptive examination indicated that the Performance Approach orientation obtained the highest mean score among participants ($M = 24.0$), reflecting its prominence within the sample (Tajeddini, 2016). This pattern suggests that externally driven motives related to demonstrating competence continue to influence individuals' involvement in planned physical activity (Teixeira et al., 2012).

Structural path analysis showed that all achievement goal dimensions were significantly associated with improvements in participants' self-efficacy and self-regulatory capacity

(Bouffard et al., 2005). The findings highlight goal orientation as a psychological foundation that supports behavioral regulation processes in sport and physical activity contexts (Biddle et al., 2008). Additional analysis revealed that the Mastery Approach exerted the strongest influence on self-regulation, as indicated by a path coefficient of $\beta = 0.373$ (Tee et al., 2021). This result is consistent with theoretical perspectives proposing that an emphasis on skill development promotes autonomous control and sustained behavioral regulation (McDonald, 2014).

The relationship between Self-Efficacy and Scheduled Time Physical Activity demonstrated a highly dominant effect, with a coefficient of $\beta = 0.918$ (Abasi et al., 2016). This finding reinforces prior empirical evidence identifying self-efficacy as the strongest predictor of various health-related behaviors (Schwarzer & Renner, 2000). The analysis also revealed a negative association between Self-Regulation and the duration of scheduled physical activity ($\beta = -0.258$) (Wang et al., 2019). Previous theoretical discussions have suggested that intensive regulatory effort may, under certain conditions, be cognitively demanding and difficult to sustain over time (Hagger et al., 2010). In structured contexts, highly regulated behavioral patterns may also reduce flexibility when external constraints emerge (Lord et al., 2010).

However, within the present multivariate model, this association may also reflect statistical suppression due to the strong concurrent contribution of self-efficacy as a parallel mediator. Substantial conceptual overlap between regulatory processes and efficacy beliefs may reduce the unique explanatory contribution of self-regulation. Therefore, the observed coefficient should be interpreted cautiously and not as evidence that self-regulation inherently impedes physical activity engagement.

Despite this negative relationship, the indirect effects of all achievement goal dimensions on physical activity remained positive and significant (Mouratidis et al., 2009). These results indicate that strong initial motivation can compensate for limitations in self-regulation through enhanced self-efficacy pathways (Trautner & Schwinger, 2020). The significance of the findings is further reflected in the role of Self-Efficacy as the primary mediator, exhibiting the largest effect size ($f^2 = 0.309$) (Lee et al., 2022). The model explained 48.3% of the variance in Scheduled Time Physical Activity, demonstrating meaningful explanatory capacity within a social cognitive framework rather than constituting definitive validation (Olson & McAuley, 2015).

The practical implications of these findings suggest that efforts to increase the duration of physical activity should prioritize strengthening beliefs in personal capability rather than focusing solely on behavioral control mechanisms (Plotnikoff et al., 2013). Model stability is further supported by positive Predictive Relevance (Q^2) values across all endogenous variables, indicating the model's suitability for application in similar populations (Sharma et al., 2019). The relevance of these results is particularly salient given the low levels of physical activity adherence observed in modern societies (Rhodes et al., 2009).

Health practitioners and sport coaches may facilitate the application of these findings by designing programs that emphasize gradual achievement or small wins to build participants' self-efficacy (Jackson, 2010). Mastery-oriented approaches should be prioritized by emphasizing individual

self-improvement rather than interparticipant competition to support long-term psychological stability (Ford & Smith, 2007). Flexibility in physical activity program design is also essential to mitigate the adverse effects of overly restrictive cognitive self-regulation (Buckley et al., 2014). The use of digital applications that provide immediate positive feedback may represent an effective strategy for sustaining approach-based motivation (Erhel & Jamet, 2013).

Future research should focus on a deeper exploration of the mechanisms underlying Self-Regulation's negative influence on physical activity duration (Hall & Fong, 2015). Longitudinal designs would provide more comprehensive insights into the dynamic relationships between achievement goals and physical activity behavior across the lifespan (Conroy et al., 2011). Integrating environmental variables, such as social support and the availability of physical facilities, may further enhance the model's predictive power beyond internal psychological factors (Yanos & Moos, 2007). The validity of future findings may also be strengthened by using objective data sources, such as motion sensors, to complement self-reported measures of physical activity duration (Sallis & Saelens, 2000). Overall, self-efficacy emerged as the primary mediator linking various achievement goal dimensions to the duration of scheduled physical activity. In contrast, excessive self-regulation may hinder the consistency of active behavior.

Conclusions

The results indicate that all achievement goal dimensions make a meaningful contribution to the formation of self-efficacy and self-regulation, both of which function as mediating mechanisms in students' participation in scheduled physical activity. Self-efficacy emerged as the most influential mediator associated with extended duration of physical activity. A negative yet statistically significant association was observed for self-regulation, which appears to reflect contextual and analytical dynamics rather than a detrimental role of regulatory processes per se. This finding highlights the importance of balancing structured behavioral control with adaptive flexibility in structured physical activity contexts. Overall, strengthening students' efficacy beliefs may represent a key pathway for sustaining engagement in scheduled physical activity, while achievement goal orientations provide the motivational foundation through which such beliefs are cultivated in elementary school settings.

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Conflict of interest

The authors report no potential conflicts of interest related to this study.

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Оцінка опосередкованого впливу саморегуляції та самоефективності щодо досягнення цілей і запланованого часу на фізичну активність

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 10 с., 6 табл., 2 рис., 54 джерел.

Обґрунтування. Фізична активність дітей молодшого шкільного віку відіграє фундаментальну роль у підтримці метаболічного здоров'я, готовності до навчання та довгострокового психологічного благополуччя. Широке розповсюдження малорухливого способу життя у поєднанні з недостатнім дотриманням рекомендованих рівнів фізичної активності свідчить про те, що інтервенції мають виходити за межі структурованих програм і враховувати психологічну готовність учнів.

Мета. Дане дослідження мало на меті вивчити, як саморегуляція та самоефективність функціонують як медіативні фактори, що пов'язують цілі досягнення із залученням учнів початкової школи до запланованої фізичної активності.

Матеріали та методи. У цьому кількісному дослідженні взяли участь 240 учнів 4–6 класів державних початкових шкіл міста Сурабая віком 10–12 років. Збір даних проводився за допомогою опитувальників закритого типу з метою оцінки цілей досягнення, саморегуляції, самоефективності та запланованого часу на фізичну активність. Для аналізу даних було застосовано моделювання структурними рівняннями методом найменших квадратів (PLS-SEM) за допомогою програмного забезпечення SmartPLS 4.0.

Результати. Аналіз виявив, що всі виміри цілей досягнення мали значущий вплив на саморегуляцію та самоефективність. Самоефективність продемонструвала сильний позитивний вплив на запланований час для фізичної активності, тоді як саморегуляція виявила значущий негативний ефект. Отримані дані вказують на те, що кожен вимір цілей досягнення опосередковано впливає на залучення до запланованої фізичної активності через саморегуляцію та самоефективність. Дослідницька модель суттєво пояснила дисперсію запланованого часу для фізичної активності та продемонструвала належну прогностичну релевантність

Висновки. Результати дослідження підтверджують, що зміцнення віри у власні сили є вагомим чинником сталості дотримання графіку фізичної активності серед учнів початкової школи, ніж надмірно суворе поведінкове регулювання. Ці дані обґрунтовують доцільність розроблення інтервенцій у сфері фізичного виховання, орієнтованих на досягнення цілей та підвищення самоефективності, задля формування стійких звичок до фізичної активності, починаючи з молодшого шкільного віку.

Ключові слова: цілі досягнення, учні початкової школи, фізична активність, самоефективність, саморегуляція.

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The Influence of a Rhythmic Motor-Learning Intervention on Selected Physical and Physiological Variables among Children with Mild Intellectual Disability

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Abstract

Objectives. This experimental study aimed to examine the effects of a 12-week unified rhythmic activity intervention on selected physical and physiological parameters among children with mild intellectual disability.

Materials and Methods. Thirty children (aged 10–14 years) diagnosed with mild intellectual disability (IQ 50–70) were randomly assigned to either an experimental group (n = 15) or a control group (n = 15). The experimental group participated in a structured unified rhythmic activity program, while the control group continued their regular school routines. Pre- and post-intervention assessments included body mass index (BMI), body fat percentage, flexibility, muscular endurance, cardiovascular endurance, resting heart rate (RHR), and vital capacity (VC). A two-way mixed-design ANOVA (2 groups × 2 time points) was employed to evaluate the main and interaction effects.

Results. A significant main effect of time was observed for flexibility ($p < 0.001$, $\eta_p^2 = 0.68$), muscular endurance ($p = 0.002$, $\eta_p^2 = 0.54$), cardiovascular endurance ($p < 0.001$, $\eta_p^2 = 0.72$), RHR ($p = 0.008$, $\eta_p^2 = 0.48$), and VC ($p = 0.001$, $\eta_p^2 = 0.58$). Additionally, significant group × time interaction effects were found for flexibility ($p < 0.001$, $\eta_p^2 = 0.62$), muscular endurance ($p = 0.003$, $\eta_p^2 = 0.51$), cardiovascular endurance ($p < 0.001$, $\eta_p^2 = 0.65$), and RHR ($p = 0.012$, $\eta_p^2 = 0.42$), with the experimental group showing superior improvements. No substantial changes were observed for BMI or body fat percentage.

Conclusions. The unified rhythmic activity intervention produced meaningful improvements in flexibility, muscular endurance, cardiovascular fitness, and resting heart rate among children with mild intellectual disability. These findings support incorporating rhythmic movement-based training into adapted physical education programs to enhance physical and physiological outcomes in this population.

Keywords: intellectual disability, rhythmic movement, physical fitness, adapted physical education, cardiovascular health.

Introduction

Intellectual disability (ID) affects approximately 1-3% of the global population, characterized by significant limitations

in both intellectual functioning and adaptive behaviour (Chandan & Dubon, 2019). Children with mild intellectual disability (IQ range 50-70) comprise the largest subgroup, representing about 85% of individuals with ID. These children often experience secondary health complications including obesity, poor cardiovascular health, and reduced physical fitness compared to their typically developing peers.

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Physical inactivity is highly prevalent among children with intellectual disabilities, with studies reporting that only 9-15% meet recommended physical activity guidelines compared to 40-50% of typically developing children (Fong Yan et al., 2024). This sedentary lifestyle contributes to higher rates of obesity (30-40% prevalence), cardiovascular disease risk, and reduced motor competence (Salaun & Berthouze-Aranda, 2012). The consequences of physical inactivity in this population extend beyond physical health, affecting psychological wellbeing, social participation, and overall quality of life (Fong Yan et al., 2024).

Traditional physical education programs often fail to adequately engage children with intellectual disabilities due to complex instructions, competitive elements, and lack of appropriate modifications (Haeghele & Sutherland, 2015). Consequently, there is a critical need for evidence-based, enjoyable, and accessible physical activity interventions specifically designed for this population. Rhythmic activities, which combine movement with music and repetitive patterns, may be particularly suitable due to their structured nature, predictability, and inherent enjoyment (Kalyva et al., 2007).

Unified rhythmic activity represents an integrated approach combining elements of dance, aerobic movement, and rhythmic gymnastics adapted for individuals with intellectual disabilities. The “unified” component emphasizes inclusive participation, social interaction, and peer support (Chandan & Dubon, 2019). Previous study has demonstrated that rhythmic movement programs can improve motor skills, balance, and coordination in children with developmental disabilities (Park & Jee, 2022; Teixeira-Machado et al., 2019). However, comprehensive examination of the effects on both physical profile (body composition, fitness components) and physiological parameters (cardiovascular function, respiratory capacity) remains limited.

Several theoretical frameworks support the use of rhythmic activities for this population. The ecological task analysis model suggests that tasks should be modified to match individual capabilities while maintaining engagement (Newton et al., 2020). Rhythmic activities naturally allow for such modifications through tempo adjustment, movement simplification, and graduated complexity. Additionally, the motivational climate theory indicates that mastery-oriented, non-competitive environments promote sustained participation, characteristics inherent to rhythmic activity programs (Back et al., 2022).

Emerging evidence suggests that music-based movement interventions may offer unique benefits for individuals with intellectual disabilities. The temporal and spatial predictability of rhythmic patterns may facilitate motor planning and execution in populations with coordination difficulties (Thaut et al., 2015). Furthermore, the social and emotional engagement fostered by group rhythmic activities may enhance adherence and psychological outcomes beyond those achieved through conventional exercise (Koch et al., 2014).

Despite promising preliminary findings, several gaps exist in the current literature. Most studies have examined motor skills or isolated fitness components rather than comprehensive physical and physiological profiles. Additionally, methodological limitations including small sample sizes, lack of control groups, and short intervention durations have limited the generalizability of findings. Moreover, few studies have specifically examined children

with mild intellectual disability, who represent the largest and potentially most responsive subgroup for physical activity interventions.

Therefore, this study aimed to investigate the effects of a 12-week unified rhythmic activity intervention on selected physical profile components (BMI, body fat percentage, flexibility, muscular endurance, cardiovascular endurance) and physiological factors (resting heart rate, vital capacity) among children with mild intellectual disability.

Materials and Methods

Study Design

This randomized controlled trial was conducted over 14 weeks, including pre-testing (week 1), 12-week intervention period, and post-testing (week 14). Participants were randomly allocated to either an experimental group (unified rhythmic activity intervention) or a control group (regular school activities) using computer-generated random numbers with an allocation ratio of 1:1. All assessments were conducted by trained evaluators blinded to group allocation.

Participants

Thirty children (18 boys and 12 girls), aged 10–14 years and diagnosed with mild intellectual disability, were recruited from two special education institutions: Star Special School and Vidya Vikasini Opportunity School in Coimbatore, Tamil Nadu, India. Participants were diagnosed with mild intellectual disability (IQ 50-70) based on standardized intelligence testing (WISC-IV or Stanford-Binet Intelligence Scales) and adaptive behaviour assessment (Vineland Adaptive Behaviour Scales-II) conducted by certified psychologists.

No significant differences were observed between groups at baseline for any variables (all $p > 0.05$), indicating successful randomization (Table 1).

Table 1. Demographic and Baseline Characteristics of Participants

Characteristic	Experimental (n=15)	Control (n=15)	p-value
Age (years)	13.4 ± 2.0	13.1 ± 2.1	0.542
Gender (Boys/Girls)	9/6	9/6	1.000
IQ Score	61.8 ± 7.2	63.1 ± 6.5	0.483
Height (cm)	145.2 ± 8.6	143.8 ± 9.1	0.674
Body Mass (kg)	42.8 ± 9.2	41.3 ± 8.7	0.656
Session Attendance (%)	94.7 ± 3.2	-	-

Values are mean ± SD. IQ = Intelligence Quotient.

All 30 participants completed the study with 100% retention (experimental group n=15, control group n=15). Attendance in the experimental group averaged 94.7% (34.1 out of 36 sessions). No adverse events or injuries occurred during the intervention period.

Selection Criteria

Participants included in the study were children aged 10–14 years who had been clinically diagnosed with mild intellectual disability, corresponding to an IQ range of 50–70.

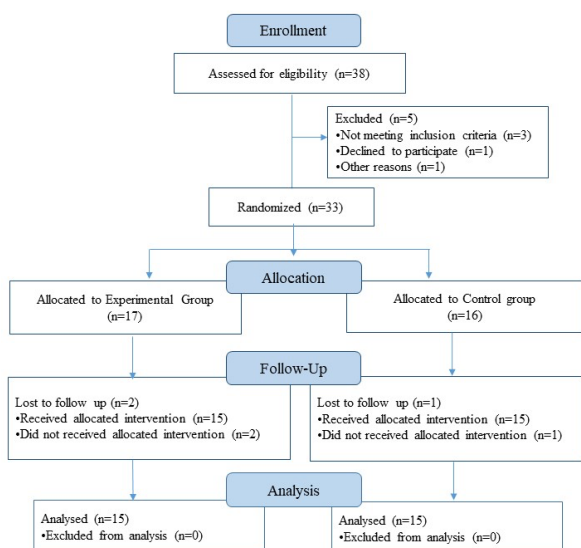


Fig. 1. CONSORT Flowchart

Eligible participants were required to demonstrate the ability to follow simple verbal and visual instructions and to have received medical clearance permitting engagement in physical activities. Written informed consent was obtained from parents or legal guardians, along with assent from the participants themselves. Only children with regular school attendance of at least 80% were included in the study. Participants were excluded if they had severe physical disabilities limiting movement, uncorrected sensory impairments such as vision or hearing deficits, or unstable medical conditions including uncontrolled seizures or cardiac disorders. Those already participating in structured physical activity programs exceeding two hours per week or those absent for more than three intervention sessions were also excluded from the study.

G*Power software (version 3.1) was used to determine sample size. With effect size (f) = 0.50, power = 0.80, alpha = 0.05, number of groups = 2, number of measurements = 2, and correlation among repeated measures = 0.5, a minimum sample size of 26 was required. To account for potential dropouts, 30 participants were recruited.

Ethical Clearance

The study was approved by the Institutional Ethics Committee AUW/IHEC/Phy.Edu/23-24/XPD-01 and conducted according to the Declaration of Helsinki. Written informed consent was obtained from parents/guardians, and verbal assent was obtained from all participants.

Anthropometric Measurements

Height: Measured using a stadiometer (Seca 213, Hamburg, Germany) to the nearest 0.1 cm with participants standing barefoot in an upright position.

Body Mass: Measured using a calibrated digital scale (Seca 813, Hamburg, Germany) to the nearest 0.1 kg, with participants wearing light clothing and barefoot.

Body Mass Index (BMI): Calculated as weight (kg) divided by height squared (m^2) (Khanna et al., 2022).

Body Fat Percentage: Estimated using skinfold thickness measurements at triceps and subscapular sites using a Harpenden skinfold caliper (Baty International, UK). Measurements were taken three times at each site by a trained assessor, and the average was used. Body fat percentage was calculated using age- and gender-specific equations (Slaughter et al., 1988).

Physical Fitness Tests

Flexibility (Sit-and-Reach Test): Participants sat with legs extended and feet against a calibrated sit-and-reach box (Baseline® Sit-and-Reach Box, Fabrication Enterprises, USA). With hands overlapped and palms down, participants slowly reached forward as far as possible, holding the maximum reach for 2 seconds. The distance reached was measured to the nearest 0.5 cm. Two trials were performed with 1-minute rest between trials, and the best score was recorded (Baltaci et al., 2003). The sit-and-reach box was checked and calibrated according to the manufacturer's instructions prior to data collection.

Muscular Endurance (Modified Curl-Up Test): Participants performed curl-ups at a cadence of 20 repetitions per minute (guided by a metronome set to 20 BPM) until exhaustion or 75 repetitions, whichever came first. A calibrated digital metronome (e.g., Soundbrenner Spark; Hong Kong / Germany) was used to ensure precise cadence. Proper form was demonstrated, and the test was terminated if participants could not maintain pace or proper technique for two consecutive repetitions (Macfarlane, 1993). The total number of correctly performed curl-ups was recorded.

Cardiovascular Endurance (6-Minute Walk Test): Following standardized protocols for individuals with intellectual disabilities, participants walked as far as possible in 6 minutes on a marked 30-meter indoor course. Encouragement was provided at regular intervals using standardized phrases (Elmahgoub et al., 2012). The total distance covered (in meters) was recorded using a calibrated digital stopwatch (CASIO HS-80TW, Casio Computer Co., Ltd., Tokyo, Japan) to ensure precise timing and consistency across all trials.

Physiological Measurements

Resting Heart Rate (RHR): Measured after 10 minutes of quiet sitting using a heart rate monitor (Polar H10, Finland). Three measurements were taken at 2-minute intervals, and the average was calculated.

Vital Capacity (VC): Measured using a portable spirometer (Micro Plus Spirometer, CareFusion, UK) following American Thoracic Society guidelines. Participants performed forced vital capacity maneuvers in a standing position. Three acceptable trials were performed with at least 1-minute rest between trials, and the highest value was recorded.

Unified Rhythmic Activity Intervention

Music selection for the intervention involved choosing age-appropriate and culturally familiar songs with clear rhythmic patterns and tempos ranging from 100 to 130 bpm. These musical choices were intended to maintain participants' engagement while providing consistent auditory cues to support movement timing. Adaptations were incorporated

Table 2. Unified Rhythmic Activity Intervention

Component	Description
Training Frequency & Duration	3 sessions/week for 12 weeks (36 sessions total); each session = 45 minutes. Conducted by a qualified Adapted Physical Education instructor experienced with children with intellectual disabilities.
Session Structure	Warm-up (10 min): Light aerobic movements and dynamic stretching to music (100–110 bpm). Main Activity (30 min): Rhythmic movement patterns including: • Basic locomotor skills (walking, marching, skipping) synchronized to music. • Dance-based steps (grapevine, step-touch, chassé). • Simple choreographed patterns (4–8 counts). • Partner and group activities to enhance social interaction. • Gradual progression from simple to complex sequences over the 12 weeks. Cool-down (5 min): Gentle stretching and breathing exercises to slow music (60–70 bpm).
Progression Plan	Weeks 1–4: Emphasis on basic rhythmic patterns, tempo consistency, and familiarization with movements. Weeks 5–8: Inclusion of partner activities, increased complexity of steps, and introduction of slightly faster tempos. Weeks 9–12: Advanced choreographed sequences, group formations, and diverse musical styles.
Music Selection	Age-appropriate, culturally familiar songs; rhythmic clarity with tempo range of 100–130 bpm; music used to maintain engagement and provide timing cues.
Adaptations & Supports	Simplified movements when needed, visual demonstrations, physical prompts, peer assistance, and mastery-oriented positive feedback throughout.

based on individual participant needs, including simplified movement sequences, visual demonstrations, physical prompting, and opportunities for peer support. Throughout the sessions, positive reinforcement and mastery-oriented feedback were emphasized to encourage confidence and skill development. The control group, in contrast, continued with their regular school schedule, which included standard physical education classes conducted twice a week for 30 minutes each, consisting of general activities such as free play, ball games, and basic exercises without any structured rhythmic activity intervention.

Statistical Analysis

Data are presented as mean $\pm$ standard deviation (SD). Normality was assessed using the Shapiro-Wilk test. A

two-way (2 groups $\times$ 2 time points) mixed-design ANOVA was used to analyze the effects of group (experimental vs. control) and time (pre vs. post) on all dependent variables. Partial eta squared (η_p^2) was used as the effect size measure for ANOVA, interpreted as small (<0.06), moderate (0.06–0.13), or large (≥ 0.14). For significant interactions, paired t-tests were conducted to assess within-group changes, and independent t-tests were used to compare between-group differences at post-intervention. Hedges' g was calculated for effect sizes of t-tests and interpreted as trivial (<0.2), small (0.2–0.6), moderate (>0.6 –1.2), or large (>1.2). Percentage change was calculated as $[(\text{post-mean} - \text{pre-mean})/\text{pre-mean}] \times 100$. Statistical significance was set at $p \leq 0.05$. All analyses were performed using SPSS version 26.0 (IBM Corporation, Armonk, NY, USA).

Results

Main Effect of Time and Group $\times$ Time Interaction

Significant main effects of time were observed for flexibility ($F=78.42$, $p<0.001$, $\eta_p^2=0.68$), muscular endurance ($F=42.15$, $p=0.002$, $\eta_p^2=0.54$), cardiovascular endurance ($F=86.34$, $p<0.001$, $\eta_p^2=0.72$), RHR ($F=31.28$, $p=0.008$, $\eta_p^2=0.48$), and VC ($F=38.91$, $p=0.001$, $\eta_p^2=0.58$). No significant main effect of time was observed for BMI ($F=2.18$, $p=0.152$) or body fat percentage ($F=3.42$, $p=0.074$).

Significant group $\times$ time interactions were reported for flexibility ($F=68.34$, $p<0.001$, $\eta_p^2=0.62$), muscular endurance ($F=38.72$, $p=0.003$, $\eta_p^2=0.51$), cardiovascular endurance ($F=72.18$, $p<0.001$, $\eta_p^2=0.65$), and RHR ($F=28.45$, $p=0.012$, $\eta_p^2=0.42$). No significant interactions were observed for BMI ($F=0.86$, $p=0.362$), body fat percentage ($F=2.91$, $p=0.098$), or VC ($F=3.28$, $p=0.082$).

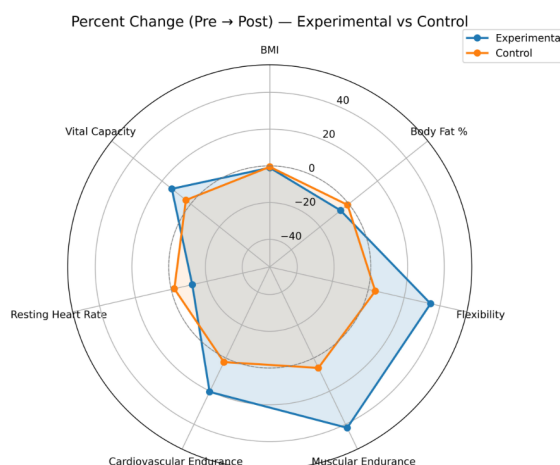


Fig. 2. Radar chart showing percent changes from pre- to post-intervention, with the experimental group demonstrating greater improvements across most variables

Within-Group Changes

The experimental group demonstrated significant improvements across multiple variables, including flexibility ($p<0.001$, $g=1.45$, $\Delta\%=+34.78$), muscular endurance ($p<0.001$, $g=1.34$, $\Delta\%=+42.15$), cardiovascular endurance

Table 3. Statistical Outcomes for Both the Groups

Dependent Variables	Group	Baseline	Post 12 Weeks	Δ % (Mean)	Hedges' g	Main Effect: Time			Interaction: Time $\times$ Group		
		Mean $\pm$ SD				F	p	η_p^2	F	p	η_p^2
BMI (kg/m ²)	Experimental	20.3 $\pm$ 3.2	20.1 $\pm$ 3.1	-0.99	0.06	2.18	0.152	0.07M	0.86	0.362	0.03S
	Control	19.9 $\pm$ 2.9	19.8 $\pm$ 2.8	-0.50	0.03						
Body Fat (%)	Experimental	24.6 $\pm$ 5.4	23.2 $\pm$ 5.1	-5.69	0.26	3.42	0.074	0.11M	2.91	0.098	0.09M
	Control	23.8 $\pm$ 4.9	23.6 $\pm$ 4.8	-0.84	0.04						
Flexibility (cm)	Experimental	18.4 $\pm$ 4.2	24.8 $\pm$ 4.6*	+34.78	1.45	78.42	<0.001	0.68L	68.34	<0.001	0.62L
	Control	17.9 $\pm$ 3.8	18.6 $\pm$ 3.9	+3.91	0.18						
Muscular Endurance (reps)	Experimental	22.3 $\pm$ 6.8	31.7 $\pm$ 7.2*	+42.15	1.34	42.15	0.002	0.54L	38.72	0.003	0.51L
	Control	21.8 $\pm$ 6.2	23.1 $\pm$ 6.5	+5.96	0.20						
Cardiovascular Endurance (m)	Experimental	412.5 $\pm$ 48.3	496.8 $\pm$ 52.6*	+20.44	1.68	86.34	<0.001	0.72L	72.18	<0.001	0.65L
	Control	408.2 $\pm$ 45.7	418.3 $\pm$ 46.9	+2.47	0.22						
Resting Heart Rate (bpm)	Experimental	88.6 $\pm$ 8.4	78.2 $\pm$ 7.6*	-11.74	1.29	31.28	0.008	0.48L	28.45	0.012	0.42L
	Control	87.3 $\pm$ 7.9	85.8 $\pm$ 8.1	-1.72	0.19						
Vital Capacity (L)	Experimental	1.82 $\pm$ 0.34	2.06 $\pm$ 0.38*	+13.19	0.66	38.91	0.001	0.58L	3.28	0.082	0.10M
	Control	1.78 $\pm$ 0.31	1.84 $\pm$ 0.33	+3.37	0.19						

Note: * – significant difference from pre to post, η_p^2 – partial eta squared. BMI = Body Mass Index. L – large, M – moderate, S – small.

($p < 0.001$, $g = 1.68$, $\Delta\% = +20.44$), resting heart rate ($p < 0.001$, $g = 1.29$, $\Delta\% = -11.74$), and vital capacity ($p = 0.008$, $g = 0.66$, $\Delta\% = +13.19$). In contrast, the control group showed no significant changes in any of the assessed variables, with all p -values exceeding 0.05 and effect sizes remaining small ($g < 0.22$).

Between-Group Comparisons at Post-Intervention

Independent t -tests at post-intervention revealed significantly better outcomes in the experimental group compared to control for flexibility ($t = 4.82$, $p < 0.001$, $g = 1.38$), muscular endurance ($t = 4.21$, $p < 0.001$, $g = 1.24$), cardiovascular endurance ($t = 5.34$, $p < 0.001$, $g = 1.56$), and RHR ($t = -3.78$, $p = 0.001$, $g = 0.92$). No significant between-group differences were found for BMI, body fat percentage, or VC at post-intervention.

Discussion

This randomized controlled trial demonstrated that a 12-week unified rhythmic activity intervention significantly improved flexibility, muscular endurance, cardiovascular endurance, and resting heart rate in children with mild intellectual disability. The large effect sizes observed for these variables ($\eta_p^2 = 0.42$ -0.72) and substantial percentage improvements (11.74-42.15%) indicate clinically meaningful changes that extend beyond statistical significance.

The experimental group demonstrated a remarkable 34.78% improvement in flexibility compared to only 3.91% in the control group. This substantial gain (6.4 cm mean improvement) aligns with previous research showing that rhythmic movement programs enhance range of motion in individuals with developmental disabilities (Teixeira-Machado & DeSantana, 2019). The repetitive, controlled stretching movements inherent in rhythmic activities,

combined with the gradual progression in movement complexity, likely contributed to these improvements. Enhanced flexibility has important functional implications for children with intellectual disabilities, potentially improving posture, reducing injury risk, and facilitating activities of daily living (Farrokhan et al., 2021).

Muscular endurance, measured by the modified curl-up test, improved by 42.15% in the experimental group (9.4 repetitions gain) compared to 5.96% in controls. This finding is consistent with previous studies reporting improved muscular fitness following dance-based interventions in children with disabilities (Joung et al., 2020). The continuous, moderate-intensity movements performed during rhythmic activities likely imposed sufficient muscular demands to stimulate neuromuscular adaptations.

The improvement in core muscular endurance has particular relevance for this population, as adequate core strength is essential for postural control, balance, and functional movement (Shields, 2013). Children with intellectual disabilities often exhibit reduced core strength compared to typically developing peers, contributing to movement difficulties and reduced participation in physical activities (Hartman et al., 2017). The observed improvements suggest that rhythmic activities provide an effective and enjoyable means of developing this critical fitness component.

The 20.44% improvement in 6-minute walk distance (84.3 meters gain) in the experimental group, with large effect size ($g = 1.68$), demonstrates substantial enhancement in cardiovascular fitness. This improvement is particularly noteworthy given that children with intellectual disabilities typically exhibit lower cardiovascular fitness than their typically developing peers and rarely engage in sufficient moderate-to-vigorous physical activity (MVPA) to improve aerobic capacity (Ptomey et al., 2017).

Importantly, the improvement in functional walking capacity has direct implications for daily life activities

and community participation. Enhanced cardiovascular fitness may enable children with intellectual disabilities to participate more fully in school activities, recreational pursuits, and social interactions that require sustained physical effort (Teixeira-Machado et al., 2019).

The 11.74% reduction in resting heart rate (10.4 bpm decrease) in the experimental group represents a physiologically significant adaptation indicating improved cardiovascular efficiency. Reduced resting heart rate is a well-established marker of cardiovascular fitness and is associated with reduced cardiovascular disease risk (Collins & Staples, 2017). This finding is particularly important given that individuals with intellectual disabilities exhibit higher prevalence of cardiovascular risk factors and metabolic syndrome compared to the general population (Zhang et al., 2017).

While the experimental group showed a modest reduction in body fat percentage (5.69% decrease), this change did not reach statistical significance, and no significant group $\times$ time interaction was observed. This finding contrasts with some previous studies reporting significant body composition improvements following physical activity interventions in individuals with intellectual disabilities (McGarty et al., 2018). Several factors may explain this outcome.

The 12-week intervention was sufficient to improve physical fitness but may have been too short to produce significant changes in body composition, particularly without dietary control. Additionally, the moderate intensity and frequency of rhythmic activities (45 minutes, three times per week) may not have generated the energy deficit necessary for fat mass reduction. Notably, improvements in physical fitness were observed independently of changes in body composition, suggesting that meaningful health benefits may occur even in the absence of substantial weight loss (Blair & Church, 2004). Both groups improved in vital capacity, with the experimental group showing a moderate effect ($g = 0.66$), suggesting potential respiratory benefits with longer intervention duration.

The rhythmic breathing patterns coordinated with movement during rhythmic activities may have contributed to improved respiratory muscle strength and coordination. Additionally, the aerobic nature of the activities may have promoted more efficient breathing patterns and enhanced respiratory function (Liem et al., 2015). Improved vital capacity has functional implications for speech production, sustained physical activity, and overall respiratory health.

Limitations

The study had several limitations including small sample size limiting subgroup analysis, single-site design affecting generalizability, lack of long-term follow-up to assess benefit retention, intervention specificity to one program type, challenges with assessor blinding, and absence of dietary and outside physical activity monitoring. Additionally, motivation and expectancy effects from the novelty and social interaction may have influenced outcomes beyond specific exercise effects.

Future Research Directions

Future research should include larger multi-site trials for enhanced generalizability, extended follow-up

periods at 3, 6, and 12 months post-intervention, dose-response studies, comparative effectiveness analyses against other interventions, mechanism studies incorporating neuroimaging and psychological assessments, cost-effectiveness evaluations, inclusion of moderate to severe intellectual disabilities and adult populations, technology integration, combined intervention approaches with nutrition, and qualitative research to understand participant experiences.

Conclusion

This randomized controlled trial demonstrates that a 12-week unified rhythmic activity intervention significantly improves flexibility, muscular endurance, cardiovascular endurance, and resting heart rate in children with mild intellectual disability, with large effect sizes indicating clinically meaningful changes. Future research with larger samples, longer intervention periods, and extended follow-up assessments will help refine our understanding of optimal program characteristics and long-term sustainability of benefits. Additionally, examining the effects of rhythmic activity on broader outcomes including cognitive function, behaviour, quality of life, and social participation would provide a more comprehensive picture of intervention benefits.

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AI Transparency

In the preparation of this manuscript, we utilized paperpal AI, as an assistive tool for editing, paraphrasing and improving the language. All AI-generated contents were thoroughly reviewed, verified, and edited by the authors.

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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Вплив інтервенції з ритмічного моторного навчання на обрані фізичні та фізіологічні показники дітей із легкою інтелектуальною недостатністю

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Цілі. Мета цього експериментального дослідження полягала у вивченні впливу 12-тижневої інтервенції з уніфікованої ритмічної активності на обрані фізичні та фізіологічні параметри дітей із легкою інтелектуальною недостатністю.

Матеріали та методи. Тридцять дітей (віком 10–14 років) із діагнозом легка інтелектуальна недостатність (IQ 50–70) були розподілені за методом рандомізації на експериментальну (n = 15) та контрольну (n = 15) групи. Експериментальна група брала участь у структурованій програмі уніфікованої ритмічної активності, тоді як контрольна група продовжувала навчання за стандартною шкільною програмою. На перед- та постінтервенційному етапах проведено аналіз таких показників: індекс маси тіла (ІМТ), відсоток жирової маси в організмі, гнучкість, м'язова витривалість, серцево-судинна витривалість, частота серцевих скорочень (ЧСС) у стані спокою та життєва ємність легень (ЖЕЛ). Для оцінки основних ефектів та ефекту взаємодії було застосовано двофакторний дисперсійний аналіз змішаного дизайну (2 групи × 2 часові точки).

Результати. Значущий основний ефект часу було виявлено для показників гнучкості ($p < 0.001$, $\eta_p^2 = 0.68$), м'язової витривалості ($p = 0.002$, $\eta_p^2 = 0.54$), серцево-судинної витривалості ($p < 0.001$, $\eta_p^2 = 0.72$), ЧСС у стані спокою ($p = 0.008$, $\eta_p^2 = 0.48$) та ЖЕЛ ($p = 0.001$, $\eta_p^2 = 0.58$). Крім того, встановлено значущі ефекти взаємодії група × час для гнучкості ($p < 0.001$, $\eta_p^2 = 0.62$), м'язової витривалості ($p = 0.003$, $\eta_p^2 = 0.51$), серцево-судинної витривалості ($p < 0.001$, $\eta_p^2 = 0.65$) та ЧСС у стані спокою ($p = 0.012$, $\eta_p^2 = 0.42$), причому експериментальна група продемонструвала суттєво кращі результати. Жодних істотних змін щодо ІМТ або відсотка жирової маси в організмі не спостерігалося.

Висновки. Інтервенція з використанням уніфікованої ритмічної активності призвела до суттєвого покращення гнучкості, м'язової витривалості, серцево-судинної підготовленості та частоти серцевих скорочень у стані спокою серед дітей із легкою інтелектуальною недостатністю. Отримані дані свідчать про доцільність включення тренувань на основі ритмічних рухів до програм адаптивного фізичного виховання з метою поліпшення фізичних та фізіологічних показників цієї групи населення.

Ключові слова: інтелектуальна недостатність, ритмічні рухи, фізична підготовленість, адаптивне фізичне виховання, серцево-судинне здоров'я.

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Technology-Enhanced Volleyball Training As an Educational Tool to Foster Perceptual-Cognitive Skills and Self-Perception in Youth

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Abstract

Objectives. The objective of this study was to analyse the educational effectiveness of an integrated training intervention conducted over one sporting year in youth volleyball players aged 10–13 years, aimed at developing perceptual-cognitive abilities, psychological characteristics, and inclusive participation in a sports learning environment.

Material and Methods. The study involved approximately 80 students, including participants diagnosed with attention deficit hyperactivity disorder (ADHD). The participants were divided into an experimental group and a control group. Training sessions were conducted twice a week and had a stable organizational structure with operational subgroups and 3×3 mini-tournaments. The control group followed a traditional training programme focused on the development of technical fundamentals, whereas the experimental group implemented playful and perceptual decision-making tasks supported by interactive light devices (reaction lights/Sportlights) designed to stimulate reaction speed, peripheral vision, and visual-motor coordination. A mixed-methods research design was applied, combining quantitative assessments with qualitative interviews involving students and coaches.

Results. The experimental group demonstrated more favourable outcomes in the development of perceptual-cognitive skills compared with the control group. In addition, participants in the experimental group reported higher levels of perceived competence and physical self-esteem. Qualitative data indicated increased engagement, motivation, and participation during training sessions.

Conclusions. The findings support the educational value of intentionally designed sports learning environments that integrate playful activities, technological tools, and traditional training methods. Such an approach may enhance perceptual-cognitive development, increase motivation, and promote inclusion in youth sports programmes.

Keywords: sport inclusion, ADHD, youth volleyball, attention, reaction time, peripheral vision, educational technologies, mixed-methods approach.

Introduction

During childhood, physical activity and sport play a key educational role, providing an ideal context for promoting overall personal development. Through movement, physical, cognitive, emotional and social dimensions intertwine, promoting meaningful learning processes, the construction of personal identity and the acquisition of transversal skills that are fundamental for everyday life (Siedentop, Hastie &

van der Mars, 2019). In a society characterised by increasing complexity and diversity, sport must move beyond a selective and purely performance-based vision to take on an educational and inclusive role, capable of responding to the diverse needs of those who practise it and valuing differences as a resource.

Youth sports contexts increasingly reflect the diversity of the social context, including participants with different learning styles, levels of development, cognitive traits and emotional-behavioural profiles. Among these, the presence of individuals with Attention Deficit Hyperactivity Disorder (ADHD) poses a significant challenge for coaches and

sports educators, who are forced to combine technical and performance objectives with special educational needs (Barkley, 2015). Difficulties in regulating attention, impulsivity, variability in activation levels and fatigue in maintaining focus on prolonged or repetitive tasks can negatively affect active participation, the quality of motor learning and the emotional experience of students, especially in the absence of structured and conscious methodological strategies (Gapin & Etnier, 2010; Pontifex et al., 2013).

For this reason, it is essential to rethink sports teaching methodologies in an inclusive way, orienting them towards the personalisation of the learning experience and the creation of stimulating, flexible and motivating environments. The coach thus takes on a central role not only as a technician but also as an educational mediator, capable of designing training sessions that take into account the different ways in which students process information and respond, in line with the principles of Universal Design for Learning applied to the motor-sports context.

The introduction of play as an educational tool, together with the use of innovative teaching technologies, such as interactive light devices (spotlights), is an appropriate response to the need for inclusion and differentiation in teaching (Di Palma et al., 2025; Susanto et al., 2024). Play, being intrinsically motivating, promotes active involvement, emotional participation and reduced performance anxiety, which are very important aspects for those who have difficulty maintaining attention (Csikszentmihalyi, 1990; Pesce et al., 2016). Electronic devices, on the other hand, allow for variable, immediate and controllable stimuli to be offered, which are useful for stimulating selective attention, peripheral vision and response speed, while promoting self-regulation and real-time decision-making processes (Renshaw et al., 2019).

The combined use of playful methodologies, technological tools and traditional practices also facilitates the transfer of skills acquired in training to real game situations, especially in situational sports such as volleyball, which are characterised by high perceptual-decision complexity and rapid changes in context (Araújo, Davids & Hristovski, 2006; Chow et al., 2021). In this sense, the sporting experience becomes an educational laboratory in which students, including those with ADHD, can experience success, strengthen their sense of competence and develop skills that are useful not only in sport but also in everyday life.

Taking these considerations into account, inclusion in sport is not just an adaptation of activities, but represents a conscious choice from a cultural and pedagogical point of view, aimed at promoting psychological and physical well-being, active participation and the sustainable and harmonious development of the individual (Dempsey, 2020).

Despite the growing interest in perceptual-cognitive training and technology-enhanced learning environments in youth sport, empirical studies examining the educational impact of such approaches in real training contexts remain limited. In particular, while several studies highlight the potential of ecological and constraints-led training environments to enhance perceptual decision-making and motor adaptability (Araújo, Davids & Hristovski, 2006; Chow et al., 2021; Renshaw et al., 2019), relatively few investigations have explored how technology-supported perceptual-cognitive training can influence not only motor

performance but also psychological variables such as self-perception, motivation and inclusion in youth athletes.

Moreover, the application of interactive technological devices in youth sport training—such as reaction lights designed to stimulate attention, peripheral vision and rapid decision-making—has been mainly examined in laboratory settings or short-term experimental protocols, whereas evidence from long-term educational interventions in authentic sports environments remains scarce. This gap is particularly relevant when considering inclusive sport contexts involving young athletes with heterogeneous cognitive and attentional profiles, including individuals diagnosed with Attention Deficit Hyperactivity Disorder (ADHD).

In light of these considerations, the present study aims to contribute to the literature by investigating the educational effectiveness of a technology-enhanced volleyball training programme implemented over an entire sporting season. Specifically, the study examines whether integrating playful learning strategies, perceptual-decision-making tasks and interactive light devices within youth volleyball training can support the development of perceptual-cognitive skills, enhance students' physical self-perception and promote inclusive participation.

Accordingly, the research addresses the following research questions:

RQ1: Does a technology-enhanced training programme lead to greater improvements in perceptual-cognitive skills (reaction time and peripheral vision) compared with traditional volleyball training?

RQ2: Does participation in a perceptual-cognitive and game-based training environment positively influence students' physical self-perception and perceived motor competence?

RQ3: How do students and coaches perceive the educational and inclusive value of technology-supported perceptual-cognitive training within a youth volleyball context?

Based on previous research on ecological dynamics and perceptual-cognitive training in sport (Araújo et al., 2006; Renshaw et al., 2019; Chow et al., 2021), it is hypothesised that students participating in the technology-enhanced training programme will demonstrate greater improvements in perceptual-cognitive performance and physical self-perception compared with those following a traditional technical training programme.

Aims of the research

This study aims to investigate the effectiveness of an integrated educational intervention, lasting one sporting year, designed and implemented within a youth volleyball team. The research aims to examine whether the combined use of playful methodologies, traditional tools and innovative technologies can generate significant effects in the development of students' perceptual-cognitive and psychological skills, in accordance with the findings in the literature on motor learning and the use of enhanced learning environments in youth sport (Siedentop et al., 2019; Chow et al., 2021; Latino et al., 2021).

Specifically, the objective is to evaluate the improvement in peripheral vision and reaction times to visual stimuli, which are fundamental skills in situational sports characterised by

rapid environmental changes and high perceptual-decision demands (Araújo et al., 2006). At the same time, the study aims to investigate the enhancement of attentional processes and decision-making speed during the different phases of play, elements closely linked to performance quality and active participation of students, especially in developmental age (Pesce et al., 2016; Renshaw et al., 2019).

Another objective is to analyse perceived self-esteem in sporting abilities, which is seen as a fundamental variable for psychological well-being, motivation and continuity in sporting activities during childhood (Harter, 2012). Finally, the study aims to explore the role of educational intervention in promoting the inclusion and active involvement of students with Attention Deficit Hyperactivity Disorder (ADHD), analysing how inclusive and well-structured teaching strategies can positively influence their participation, sense of belonging to the group and overall quality of the sporting experience (Barkley, 2015; Pontifex et al., 2013).

Material and Methods

Research Design

The research was conducted using a mixed methodological approach, combining quantitative and qualitative tools, considered complementary for examining changes in terms of both performance and experience and education, in accordance with the principles of mixed methods research in motor and social sciences (Creswell & Plano Clark, 2008).

The quantitative analysis was conducted by comparing the results obtained in the pre-intervention (T0) and post-intervention (T1) phases in the two study groups (experimental group and control group).

Participants

The research sample consisted of approximately 80 students regularly enrolled in a volleyball club on the island of Ischia. Participants were selected from the club's youth teams and then divided into two groups: a sample group, which took part in an innovative educational programme, and a control group, which continued with the traditional training programme.

The sample consisted of both male and female students, with a prevalence of females, allowing the effects of the educational intervention to be observed in a context representative of the sporting reality in question.

In both groups, there were five students with a certified diagnosis of Attention Deficit Hyperactivity Disorder (ADHD), issued by healthcare professionals according to internationally recognised diagnostic criteria.

The criteria for inclusion in the study were clearly defined. All participants had to be regularly enrolled in the sports club's volleyball activities and attend weekly training sessions on a continuous basis. An additional criterion was the willingness to participate in the entire research process, including the initial and final assessment phases and the activities planned for the educational intervention. Participation was voluntary and accompanied by the written informed consent of parents or legal guardians, in accordance with the ethical principles of research in education and

sport. For pupils with ADHD, a certified clinical diagnosis was required in order to ensure the correct identification of specific educational needs and an appropriate interpretation of the results (Barkley, 2015).

An age range of 10 to 13 years was also identified, which was considered particularly significant from the point of view of motor, cognitive and emotional development. At this stage of their sporting career, pupils play volleyball at the second introductory level (the "red" level), which is still characterised by predominantly general training and no fixed specialisation in specific playing roles, as recommended by long-term athlete development models (Balyi, Way & Higgs, 2013).

Group Allocation

Participants were not assigned to groups by pure randomisation, but by a stratified allocation procedure, adopted in order to ensure the greatest possible homogeneity between the sample group and the control group with respect to the main potentially confounding variables.

In particular, participants were initially divided into homogeneous subgroups based on age group (10–11 years; 12–13 years), gender, level of sporting experience (years of volleyball practice) and the presence or absence of a certified diagnosis of Attention Deficit Hyperactivity Disorder (ADHD). Within each group, the students were then assigned to the two groups in order to obtain as balanced a distribution as possible of the characteristics considered, reducing the risk of systematic distortions in the results attributable to initial differences between the groups.

This procedure was found to be more compatible with the real sporting context and with the pre-existing organisation of the club's youth groups, allowing for the preservation of educational continuity and stability of the training groups, in line with the methodological recommendations for applied research in the field of motor and sports activities (Thomas, Nelson & Silverman, 2023).

Intervention

Common Structure

Training sessions were held twice a week and involved, for each session, approximately 20 students from the sample group and 20 students from the control group, within separate organisational contexts.

In both groups, the warm-up phase was identical in order to ensure equivalent starting conditions and reduce the risk of injury. This phase consisted of an initial moderate-intensity run, accompanied by various gaits, followed by joint mobilisation and muscle activation exercises, presented in the form of games.

The division into subgroups was also adopted to allow, at the end of each training session, mini 3-on-3 volleyball tournaments to be held within each group, in which the students competed exclusively with teammates belonging to the same sample or control group.

Control Group

After the warm-up phase, the control group continued with the traditional training programme, focused on learning

and consolidating the technical fundamentals of volleyball, game organisation and standard motor exercises, without the use of specific technological devices for perceptual-cognitive stimulation.

Experimental Group

In contrast, the sample group was progressively directed towards an innovative educational intervention, focused on the development of reactivity, speed of response to stimuli, peripheral vision and visuomotor skills, through the use of interactive light devices (spotlights).

The activities were organised into mini-challenges, with the aim of promoting attention, decision-making and active involvement of the students, in line with the constraints-led approach and training models based on the manipulation of environmental stimuli (Renshaw et al., 2019).

With regard to reactivity training, an initial exercise was suggested involving running sideways to the right and left within a three-metre area of the pitch. At a colour signal given by the instructor, the students had to respond promptly by running to the side “dens” of the relevant colour.

A further exercise involved the direct use of spotlights arranged within a square marked out by cones, where students had to orient their run according to randomly activated light stimuli.

To develop peripheral vision and hand-eye coordination, an exercise was introduced using a poster structured in coloured rows and columns, requiring rapid identification of stimuli and coordinated motor responses.

Additional exercises integrated perceptual stimuli with volleyball-specific skills, such as passing and blocking actions performed in response to light signals positioned on the ground or attached to the net.

The educational intervention was developed gradually, adjusting the difficulty of the exercises according to the characteristics and learning times of the students, with particular attention to those with ADHD.

Targeted strategies included short tasks, immediate stimuli, frequent rotation of activities and the use of immediate feedback and positive reinforcement (Barkley, 2015; Gapin & Etnier, 2010).

Procedure

The tests were administered at two distinct times: before the start of the educational intervention (pre-test, T0) and at the end of the sporting year (post-test, T1), keeping the environmental conditions, the organisation of the space and the settings of the devices unchanged.

Following the completion of the intervention, qualitative data were collected through semi-structured interviews conducted with students and coaches.

Measurements

Perceptual-Cognitive Measures

Specific physical tests aimed at assessing reaction times to visual stimuli were used. Interactive Spotlights (reaction lights) were used, controlled by a dedicated application managed by the instructor, allowing stimuli to be activated in a programmed and random mode.

The devices were placed on the ground within a marked area, maintaining a constant distance of approximately 2–3 metres. Each participant completed several trials, and reaction time was calculated as the average value of valid attempts.

Errors were excluded and repeated. All measurements were conducted by the same instructor following a standardised procedure.

Psychological Measures

To assess psychological variables, the Physical Self-Description Questionnaire – Short Form (PSDQ-S) was administered.

The tool was linguistically adapted to the 10–13 age group, including simplification of language and back-translation by an external bilingual translator.

The questionnaire assessed perceived motor competence, confidence in physical abilities and overall physical self-esteem using a Likert scale.

Internal consistency showed satisfactory Cronbach's α values ($\alpha > .70$).

Qualitative Data

Semi-structured interviews were conducted with students and coaches to explore perceptions, experiences and changes observed during the intervention.

The interviews addressed engagement, motivation, attention, decision-making, emotional experiences and inclusion.

Qualitative Procedure

The interviews involved 24 students (12 per group) and four coaches.

Students were selected through purposive sampling to ensure heterogeneity, including participants with ADHD.

Data collection took place at the end of the intervention in a familiar environment. Interviews lasted approximately 20–30 minutes for students and 30–40 minutes for coaches.

All interviews were audio-recorded and transcribed verbatim.

Data Analysis

Quantitative Analysis

Descriptive statistics (mean $\pm$ standard deviation) were calculated for each variable.

Inferential analysis was conducted using a two-way mixed ANOVA with:

between-subject factor: Group (experimental vs control)
within-subject factor: Time (pre-test vs post-test)

The level of statistical significance was set at $p < .05$.

Effect sizes were calculated using partial eta squared (η^2_p).

Qualitative Analysis

Qualitative data were analysed through thematic coding, including:

- exploratory reading;

- open coding;
- aggregation into categories;
- identification of themes.

Coding was conducted by two independent researchers. Discrepancies were resolved through consensus.

Credibility was ensured through triangulation, comparison between groups, informal member checking and thematic saturation.

Results

The results of the study are presented in accordance with the mixed-methods design and include quantitative and qualitative findings.

In the reaction tests carried out using interactive light devices (reaction lights), the experimental group showed a reduction in average reaction time from 820 ± 95 ms in the pre-test phase to 672 ± 88 ms in the post-test, corresponding to an improvement of 18%. In contrast, the control group recorded a more modest decrease, from 815 ± 90 ms to 766 ± 85 ms, with an overall reduction of 6%. The mixed ANOVA revealed a significant Group $\times$ Time interaction effect for reaction time ($F_{(1,72)} = 14.62$, $p < .001$, $\eta^2_p = .17$), indicating that the reduction in reaction time over time was significantly greater in the experimental group compared with the control group.

Similar results emerged with regard to visual perception skills. The experimental group showed an increase in average scores from 42.3 ± 6.1 to 51.6 ± 6.4 (+22%), while the control group showed a more limited increase from 43.0 ± 5.8 to 46.4 ± 6.0 (+8%). The mixed ANOVA showed a significant interaction effect between Group and Time ($F_{(1,72)} = 11.84$, $p = .001$, $\eta^2_p = .14$), indicating that the improvement in perceptual-visual abilities was significantly greater in the experimental group.

Analysis of the Physical Self-Description Questionnaire – Short Form (PSDQ-S) scores also revealed a more consistent improvement in the experimental group. In particular, the average score increased from 3.21 ± 0.41 to 3.66 ± 0.45 (+14%), while in the control group the increase was more modest (from 3.18 ± 0.39 to 3.31 ± 0.42 , +4%). The ANOVA results confirmed a significant Group $\times$ Time interaction effect ($F_{(1,72)} = 9.27$, $p = .003$, $\eta^2_p = .11$), suggesting that the technology-enhanced training programme produced a significantly greater improvement in perceived physical competence compared with traditional training.

A specific analysis was also conducted on students diagnosed with Attention Deficit Hyperactivity Disorder

Table 2. Results of the mixed ANOVA (Group $\times$ Time)

Variable	$F_{(1,72)}$	p	Partial η^2
Reaction time	14.62	<.001	.17
Perceptual-visual abilities	11.84	.001	.14
Physical self-esteem	9.27	.003	.11

(ADHD), who were present in both groups ($n = 5$ per group). Although the subgroup size was limited, inferential analyses were performed to explore whether the intervention produced similar patterns of change within this population. As in the main analysis, a mixed two-way ANOVA (Group $\times$ Time) was applied to examine differences between the experimental and control groups across the pre- and post-test phases.

In this subgroup as well, a trend consistent with that observed in the overall sample emerged, with even more pronounced improvements in the experimental group. In particular, students with ADHD in the experimental group showed a reduction in reaction time from 840 ± 110 ms in the pre-test to 672 ± 95 ms in the post-test (–20%), whereas the control group showed a smaller decrease from 835 ± 105 ms to 777 ± 98 ms (–7%). The mixed ANOVA revealed a significant Group $\times$ Time interaction effect for reaction time ($F_{(1,8)} = 6.42$, $p = .035$, $\eta^2_p = .45$), indicating that the reduction over time was significantly greater in the experimental group.

Similarly, indicators related to peripheral stimulus management improved more markedly in the experimental group, increasing from 41.0 ± 7.0 to 50.8 ± 7.5 (+24%), compared with a more limited increase in the control group from 41.5 ± 6.5 to 45.2 ± 6.8 (+9%). The interaction effect between Group and Time was also significant ($F_{(1,8)} = 5.31$, $p = .049$, $\eta^2_p = .40$), suggesting that the technology-enhanced training programme produced greater improvements in perceptual-visual processing among students with ADHD.

In terms of physical self-esteem, measured using the Physical Self-Description Questionnaire – Short Form (PSDQ-S), students with ADHD in the experimental group showed a more pronounced improvement, with scores increasing from 3.10 ± 0.45 to 3.60 ± 0.50 (+16%), while the control group showed a more modest increase from 3.15 ± 0.40 to 3.24 ± 0.42 (+3%). The mixed ANOVA confirmed a significant Group $\times$ Time interaction effect ($F_{(1,8)} = 4.88$, $p = .058$, $\eta^2_p = .38$), indicating a strong trend favouring the experimental intervention.

Although these findings should be interpreted cautiously due to the limited sample size of the subgroup, they suggest that the integrated educational intervention may have

Table 1. Pre-/post-test comparison between the experimental group and the control group for the quantitative variables analyzed

Variable	Group	n	Pre-test (T0) M $\pm$ SD	Post-test (T1) M $\pm$ SD	% Change
Reaction time (ms)	Experimental	38	820 $\pm$ 95	672 $\pm$ 88	–18
	Control	36	815 $\pm$ 90	766 $\pm$ 85	–6
Perceptual-visual abilities (composite score)	Experimental	38	42.3 $\pm$ 6.1	51.6 $\pm$ 6.4	+22
	Control	36	43.0 $\pm$ 5.8	46.4 $\pm$ 6.0	+8
Physical self-esteem (PSDQ-S)	Experimental	38	3.21 $\pm$ 0.41	3.66 $\pm$ 0.45	+14
	Control	36	3.18 $\pm$ 0.39	3.31 $\pm$ 0.42	+4

Table 3. ADHD subgroup – descriptive pre-/post-test comparison

Variable	Group	Pre-test (T0) M ± SD	Post-test (T1) M ± SD	% Change	F _(1,8)	p	η ² _p
Reaction time (ms)	ADHD Experimental (n = 5)	840 ± 110	672 ± 95	−20	6.42	.035	0.45
	ADHD Control (n = 5)	835 ± 105	777 ± 98	−7			
Peripheral vision (score)	ADHD Experimental (n = 5)	41.0 ± 7.0	50.8 ± 7.5	+24	5.31	.049	0.40
	ADHD Control (n = 5)	41.5 ± 6.5	45.2 ± 6.8	+9			
Physical self-esteem (PSDQ-S)	ADHD Experimental (n = 5)	3.1 ± 0.45	3.60 ± 0.50	+16	4.88	.058	0.38
	ADHD Control (n = 5)	3.15 ± 0.40	3.24 ± 0.42	+3			

a particularly positive impact on attentional regulation, perceptual processing and physical self-perception in students with ADHD.

The analysis of the transcripts was conducted following a multi-stage procedure: an initial exploratory reading, open coding, aggregation of codes into conceptual categories, and identification of emerging themes. The coding was carried out by two independent researchers; any interpretative discrepancies were discussed until a shared consensus was reached. The credibility of the results was further strengthened through the triangulation of sources (students and coaches), systematic comparison between the sample group and the control group, a form of informal member checking through the summary feedback of the content that emerged to some participants, and the achievement of thematic saturation, observed when the last interviews analysed did not produce any new relevant themes.

The interviews with the students in the sample group reveal a representation of the training experience that is strongly characterised in terms of active involvement and significance. The students describe the sessions as “more dynamic”, “less boring” and “more like real play”, highlighting how the presence of variable visual stimuli and structured exercises in the form of challenges encouraged greater concentration and constant participation. Many students report feeling “more attentive” and “more ready to react”, emphasising greater awareness of their response times and ability to read game situations. Activities with spotlights are often associated with the perception of more immediate and intuitive learning, facilitating understanding of when and how to act on the pitch.

One important aspect concerns the perception of one’s role within the team. Students in the sample group report greater confidence in their abilities, expressing the feeling of “making fewer mistakes” and “feeling useful during the game”. This perception is particularly evident during the 3 vs 3 mini tournaments, described as moments when it is possible to “immediately put into practice” what has been learned and experience successful situations, even for students who are less confident or have greater attention difficulties.

On the contrary, interviews with students in the control group reveal a more stable and traditional narrative of the sporting experience. While recognising the importance of technical training and the educational value of volleyball, the pupils refer to a lesser extent to perceived changes in attention and decision-making. Their descriptions focus mainly on improving fundamentals and the correct execution of technical movements, with less emotional involvement

and less awareness of the perceptual-cognitive processes related to the game.

A specific analysis of the interviews with students with ADHD highlights particularly significant differences. The pupils with ADHD in the sample group describe the activities as “easier to follow” and “less mentally tiring”, emphasising how the variety of stimuli and the brevity of the exercises helped them to maintain their attention and not “lose track” of the activity. There were frequent references to reduced frustration and greater personal satisfaction, associated with the possibility of succeeding in the tasks set and actively contributing to team play. These students also reported an increased sense of belonging to the group and a more positive perception of themselves as players.

The pupils with ADHD in the control group, while expressing appreciation for the sporting activity in general, showed greater difficulty in maintaining concentration during repetitive exercises and in the presence of prolonged waiting times. Their narratives reveal greater attentional fatigue and a lower perception of personal effectiveness, especially in the more structured and less dynamic phases of training.

Interviews with coaches confirm and elaborate on the students’ perceptions. Coaches in the sample group report noticeable changes in attentional behaviour, describing students as “more present”, “more responsive” and “more capable of making quick decisions” during exercises and small-sided games. Particular emphasis is placed on the improved participation of pupils with ADHD, who are described as less impulsive, more regulated and more involved in following instructions and working to deadlines. Coaches also highlight a more collaborative training atmosphere, characterised by greater peer interaction and a reduction in exclusionary or inattentive behaviour.

In the control group, coaches recognise progress mainly on a technical level, but report more modest changes in terms of attention, decision-making speed and the involvement of students with ADHD. Group dynamics are described as generally stable, but less oriented towards active participation and empowerment of students within the game.

Discussion

The findings of the present study suggest that the technology-enhanced training programme was associated with significantly greater improvements in perceptual-cognitive performance and physical self-perception compared with the traditional training approach. In particular, the experimental group showed statistically

significant improvements in reaction time, perceptual-visual processing and perceived physical competence, as indicated by the Group $\times$ Time interaction effects observed in the mixed ANOVA analyses. These results can be interpreted within the theoretical framework of ecological dynamics and the constraints-led approach to skill acquisition, which emphasise the role of environmental information and task constraints in shaping motor learning (Araújo, Davids, & Hristovski, 2006; Renshaw et al., 2019; Chow et al., 2021).

From this perspective, the integration of interactive light stimuli and game-based exercises may have increased the informational richness of the training environment, requiring athletes to continuously detect relevant cues and adjust their actions accordingly. The significant reduction in reaction times observed in the experimental group is consistent with the idea that repeated exposure to variable and unpredictable stimuli can enhance the coupling between perception and action, facilitating faster decision-making processes during sport performance (Renshaw et al., 2019). In situational sports such as volleyball, where players must constantly adapt to rapidly changing contexts, the ability to process visual information efficiently represents a key component of effective motor behaviour (Araújo et al., 2006; Chow et al., 2021).

The improvement observed in perceptual-visual abilities further supports this interpretation. Training tasks that required athletes to react to randomly activated light signals likely stimulated attentional orientation, peripheral visual awareness and rapid stimulus discrimination. According to ecological models of skill acquisition, such training conditions can enhance athletes' sensitivity to environmental affordances, thereby improving their ability to identify and act upon relevant opportunities for action within the game environment (Araújo et al., 2006; Chow et al., 2021). In this sense, the perceptual-decision-making demands embedded in the exercises may have contributed directly to the improvements observed in the experimental group.

Another relevant outcome concerns the psychological dimension of the intervention. The significant increase in PSDQ-S scores among students in the experimental group suggests that participation in the technology-enhanced programme may have contributed to strengthening students' perception of physical competence and self-confidence. This finding is consistent with theoretical perspectives emphasising the role of successful experiences and positive feedback in the development of self-perception during childhood (Harter, 2012; Marsh, Martin, & Jackson, 2010). In the present study, the use of short challenges, immediate feedback provided by the devices, and the possibility of experiencing repeated success during training tasks may have created conditions that supported the development of perceived competence.

Motivational theory also provides a useful framework for interpreting these results. According to self-determination theory, environments that support competence, autonomy and enjoyment can foster intrinsic motivation and sustained engagement in physical activity (Deci & Ryan, 2000; Csikszentmihalyi, 1990). The playful structure of the activities and the dynamic nature of the training tasks described by participants in the qualitative interviews suggest that the intervention may have created a learning climate characterised by higher levels of engagement and perceived challenge. These conditions are known to promote deeper

involvement and persistence in skill acquisition processes (Pesce et al., 2016).

The results relating to students with ADHD, although exploratory due to the small size of the subgroup, provide additional insights into the potential educational value of the intervention. The quantitative analyses indicate larger improvements in reaction time and perceptual-visual processing within the experimental subgroup, accompanied by positive perceptions reported in the qualitative interviews. These findings may be interpreted in light of research suggesting that structured, dynamic and stimulus-rich environments can support attentional regulation and cognitive engagement in individuals with ADHD (Barkley, 2015; Gapin & Etnier, 2010; Pontifex et al., 2013). The presence of short tasks, immediate stimuli and frequent activity changes may have reduced cognitive fatigue and facilitated sustained attention during training.

Importantly, the qualitative findings complement the quantitative results by providing insight into how the intervention was experienced by participants. Students in the experimental group described the training sessions as more engaging and cognitively stimulating, while coaches reported improvements in attentional behaviour and decision-making during game situations. This convergence between objective performance measures and subjective perceptions strengthens the interpretation that the intervention influenced both behavioural and experiential dimensions of learning. Such triangulation between quantitative and qualitative data is a central advantage of mixed-methods research designs, allowing a more comprehensive understanding of educational processes in sport contexts (Creswell & Plano Clark, 2008).

Overall, the qualitative analysis shows that the integrated educational intervention had a significant impact on the perceptions of pupils and coaches, helping to improve not only performance but also the quality of the sporting experience, emotional experience and relational dynamics. The integration of qualitative data with quantitative results reinforces the interpretation of the effectiveness of the intervention, confirming the value of playful, technologically supported and inclusive approaches in youth sport, with particular reference to students with ADHD.

Taken together, the findings of this study support the theoretical proposition that learning environments intentionally designed to manipulate informational constraints and incorporate perceptual-decision-making challenges can enhance both motor and psychological outcomes in youth sport. Within the framework of ecological dynamics, the integration of technological tools such as reaction lights may represent a practical strategy for increasing task variability and promoting adaptive behaviour in athletes. At the same time, the positive psychological responses reported by participants highlight the importance of designing training environments that are not only technically effective but also engaging and inclusive for young athletes.

Conclusions

The study suggests that an integrated educational intervention, based on the integration of playful methodologies, traditional technical training and the use of

interactive light devices (spotlights), may be associated with improvements in perceptual-cognitive skills and in certain psychological dimensions relevant to youth volleyball (Siedentop et al., 2019; Renshaw et al., 2019). In particular, a comparison of pre- and post-intervention measurements shows favourable trends in the sample group compared to the control group in terms of reaction times, functional indicators related to peripheral vision, and perception of physical competence/self-esteem. These results are consistent with the theoretical models of ecological dynamics and the constraints-led approach, according to which motor learning emerges from the interaction between the individual, the task and the environment and can be supported by the intentional design of stimuli and situational demands (Araújo et al., 2006; Chow et al., 2021; Renshaw et al., 2019). In situational sports such as volleyball, the ability to perceive relevant information, select useful signals and quickly transform them into appropriate motor actions is in fact a central component of effective participation in the game (Araújo et al., 2006; Chow et al., 2021).

With regard to students diagnosed with Attention Deficit Hyperactivity Disorder (ADHD), the quantitative and qualitative results should be interpreted exclusively in an exploratory manner, given the extremely small size of the subgroup ($n = 5$ per group). From this perspective, the data collected do not allow for robust inferences, but offer preliminary indications about the possible compatibility of short, varied activities supported by immediate feedback with some of the attentional and self-regulation needs typical of ADHD (Barkley, 2015; Pontifex et al., 2013). The perceptions that emerged from the interviews, which describe the experience as more accessible and less mentally tiring, contribute to outlining interpretative hypotheses that will need to be verified in future studies with larger samples and more controlled methodological designs (Gapin & Etnier, 2010).

The integration of quantitative and qualitative data allows for a more articulated reading of the intervention: the changes measured on the perceptual-motor level are accompanied by perceptions of greater involvement, confidence and sense of usefulness in the game, as well as observations by coaches who report changes in attentive behaviours and relational dynamics within the team. In this sense, the results support the idea that inclusion in sport is not limited to simple formal participation, but requires intentional design of the training environment, capable of offering differentiated and meaningful opportunities for learning and success for all students (Goodwin & Watkinson, 2000). Furthermore, the increase in the perception of physical competence/self-esteem is consistent with models that emphasise the role of successful experiences and feedback in self-consolidation during childhood (Harter, 2012; Marsh et al., 2010), as well as with motivational perspectives focused on intrinsic motivation and optimal engagement in activities perceived as challenging and meaningful (Csikszentmihalyi, 1990; Deci & Ryan, 2000).

While recognising the limitations inherent in a study conducted in a real-world setting — including the absence of randomisation, individual variability and the small size of some subgroups — this work provides useful insights for educational and sports practice. In particular, the systematic integration of perceptual-decision-making exercises supported by interactive technologies and combined with small-sided games (3 vs 3) may represent a potentially

replicable intervention model in youth sports, with possible positive effects on the quality of the sporting experience, motivation and active participation of students (Côté & Hancock, 2016; Renshaw et al., 2019). Future studies should expand the sample, include longitudinal follow-ups and adopt observational measures in a competitive context in order to verify the stability of the results and their transferability to official play, in line with the principles of integration and triangulation inherent in mixed methods designs (Creswell & Plano Clark, 2008).

Ethics Approval

The study was conducted in accordance with the ethical principles for research involving human participants. It was carried out within a regular educational and sports context and did not involve any invasive or high-risk procedures. Formal approval from an institutional ethics committee was not required in accordance with the local organizational conditions under which the study was conducted. All procedures complied with internationally accepted ethical standards in the field of education and sport.

Informed Consent

Written informed consent was obtained from the parents or legal guardians of all participants prior to their inclusion in the study. Participants were also informed about the aims and procedures of the research in an age-appropriate manner, and their participation was voluntary.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to the involvement of minors and ethical considerations related to privacy and confidentiality, the data are not publicly available.

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AI Transparency Statement

Artificial intelligence tools were not used in the design of the study, data collection, analysis, or interpretation of the results. AI-assisted tools may have been used solely for language editing and proofreading purposes, without affecting the scientific content of the manuscript.

Conflict of interest

The authors declare that they have no conflicts of interest.

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Тренування з волейболу з використанням сучасних технологій як освітній інструмент розвитку перцептивно-когнітивних навичок та самосприйняття юних спортсменів

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

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Мета. Метою дослідження було проаналізувати освітню ефективність інтегрованої тренувальної інтервенції, проведеної протягом одного спортивного року з юними волейболістами віком 10–13 років, спрямованої на розвиток перцептивно-когнітивних здібностей, психологічних характеристик та інклюзивної участі в середовищі спортивного навчання.

Матеріали та методи. До дослідження було залучено приблизно 80 учнів, серед яких були учасники з діагнозом розлад дефіциту уваги та гіперактивності (РДУГ). Учасники були розподілені на експериментальну та контрольну групи. Тренування проводилися двічі на тиждень і мали сталу організаційну структуру з робочими підгрупами та мінітурнірами

у форматі 3×3. Контрольна група займалася за традиційною програмою підготовки, зосередженою на розвитку технічних основ, тоді як в експериментальній групі впроваджувалися ігрові та перцептивні завдання на ухвалення рішень за підтримки інтерактивних світлових пристроїв (світлові тренажери реакції / Sportlights), розроблених для стимуляції швидкості реакції, периферичного зору та зорово-моторної координації. Було застосовано змішаний дизайн дослідження, що поєднував кількісне оцінювання з якісними інтерв'ю із залученням учнів та тренерів.

Результати. Експериментальна група продемонструвала кращі результати у розвитку перцептивно-когнітивних навичок порівняно з контрольною групою. Крім того, учасники експериментальної групи відзначили вищий рівень суб'єктивного відчуття компетентності та фізичної самооцінки. Якісні дані показали підвищення рівня залученості, мотивації та активності під час тренувальних занять.

Висновки. Результати підтверджують освітню цінність інтенційно спроектованих середовищ спортивного навчання, що інтегрують ігрову діяльність, технологічні інструменти та традиційні методи тренування. Такий підхід може сприяти перцептивно-когнітивному розвитку, підвищенню мотивації та впровадженню інклюзії в юнацьких спортивних програмах.

Ключові слова: інклюзія в спорті, РДУГ, юнацький волейбол, увага, час реакції, периферичний зір, освітні технології, змішаний метод дослідження.

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Enhancing Selective Attention in Youth Basketball: Cognitive and Physiological Outcomes of a Representative Training Intervention

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Abstract

Objectives. The study aimed to evaluate the effectiveness of a basketball training workshop designed to enhance selective attention and interference control in U-17 athletes through increased attentional load during practice.

Material and Methods. The study employed a mixed-methods experimental design. Forty competitive basketball players aged 16 years participated in the study and were divided into an experimental group (n = 21) and a control group (n = 19). Selective attention was assessed using the Stroop Colour and Word Test during the pre- and post-intervention phases. Qualitative data were collected through systematic observations and semi-structured interviews with athletes and coaches. The experimental intervention consisted of a basketball training programme that systematically manipulated task constraints and incorporated ecologically representative exercises aimed at increasing attentional demands.

Results. After six months of intervention, the experimental group demonstrated a significant reduction in the Stroop interference index compared to the control group. In addition, athletes in the experimental group showed significantly decreased response times and fewer errors in the incongruent condition of the test. Qualitative findings indicated the development of more effective attentional strategies, improved ability to filter irrelevant stimuli, enhanced control of impulsive responses, and faster recovery of attentional focus in stressful game situations.

Conclusions. The results suggest that a basketball training programme based on systematic manipulation of practice constraints and ecologically valid exercises can effectively support the development of selective attention and interference control in adolescent athletes. Such approaches may contribute to improved decision-making and performance in open-skill team sports.

Keywords: executive functions, selective attention, interference control, basketball, decision making, cognitive training.

Introduction

In contemporary team sports, athletic performance is increasingly interpreted as the result of dynamic interaction between physical, technical, tactical, and cognitive components. In particular, in contexts with high environmental and temporal complexity, such as basketball, the effectiveness of motor action depends largely on the athlete's ability to perceive, select, and use relevant information in extremely short times. From this perspective, performance cannot be reduced to automated

motor execution, but must be understood as a continuous perceptual-decision-making process, strongly mediated by higher cognitive functions. Among these, selective attention plays a central role. It can be defined as the ability to intentionally allocate attentional resources to stimuli that are functional to the task, while simultaneously inhibiting irrelevant or interfering information (Latino et al., 2021). In open-skill sports contexts, this ability is crucial for managing the simultaneity of stimuli and the unpredictability of game situations. Recent studies in cognitive neuroscience applied to sport emphasize that selective attention is closely linked to executive control and cognitive inhibition mechanisms, especially under time and competitive pressure (Diamond, 2013; Diamond and Ling, 2016; Best, 2019).

During adolescence, and particularly between the ages of 15 and 17, the neurocognitive systems responsible for attentional control and inhibition are still maturing. The literature highlights how, during this stage of development, executive functions are particularly sensitive to environmental stimuli and structured experiences, making the sporting environment a potentially privileged context for their development (Best and Miller, 2010; Diamond, 2013; Ludyga et al., 2020).

Numerous studies conducted in recent years indicate that sports practice, and in particular open-skill sports, is associated with higher levels of selective attention, cognitive flexibility, and inhibitory control compared to both sedentary individuals and athletes engaged in sports characterized by more predictable environments (Koch et al., 2021; Scharfen and Memmert, 2019; Vestberg et al., 2020). These results suggest that it is not the practice of sport itself that determines cognitive benefits, but the perceptual-decision-making nature of the demands imposed by the training and competition context. Recent studies have shown that structured sport-based educational laboratories can improve both executive functions and social inclusion in adolescents (Gravino et al., 2025).

Basketball is a prime example of a high-cognitive-intensity open-skill sport. Athletes are required to constantly monitor a multitude of visual and auditory stimuli—the position of the ball, the movements of teammates and opponents, available space, time remaining—selecting the most relevant information for the action in a fraction of a second. At the same time, they must inhibit impulsive responses and ineffective automatisms, especially under conditions of emotional stress and competitive pressure.

Methodologically, selective attention and interference control are frequently assessed using the Stroop Color and Word Test, which is still considered one of the most reliable tools for analyzing cognitive inhibition. Although the Stroop paradigm has historical origins, recent literature confirms its validity and use in studies on athletes and active populations, particularly for assessing changes in executive control processes associated with training and sports experience (Scarpina & Tagini, 2017; Koch et al., 2021).

At the same time, in recent years, a pedagogical-sports perspective has emerged that emphasizes the intentional design of training sessions as cognitive learning environments. In particular, Representative Learning Design and the constraints approach emphasize the importance of structuring exercises that maintain key information from the competition context, stimulating authentic decision-making processes and promoting the transfer of learned cognitive skills (Pinder et al., 2011; Renshaw et al., 2019). Despite the growing body of literature documenting the relationship between sport practice and executive functions, an important gap remains in understanding how specific training designs can intentionally stimulate these cognitive processes. Much of the existing research has focused on cross-sectional comparisons between athletes and non-athletes or between different types of sports, highlighting cognitive advantages associated with participation in open-skill disciplines. However, fewer studies have experimentally examined how training environments within sport practice can be deliberately structured to promote the development of executive functions.

Moreover, when cognitive training is investigated, it is often implemented through laboratory-based or decontextualized tasks that are only partially connected to the perceptual–motor demands of real sport situations. This creates a conceptual limitation: while sport performance emerges from dynamic interactions between perception, decision making, and action, many cognitive interventions isolate cognitive processes from the ecological context in which they normally operate.

From the perspective of Representative Learning Design and the constraints-led approach, cognitive development in sport should emerge from repeated exposure to tasks that preserve the informational and decision-making structure of the competitive environment. Training situations characterized by high informational density, time pressure, and variable rules may therefore stimulate selective attention and inhibitory control mechanisms by requiring athletes to continuously filter relevant cues, inhibit automatic responses, and update attentional priorities. However, empirical evidence on the effectiveness of such ecologically designed interventions in improving executive functions in adolescent athletes is still limited. In light of these theoretical assumptions, it seems relevant to investigate whether a basketball laboratory explicitly designed to increase attentional load and stimulus selection demands can produce measurable effects on selective attention in adolescent athletes.

Aim of the study is to evaluate the effectiveness of a six-month basketball workshop on the development of selective attention in 16-year-old athletes, using a mixed-methods experimental design.

Research Hypothesis. The athletes in the experimental group will show a significant improvement in selective attention and interference control scores on the Stroop test compared to the control group.

Qualitative data will highlight an evolution in attentional strategies, the ability to filter out distractions, and cognitive awareness of sporting action in the athletes in the experimental group.

Material and Methods

Research Framework

The research adopts an experimental design with an experimental group and a control group, integrating quantitative and qualitative methods. This approach allows for the analysis of both measurable changes in selective attention processes and behavioral and perceptual transformations experienced by athletes in the context of training and competition.

Participants

The sample consisted of 40 16-year-old basketball players involved in structured youth competitive activities.

- Experimental group (EG): 21 athletes involved in the laboratory with attentive focus.
- Control group (CG): 19 athletes who followed the regular training program.

All participants had at least five years of sporting experience, regular weekly training, and no neurological

or cognitive diagnoses. Informed consent was obtained from parents or legal guardians, in accordance with the ethical principles of sports research. A post-hoc statistical power analysis was conducted using G*Power software. Considering the total sample size ($N = 40$), an alpha level of .05, and the repeated-measures design adopted in the study, the analysis indicated adequate statistical power ($> .80$) to detect medium interaction effects between time and group.

Quantitative Tools: Stroop Color and Word Test

Selective attention was assessed using the Stroop Color and Word Test, administered pre-intervention (T0) and post-intervention (T1). The test comprises three standardized conditions:

- reading words,
- naming the color of neutral stimuli,
- naming the color of incongruent words.

The main indicator considered is interference control, obtained from the combined analysis of response times and errors in the incongruent condition with respect to color naming. This index reflects the ability to inhibit automatic responses and maintain attentional focus on the relevant rule.

Qualitative Analysis

Systematic Observations

During the intervention, structured observations of training sessions and game situations were conducted, focusing on attentional and decision-making behaviors. The categories observed included:

- manifestations of distraction,
- speed and quality of decisions,
- adaptation to changing rules,
- error management,
- functional communication with teammates.

The observations were recorded in structured diaries and analyzed to identify developmental patterns in attentive behavior.

Semi-structured Interview

At the end of the experimental intervention, semi-structured individual interviews were conducted with a subsample of athletes belonging to the experimental group and the control group, with the aim of exploring the subjective perception of attentional processes, distraction management strategies, and the transfer of attentional skills to the training and competition context.

The interviews took place in a quiet and familiar environment for the athletes and lasted between 20 and 30 minutes. All interviews were audio-recorded with prior consent, transcribed in full anonymously, and subsequently analyzed.

The interview outline was constructed in line with the theoretical framework of the study and divided into thematic areas, maintaining a flexible structure that allowed for in-depth exploration of the athletes' responses:

Area 1 – Perception of attention in the sporting context

1. How would you describe your level of attention during training and matches?

2. At what points in the game do you find it most difficult to maintain concentration?
3. What do you think are the main sources of distraction during a basketball game?

Area 2 – Selective attention and distraction management

4. When you are on the court, how do you know which information is really important for the action you are about to take?
5. Do you ever find yourself distracted during the game? If so, what happens at that moment?
6. Have you developed strategies to ignore irrelevant stimuli, such as noise, opponents, or previous mistakes? If so, what are they?

Area 3 – Interference control and cognitive inhibition

7. In situations of pressure or stress (e.g., little time left on the clock or aggressive defense), how does your thinking and decision-making change?
8. Do you ever have to block an impulsive action in order to choose a more effective solution? Can you give a concrete example?
9. Compared to the past, do you feel you are better able to control your automatic reactions during the game? In what way?

Area 4 – Laboratory experience and attentional load

10. How did you experience the laboratory exercises in which the rules or tasks changed frequently?
11. Which exercises required the most attention and why?
12. In your opinion, did these exercises change the way you pay attention on the field?

Area 5 – Cognitive awareness and self-regulation

13. Can you describe what happens in your mind before you make an important decision on the field?
14. Do you use personal routines (e.g., breathing, keywords, focusing your gaze) to help you concentrate?
15. Do you think you are more aware of your mental processes today than you were before the intervention? Why?

Area 6 – Transfer to the competition context

16. Have you noticed any changes in the way you play during official matches? In what specific situations?
17. Do you think that what you learned in the lab is transferable to game situations? Can you provide specific examples?
18. At what points in the game do you feel you manage your attention better than in the past?

Area 7 – Overall evaluation of the experience

19. How has the lab influenced the way you train and play?
20. If you had to explain to another athlete what you have learned in terms of attention and concentration, what would you say?
21. Is there anything you would change or improve in the workshop to make it more effective?

Methodological note

The questions were used as a flexible guide to encourage athletes to narrate their subjective experiences and to allow for further exploration based on their answers. The qualitative data analysis was conducted through thematic

analysis, using progressive coding of the transcripts, aimed at identifying recurring themes related to selective attention, interference control, self-regulation strategies, and the transfer of cognitive skills to the sporting context.

Experimental Activities

The basketball workshop was designed as an intentional integrated cognitive stimulation intervention, based on the principles of Representative Learning Design and the constraints approach, with the aim of enhancing selective attention and interference control through highly ecologically representative motor tasks. According to this perspective, learning and adaptation (Susanto et al., 2024b) emerge from the interaction between athlete, task, and environment, and are most effective when exercises maintain the perceptual and decision-making information typical of the real competitive context (Pinder et al., 2011; Renshaw et al., 2019).

The most recent literature on team sports highlights how cognitive training is most effective when it is not separated from motor action but integrated into tasks that simultaneously require perception, decision-making, and execution, thus promoting the transfer of cognitive skills to real play (Scharfen & Memmert, 2019; Vestberg et al., 2020; Ludyga et al., 2020). In this sense, the workshop was not conceived as 'isolated' cognitive training, but rather as a qualitative reorganisation of the usual technical-tactical exercises, aimed at increasing the attentional load and the need to select relevant stimuli.

The intervention was developed over a period of six months, with two sessions per week, integrated into the team's normal training program. Each session dedicated to the workshop lasted between 30 and 40 minutes and was included in the central part of the training, in order to ensure an adequate level of physical and cognitive activation, avoiding both conditions of excessive fatigue and low attentional activation.

The exercises were designed through the systematic manipulation of constraints, in particular:

- informational constraints, through the introduction of relevant visual and auditory stimuli (coaches' signals, color cues, keywords) and intentionally inserted irrelevant stimuli, with the aim of stimulating attentive selection;
- temporal constraints, progressively reducing the time available to make decisions, in order to increase cognitive pressure and the need to inhibit automatic responses;
- regulatory constraints, through frequent changes in the rules of the game (e.g., limitations on passes, conditions for valid baskets, sudden changes in objectives), to stimulate cognitive flexibility and continuous updating of attentional priorities;
- spatial constraints, modifying the size and configuration of the field, to alter the available perceptual information and require constant reorganization of visuospatial attention.

The progression of the intervention was structured in a gradual manner. In the initial stages, the exercises involved a limited number of simultaneous constraints, with the aim of promoting understanding of the attentional demands. In the subsequent stages, the complexity was increased by introducing more competing sources of information, situations

of numerical superiority and inferiority, and tasks with variable rules during the exercise. This progression is consistent with evidence indicating that controlled task variability promotes perceptual-decision adaptation and cognitive robustness in open-skill sports (Renshaw et al., 2019).

Particular emphasis was placed on the use of high-cognitive-intensity small-sided games, considered a privileged tool for training selective attention and decision making, as they reproduce in a simplified but representative form the informational demands of real play (Santos et al., 2018; Clemente et al., 2021). In such situations, athletes were constantly called upon to discriminate relevant stimuli, update their decisions, and inhibit impulsive responses, especially in the presence of sudden changes in game conditions.

Alongside the manipulation of constraints, the workshop included specific moments dedicated to the development of attentional routines and self-regulation strategies, such as the conscious use of breathing, focusing keywords, and attentional landmarks. The inclusion of these strategies is supported by recent studies highlighting the role of cognitive routines and attentional control in managing pressure and stabilizing performance in team sports (Larkin et al., 2021; Englert et al., 2020).

Overall, the intervention was designed as an intentional learning environment, in which selective attention was not trained directly or explicitly, but was continuously elicited through the structure of the task. This approach is in line with the latest literature, which emphasizes that the development of executive functions in sport emerges mainly from systematic exposure to cognitively demanding contexts, rather than from decontextualized exercises (Diamond & Ling, 2016; Ludyga et al., 2020).

Results

Quantitative Results

Analysis of the data obtained from the Stroop Color and Word Test revealed a pre-post differential trend between the experimental group (EG) and the control group (CG), indicating a specific effect of the intervention on interference control and, more generally, on selective attention processes. In the pre-intervention phase (T0), the two groups had a substantially overlapping profile in the incongruent condition, both in terms of response times and errors, suggesting a homogeneous baseline condition and reducing the likelihood that subsequent differences were attributable to initial inequalities. Descriptive statistics for the Stroop measures in both groups and measurement points are reported in Table 1. At baseline (T0), the experimental group (EG) and the control group (CG) showed comparable performance in the incongruent condition in terms of response times and error rates, supporting the assumption of initial equivalence between groups.

Pre-post trend in the incongruent condition (primary outcome)

After six months of intervention (T1), the EG showed a marked improvement in the incongruent condition, expressed by:

- a reduction in response times, with an average shift from approximately 48–50 s to 39–41 s ($\Delta \approx -9/-11$ s);
- a reduction in color naming errors, equal to approximately -22% compared to the initial values.

Table 1. Descriptive statistics for the Stroop measures in both groups

Group	Time	Response time (s)	Errors (n)	Interference index
Experimental group (EG)	T0	49.1 ± 4.7	12.3 ± 3.2	35.2 ± 5.8
Experimental group (EG)	T1	40.0 ± 4.2	9.6 ± 2.5	28.6 ± 5.1
Control group (CG)	T0	48.7 ± 4.5	12.1 ± 3.0	34.8 ± 5.6
Control group (CG)	T1	46.4 ± 4.4	11.9 ± 2.9	33.1 ± 5.3

This combination of outcomes is particularly relevant as it indicates an improvement that is not limited to speed of execution but also involves accuracy: the EG responded faster without paying a cost in terms of increased errors, but rather showing a decrease in errors. In functional terms, this is consistent with an enhancement of the ability to maintain the attentional rule (naming the color) and inhibit interfering automatism (reading the word) in conditions of conflict.

In the CG, on the contrary, the pre-post trend was modest and unsystematic:

- reduction in incongruent times in the order of 2–3 s;
- no consistent reduction in errors, with fluctuations not attributable to a stable pattern of improvement.

Overall, these data indicate that the improvement observed in the EG cannot be explained solely by familiarization with the procedure or by a generic effect of sports training, since the GC—despite training regularly—does not show a comparable trajectory.

Stroop interference index (composite outcome)

Considering the synthetic interference control indicator (derived from the combined analysis of times and errors in the condition inconsistent with color naming), the EG showed an average reduction in interference of 18–20%, while in the GC the reduction was limited and less than 5%. The magnitude of the difference between groups, combined with the consistency between components (times and errors), suggests that the intervention acted on a specific executive construct—inhibition and attentive selection—rather than on a generic processing speed.

Repeated measures ANOVA revealed a significant main effect of time, $F(1,38) = 18.42$, $p < .001$, indicating an overall pre-post change across participants. Confidence intervals were also calculated to provide an estimate of the precision of the observed effects.

More importantly, a significant time $\times$ group interaction emerged, $F(1,38) = 9.87$, $p = .003$, $\eta^2p = .21$. Repeated measures analysis confirmed the presence of:

- a main effect of time, $F(1,38) = 18.42$, $p < .001$, indicative of an overall pre-post change;
- above all, a significant time $\times$ group interaction, $F(1,38) = 9.87$, $p = .003$, $\eta^2p \approx .21$.

According to conventional benchmarks, this value corresponds to a medium-to-large effect size, indicating a substantial difference in the evolution of interference control between the two groups.

The significance of the interaction, together with the effect size ($\eta^2p \approx .21$, medium-high), indicates that the

change over time is not uniform in the two groups, but is differentiated and therefore plausibly attributable to the experimental component of the program (systematic increase in attentional load through informational, temporal, and regulatory constraints). The analysis of simple effects further specified this result, showing that the pre-post improvement is statistically significant in the EG ($p < .001$) and not significant in the GC ($p > .10$). In interpretative terms, this supports the hypothesis that the intervention produced a specific gain in interference control compared to ordinary training.

Improvement profile: efficiency, accuracy, and stability

In addition to statistical significance, the data describe an improvement with three relevant characteristics:

1. Efficiency: the reduction in time in the incongruent condition in the EG ($\approx -9/-11$ s) suggests greater speed in implementing the correct rule in the presence of stimulus-response conflict.
2. Accuracy: the simultaneous reduction in errors ($\approx -22\%$) indicates an increase in precision in selecting relevant information (color) and filtering out interference (word). This pattern is particularly informative because a simple increase in speed could, in some cases, be accompanied by an increase in errors (speed-accuracy trade-off). In the EG, on the other hand, the trajectory is consistent with a real improvement in executive control.
3. Stability of attentional control: a further significant element concerns the reduction in intra-individual variability in the EG at post-test, highlighted by the decrease in score dispersion. This result suggests not only an average improvement, but also greater consistency of performance under conditions of interference, i.e., a form of “robustness” of attentional control. In the GC, variability remained essentially unchanged, indicating less stable control that is more susceptible to fluctuations.

Exclusion of alternative interpretations

In the context of a pre-post design with a control group, some alternative factors are partially contained:

- Practice/test-retest effect: potentially present in both groups; however, the magnitude of change in the EG and the modest variation in the CG suggest that familiarization is not sufficient to explain the effect.
- Neurocognitive maturation: plausible in adolescence and expected in both groups; again, the time $\times$ group interaction indicates that the increase is greater in the SG than expected for maturation or ordinary training.
- General sports training: both groups are competitive athletes; the difference between trajectories reinforces the interpretation that it is the component of constraint manipulation and increased attentional load that produces the additional effect.

Overall, the quantitative results show that the high attentional demand basketball laboratory is associated with a significant and specific improvement in Stroop interference control. This improvement manifests itself as: (a) a consistent reduction in incongruent times, (b) a parallel reduction in errors,

(c) a decrease in the interference index of 18–20% in the EG versus <5% in the GC, (d) a significant time $\times$ group interaction with a medium-high effect size, and (e) greater intra-individual stability at post-test. These elements, considered together, indicate a measurable enhancement of selective attention and cognitive inhibition processes in conflict conditions, consistent with the main hypothesis of the study.

Qualitative Tools

The qualitative analysis of the semi-structured interviews and systematic observations provided a detailed picture consistent with the quantitative results, highlighting a progressive evolution in the experimental group (EG) in terms of attentional strategies and inhibitory control applied to the game context. The triangulation between sources (subjective narratives and observed behavioral indicators) allows us to describe not only what has changed, but also how this change manifested itself in the ecological context of training and competition. The thematic analysis led to the identification of five recurring macro-themes in the EG, with less frequent, weaker, or predominantly generic patterns in the control group (CG): (1) selection and prioritization of relevant stimuli, (2) management of distractions and recovery of focus, (3) inhibition of impulsivity under pressure, (4) attentive routines and self-regulation, (5) transfer to competition situations.

Theme 1 – Rapid selection of relevant stimuli and redefinition of attentional priorities

In the SG, there is a clear shift from predominantly reactive attention management (“I follow what is happening”) to a more intentional and hierarchical selection (“I look for the information that matters first”). Athletes describe a change in the way they “read” the situation, reporting greater speed in identifying functional signals (ball, spaces, free teammate, defensive positioning) and a reduction in the tendency to be distracted by competing or irrelevant stimuli. This process is frequently linked to laboratory exercises characterized by rule changes, information constraints, and interfering stimuli: Marco (EG, guard) states, “when they changed the rules unexpectedly, I had to stop doing things automatically; I had to understand immediately what mattered,” while Luca (EG, point guard) explains a prioritization criterion: “Before, I used to get lost, but now I look for the right information first: ball, space, free man; I cut out the rest.”

The observations converge with these narratives, showing that in the final stages of the intervention, the EG shows greater adherence to the binding rule of the exercise, especially when it is modified “on the fly,” with fewer episodes of operational disorientation and shorter adaptation times to the new instruction. Compared to the GC, in which responses tend to remain more prescriptive and generic (“I have to stay focused”), in the EG the selection appears more procedural and situational, with explicit references to cues and priorities.

Theme 2 – Managing distractions and regaining focus after an error (attentional reset)

A second core theme concerns the ability to recognize loss of concentration and quickly regain focus, especially

after errors, ineffective choices, or emotional interference. EG athletes report an increase in metacognitive awareness (“I notice it sooner”), accompanied by a reduction in the time needed to return to the task. Davide (EG, wing) explicitly describes this transition: “I still get distracted, but I notice it sooner and get back into the game right away; before, I would be out of it for two plays.” Andrea (EG) links this process to error management: “If I make a mistake, I think about it, but then I say to myself, ‘next play,’ and get back on defense.”

Systematic observations confirm a consistent behavioral change: in the final sessions of the workshop, the EG shows a decrease in episodes of disorganization following an error (e.g., delays in returning to defense, protests, hesitation, or “freezing” after a wrong choice) and an increase in the speed with which the athlete realigns with the next task. In the CG, on the contrary, sequences of error persistence (repetition of impulsive or ineffective choices after a negative event) and greater vulnerability to situational distractions (noise, provocation, frustration) were more frequent, without any declared recovery strategies.

Theme 3 – Interference control and inhibition of impulsive responses under pressure

A particularly recurring theme in EG concerns impulse control and the ability to suspend automatic responses under time and competitive pressure. Athletes describe a change in their “impulsivity threshold”: they do not eliminate the speed typical of the game, but they acquire the ability to introduce a micro-space of control (“half a second”) before the action, especially in situations requiring rapid decision-making. Matteo (EG) reports: “In exercises with little time, I have learned not to shoot immediately: I wait half a second and often see the pass,” while Simone (EG, center) adds: “I have retained the habit of controlling myself; I don’t force it if there is no advantage.”

The observations support this theme by showing, in EG, higher decision-making quality in critical phases (end of quarter, quick transitions, throw-ins) and a reduction in hasty actions in response to situational stress (aggressive defense, reduced time). In particular, the choice of functional solutions (extra pass, reversal, attack of the real advantage) appears to be more frequent than automatic solutions (immediate shot, individual forcing) observed more frequently in the GC under the same conditions.

Theme 4 – Emergence of attentive routines and self-regulation strategies (breathing, keywords, rituals)

A fourth thematic core concerns the emergence of attentive self-regulation strategies, described as simple and repeatable tools for stabilizing focus and containing emotional interference. The EG reports practices such as conscious breathing, the use of focusing keywords, and pre-action rituals. Francesco (EG) states, “When I feel like I’m getting out of control, I take a breath and say to myself, ‘simple,’” while Giorgio (EG) highlights the adoption of a stable routine in free throws: “I always do the same thing on free throws, so I don’t think too much.”

This theme is relevant because it indicates not only a change in performance but also a transformation in self-

regulation skills: athletes describe concrete and applicable strategies related to task cues (moments of pressure, interruptions, free throws, mistakes). In the CG, such strategies are less frequently explicit; when present, they tend to be formulated in a generic way (e.g., “I try to calm down”), without structured operational routines.

Theme 5 – Transfer situated in competition situations and functional generalization

The theme of transfer appears in the EG formulated in a situational way, with references to specific and recognizable contexts of competitive performance. Athletes describe an improvement in detecting changes in the context (e.g., defensive adjustments, changes in pace, external pressures) and in quickly updating the rule of action, recalling the similarity with exercises with variable constraints. Nicola (EG, point guard) states: “In competition, I notice when the defense changes sooner, as in exercises with changing rules,” while Alessandro (EG) links selective attention to the ability to filter out external interference: “Even if the crowd is shouting or someone is talking to me, I stay focused on the game.”

Observations in context confirm that EG adapts better to situational demands: in the final stages of the course, there is greater continuity of focus in transitions, more readiness in defensive reorganization, and greater adherence to instructions in exercises with variable objectives. In contrast, in the CG, the transfer is expressed mainly as intent (“I need to concentrate more”) rather than as an operational change, and observations indicate greater susceptibility to interference at critical moments.

Overall, the qualitative results indicate that the workshop promoted a change in the SG that cannot be reduced to a generic “greater concentration” but can be traced back to specific processes of attentional control: (a) prioritization of relevant stimuli, (b) filtering of irrelevant stimuli and resistance to interference, (c) inhibition of impulsive responses under pressure, (d) rapid recovery of focus after error, (e) consolidation of self-regulation strategies and their transfer to the competition. This profile is consistent with the improvement observed in the Stroop test, as it describes a functional enhancement of inhibition and attentive selection processes in conditions of information conflict, with concrete and observable manifestations in game behavior.

Discussion

The results of the study indicate that a basketball laboratory designed to systematically increase perceptual-decision complexity—through informational, temporal, regulatory, and spatial constraints—is associated with a significant improvement in Stroop interference control and consistent experiential and behavioral changes. The extent of the quantitative improvement (18–20% reduction in interference in the EG, with significant time $\times$ group interaction) is consistent with the idea, supported by recent literature, that open-skill sports practice and, above all, repeated exposure to cognitively demanding tasks, can promote superior performance in the domains of executive functions related to inhibition and attentional control. Evidence from comparative studies between open-skill and

closed-skill athletes (Koch et al., 2021) and meta-analytic syntheses that attribute an average advantage to open-skill sports in the expression of executive functions (Heilmann et al., 2022), suggesting that it is not “sport” itself that produces the effect, but the quantity and quality of attentional-decision-making demands imposed by the environment. In theoretical terms, the Stroop outcome can be interpreted as an improvement in the ability to maintain the relevant rule and inhibit the automatic response in conditions of conflict, a process that in neurocognitive literature is considered a robust indicator of interference control and cognitive inhibition (Scarpina & Tagini, 2017).

Integration with qualitative data reinforces the causal interpretation and, above all, clarifies the possible mechanisms of transfer from the laboratory to the sporting context. The interviews show that the athletes in the experimental group do not describe a generic “being more focused,” but report a change in the management of information conflict: selecting “the right signal,” filtering out noise (audience, opponents, previous error), interrupting impulsive choices, and quickly updating the rule of action when the exercise changes. This narrative profile is consistent with the ecological-dynamic hypothesis that learning emerges from the coupling of information and movement and is enhanced when the task reproduces the informational and decision-making demands typical of competition (Representative Learning Design). In other words, in the laboratory, the athlete was repeatedly exposed to conditions in which performance depended on inhibiting automatisms (e.g., shooting “as soon as free,” attacking “as soon as I receive”) and updating attentional priority under constraints (reduced time, restricted space, variable rules), i.e., exactly the type of situation in which interference control becomes functional. The use of small-sided games with high decision-making density is particularly plausible as a “vehicle” for this effect: in the literature on small-sided games in team sports, the manipulation of space, number of players, and rules is indicated as a lever for modulating perceptual load and decision making, making training more representative and transferable (Clemente et al., 2021; Ramos et al., 2020). It is important to emphasize that the laboratory did not isolate cognition from motor skills but incorporated it into technical-tactical tasks, a choice consistent with recent methodological indications that point to interpretative limitations of cognitive tests when they are not linked to contexts of action and recommend integrated approaches in the cognitive assessment of athletes (Susanto et al., 2024a).

A crucial point concerns the validity of the Stroop test as an outcome in sport. The Stroop does not measure sport-specific skills, but offers a standardized measure of interference control useful for detecting changes in basic executive processes, which research links to performance in competitive contexts where time pressure, stress, and mental fatigue increase the risk of automatic and dysfunctional responses. Precisely for this reason, the convergence between Stroop improvement and qualitative reports (reduction in impulsivity, recovery of focus after error, faster selection of signals) is a strong element: it mitigates the classic criticism of the poor ‘ecological validity’ of neuropsychological tasks and suggests that, in this case, the test has functioned as a sensitive indicator of a change that athletes also recognize in the game. This interpretation is in line with recent research on inhibition in sport, which

highlights a bidirectional relationship between sports practice and inhibitory control and emphasizes that more experienced athletes tend to perform better in inhibition tasks, especially when the sporting context requires quick decisions and control under pressure (Albaladejo-García et al., 2023; Rahimi et al., 2022). Furthermore, the emergence of attentional routines and self-instructions (breathing, keywords, pre-action rituals) may be linked to attention stabilization and pressure management, especially when routines are simple, repeatable, and linked to task-relevant cues.

In terms of application, the results suggest that the effectiveness of the workshop stems from a combination of three factors: intensity of exposure (two sessions per week for six months), intentional design of constraints, and progression of complexity (from few constraints to competing constraints and changes during action). This triad is also consistent with the literature on physical activity interventions and executive functions in childhood: the most recent meta-analyses indicate that structured and continuous programs can produce improvements in executive functions in children and adolescents, although the effect depends on the “dose” and quality of the task (e.g., cognitive demand and engagement) rather than on the mere volume of activity (Li et al., 2025). At the same time, a rigorous discussion must recognize the methodological limitations typical of an experiment: the absence of full randomization, the possible influence of contextual factors (coaching style, cohesion, motivation), the use of a single main test for executive function (Stroop), and the need to include complementary measures in future studies (e.g., motor inhibition tasks such as stop-signal, more ecological assessments of decision making, and indicators of performance in competition). Furthermore, recent literature calls for avoiding a “dogmatic” application of the constraints-led approach: the quality of the effect depends on how constraints are selected and their link to the information actually available in competition; poorly calibrated constraints can increase noise and frustration without improving the functionality of perception (Bobrowicki et al., 2023). In summary, the present study supports the idea that training designed as a cognitive learning environment can produce measurable benefits on selective attention, but also suggests that such benefits require careful instructional engineering of the task, controlled progression, and a broader set of measures to fully describe the transfer to performance.

Conclusion

In conclusion, the results of this study support the effectiveness of a six-month basketball laboratory, structured according to principles of representative design and systematic manipulation of constraints, in promoting improved selective attention and interference control in athletes under 17. Quantitatively, the reduction in the Stroop interference index in the experimental group, together with the significant time $\times$ group interaction, indicates an enhancement of cognitive inhibition processes and maintenance of the relevant rule in conditions of stimulus-response conflict. Qualitatively, the triangulation between interviews and observations documents convergent changes in attentional and self-regulatory strategies: athletes report a more efficient hierarchy of informational stimuli, a greater ability to filter situational interference (noise,

provocations, outcomes of previous actions), faster attentional realignment times after errors, and more stable control of impulsive responses in high-pressure situations, with examples of transfer reported in competition situations (adaptation to defensive changes and management of critical phases). Overall, the integration of the results suggests that high-density information training interventions, incorporated into technical-tactical exercises and not decontextualized from the action, can contribute to the development of executive components functional to performance in open-skill sports in adolescence. Looking ahead, further research will be needed to consolidate the robustness of these findings through more controlled experimental designs, the use of complementary cognitive batteries, and the inclusion of ecological indicators of decision-making and competition performance (Di Palma et al., 2025), in order to clarify the degree of generalizability, mediating mechanisms, and the optimal “dose” of the intervention.

Ethics Approval and Consent to Participate

The study was approved by the University of Naples Parthenope (DiSMMeB, Prot. No. 88779/2025). The research was conducted in accordance with established ethical standards for research involving human participants. Informed consent was obtained from all participants and/or their legal guardians prior to participation.

Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

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

AI Transparency Statement

No AI tools were used in the design, data collection, analysis, or writing of this study.

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Покращення селективної уваги в юнацькому баскетболі: когнітивні та фізіологічні результати репрезентативної тренувальної інтервенції

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; Е – збір коштів

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Цілі. Дослідження мало на меті оцінити ефективність програми тренувань з баскетболу, розробленої для покращення селективної уваги та контролю інтерференції у спортсменів вікової категорії до 17 років шляхом підвищення атенційного навантаження під час практичних занять.

Матеріали та методи. У дослідженні було застосовано експериментальний дизайн зі змішаними методами. У дослідженні взяли участь сорок кваліфікованих баскетболістів віком 16 років, які були розподілені на експериментальну (n = 21) та контрольну (n = 19) групи. Селективна увага оцінювалася за допомогою тесту Струпа (методики словесно-колірної інтреференції) під час перед- та постінтервенційної фаз дослідження. Якісні дані зібрано шляхом проведення систематичних спостережень та напівструктурованих інтерв'ю зі спортсменами та тренерами. Експериментальна інтервенція включала програму баскетбольних тренувань із систематичним маніпулюванням обмеженнями завдань та впровадженням екологічно репрезентативних вправ, спрямованих на підвищення вимог до уваги.

Результати. Після шести місяців інтервенції в експериментальній групі спостерігалось значуще зниження індексу інтерференції Струпа порівняно з контрольною групою. Крім того, спортсмени експериментальної групи продемонстрували суттєве скорочення часу реакції та зменшення кількості помилок в інконгруентних умовах тесту. Якісні дані вказали на розвиток ефективніших атенційних стратегій, покращення здатності фільтрувати нерелевантні подразники, посилення контролю імпульсивних реакцій та швидше відновлення концентрації уваги у стресових ігрових ситуаціях.

Висновки. Результати дослідження свідчать про те, що програма баскетбольних тренувань, заснована на систематичному маніпулюванні практичними обмеженнями та використанні екологічно валідних вправ, може ефективно підтримувати розвиток селективної уваги та контролю інтерференції у підлітків-спортсменів. Такі підходи можуть сприяти покращенню процесу ухвалення рішень та результативності у командних видах спорту, що вимагають застосування відкритих навичок.

Ключові слова: когнітивні функції, селективна увага, контроль інтерференції, баскетбол, ухвалення рішень, когнітивне тренування.

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Measurement Reliability and the Effectiveness of Shooting Training in Beginner Basketball Athletes Based on ARISEBA-Tech

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Abstract

Background. Basketball shooting performance is influenced by multiple physical, technical, and perceptual-motor factors, leading recent research to emphasize the role of technology-assisted training and objective performance measurement. However, standardized shooting assessment instruments remain largely dependent on manual observation and are rarely integrated with systems capable of supporting structured motor learning process control.

Objectives. This pilot study aimed to evaluate the measurement reliability of ARISEBA-Tech and to examine the effectiveness of an eight-week technology-assisted shooting training program in beginner basketball athletes.

Materials and Methods. A quasi-experimental pretest–posttest design, combined with test–retest reliability analysis, was employed. Twenty-nine beginner university basketball players completed standardized shooting assessments (BJSAT, SST, and CBST), which were recorded automatically using ARISEBA-Tech. Reliability was assessed using intraclass correlation coefficients (ICC) and coefficients of variation (CV). Performance changes were analyzed using paired-sample t-tests or Wilcoxon signed-rank tests, with effect sizes calculated using Cohen's d.

Results. Most shooting performance variables demonstrated good to very good reliability ($ICC > 0.80$). Time-based variables showed lower variability compared with accuracy-related measures. Following the intervention, significant improvements were observed in shooting accuracy and execution efficiency ($p < 0.05$), with moderate to large effect sizes ($d = 0.38$ – 1.33).

Conclusions. ARISEBA-Tech provides reliable automated performance measurement and shows potential to support the structured regulation of motor learning processes in beginner shooting training. As a pilot study, the findings provide preliminary empirical evidence rather than generalizable conclusions, indicating the need for larger controlled studies and the integration of movement technique analysis.

Keywords: basketball, training, shooting performance, sensor-based assessment.

Introduction

Basketball is a dynamic team sport that requires repeated high-intensity actions, including shooting under time pressure and defensive constraints (Cao et al., 2024; Bourdas et al., 2024). Team success is largely determined by shooting effectiveness, particularly in critical game situations such as the final moments of a match (Cabarkapa et al., 2023), making shooting performance a key indicator of

basketball proficiency. Shooting performance emerges from complex interactions among individual characteristics, task demands, and game environmental conditions (Amaro et al., 2024), and is influenced by physical condition (Brini et al., 2025), shooting angle and velocity (Chen, 2024), as well as the coordination of motor control, visual perception, and psychological stability, especially under conditions of fatigue and pressure (Chmiel & Buryta, 2025; Court Gold et al., 2025). In addition, lower-limb strength, dynamic balance, and postural control contribute significantly to shooting accuracy and consistency (Ji, 2020; Boddington et al., 2019; Ntasis, 2019; Röscher et al., 2022; Zhang, 2025). In practice,

shooting occurs in multiple forms and contexts, including free throws, jump shots, lay-ups, and three-point shots, and can be performed under unguarded or guarded conditions (Cabarkapa et al., 2023; Chen, 2024; Court Gold et al., 2025).

This complexity indicates that shooting is a skill that requires precise training methods and objective measurement approaches. In recent years, digital technologies have increasingly been used to support basketball shooting training, enabling objective data collection, real-time performance monitoring, automated regulation of practice repetitions, optimization of execution timing, and more accurate feedback compared with traditional observational methods (Zhao et al., 2023; Weng et al., 2025; Svoboda et al., 2024). Previous studies have shown that technology-assisted training can enhance training efficiency, regulate practice repetitions, optimize execution timing, and improve systematic monitoring of shooting outcomes (Boonsom & Bungmark, 2024; Xue, 2024; Bourdas et al., 2024).

From a motor learning perspective, basketball shooting represents a complex perceptual-motor skill that requires not only movement execution but also regulation of the learning process during practice. Motor performance depends on the flexibility of cognitive control systems, efficient allocation of attentional resources, and information processing capacity that support adaptive motor behavior (Gentili et al., 2015; Gutiérrez-Capote et al., 2023). Effective skill acquisition is strongly influenced by structured control of practice variables, including repetition frequency, feedback timing, and monitoring of motor adaptation (Choo et al., 2024; Williams & Hodges, 2023; Ren et al., 2025). These mechanisms are essential for facilitating motor memory formation, improving movement consistency, and supporting long-term retention of shooting skills, particularly among beginner athletes who require guided and adaptive training environments (Kubicek et al., 2023; Dehais et al., 2020).

In terms of performance assessment, several standardized basketball shooting instruments such as the Basketball Jump Shooting Accuracy Test (BJSAT) (Boddington et al., 2019; Boddington et al., 2020), Basketball Long-Range Accuracy Performance Index (BALPAI) (Rösch et al., 2022), Standardized Shooting Task (SST) (Daub et al., 2023), and Combined Basketball Skill Test (CBST) (Conte et al., 2019) have demonstrated good validity and reliability. However, these instruments still rely heavily on manual observation, which introduces subjectivity and limits implementation efficiency and measurement consistency.

More importantly, this situation reflects a conceptual gap between the intended role of technology in training namely supporting structured regulation of the motor learning process and current measurement practices that remain focused primarily on evaluating final performance outcomes. Existing instruments are not integrated with technological systems capable of adaptively controlling practice variables, monitoring skill development in real time, and providing continuous feedback during training. Thus, although technology has been used to record performance outcomes, its integration with mechanisms for motor learning process control remains limited.

To address this gap, the present study develops and evaluates ARISEBA-Tech, a sensor-based system designed to integrate automatic recording of shooting accuracy, monitoring of execution time, and real-time regulation of training repetitions. The system is intended not only as a training aid but also as

an automatic recording system that can be integrated with standardized shooting instruments to enhance measurement objectivity while supporting more effective control of the motor learning process. Given that ARISEBA-Tech is still in an early stage of development, this research is positioned as a pilot study aimed at providing preliminary empirical evidence regarding measurement reliability and training effectiveness, rather than producing broad generalizations.



Fig. 1. System ARISEBA-Tech

Therefore, this study is expected to contribute to bridging the gap between shooting performance measurement and motor learning process control in technology-assisted basketball training. This investigation is particularly relevant given the limited evidence on technology-based basketball training for junior and beginner athletes, who require structured training and appropriate assessment to support long-term development (Slimi et al., 2025; Huang & Chen, 2023; Conte et al., 2019; Wang, 2024). Accordingly, this study aims to: (1) evaluate the reliability of basketball shooting performance measurements produced by the ARISEBA-Tech system when implementing standardized shooting instruments (BJSAT, SST, and CBST); and (2) examine the effectiveness of integrating ARISEBA-Tech into a structured training program to improve the shooting accuracy of beginner basketball athletes.

Materials and Methods

Research Design

This study is a pilot study, using a quasi-experimental design with a pretest–posttest approach, accompanied by an evaluation of measurement reliability.

Participants

A total of 29 beginner university basketball players (age 18–22 years; mean height 177.3 ± 4.1 cm; mean body mass 67.5 ± 5.2 kg) with less than one year of formal training experience participated in this study. The sample size was determined based on pilot study conventions rather than formal statistical power calculations. In pilot intervention research, a sample size of approximately 20–30 participants is generally considered adequate to evaluate feasibility, estimate preliminary effect sizes, and assess measurement reliability prior to conducting larger confirmatory trials. Therefore, the inclusion of 29 participants was considered sufficient to provide preliminary empirical evidence regarding the reliability and effectiveness of ARISEBA-Tech,

while acknowledging that the findings are exploratory and not intended for population generalization.

Inclusion criteria were: (1) no musculoskeletal injury within the past six months and (2) regular participation in basic basketball training activities. Participants with medical conditions limiting the ability to perform high-intensity physical activity were excluded. All participants provided informed consent, and the study was approved by the institutional ethics committee and conducted in accordance with the Declaration of Helsinki.

Instruments

Basketball Jump Shooting Accuracy Test (BJSAT)

BJSAT is used to assess jump shot accuracy from eight predetermined shooting spots, consisting of four spots at two-point range and four spots at three-point range. Each participant completed four trials. Each shot was scored as follows: score 0: the ball does not touch the rim, score 1: the ball touches the rim, score 2: the ball touches the rim and goes in, score 3: the ball goes into the basket without touching the rim. The total score of each trial was divided by the number of shooting spots (8), then the values from the four trials were summed to obtain the final BJSAT score.

Standardized Shooting Task (SST)

SST is used to assess shooting accuracy under several conditions, which include: (1) free throw shooting, consisting of 60 attempts without a time limit; (2) two-point spot-to-spot shooting from seven shooting spots with a time limit of 4 minutes; and (3) three-point spot-to-spot shooting from seven shooting spots with a time limit of 4 minutes. Performance variables analyzed include the number of made shots for each type of shooting (free throw, two-point, and three-point).

Combined Basketball Skill Test (CBST)

CBST is used to assess integrated basketball skills through 12 trials, consisting of: 4 jump shot trials, 4 lay-up trials, and 4 reverse lay-up trials, with the execution order made uncertain (randomized manually or using a system). After the randomization mechanism is applied, a “Visual Stimulus” appears on the prepared screen. The visual stimulus is described as the appearance of a dark orange ball image for jump shots, blue for lay-ups, and red for reverse lay-ups. The performance variables measured include shooting accuracy and task completion time. Thus, the best value for shooting accuracy is 12 points. The completion time reflects the duration of the execution of the activity sequence, including passing, dribbling, changes of direction, and shooting execution. The best time from each type of shooting is used as the performance score for completion time.

ARISEBA-Tech System

ARISEBA-Tech is a sensor-based basketball shooting performance recording system; this system is capable of automatically recording shooting outcomes, calculating the

number of repetitions, and regulating and displaying the duration of shooting execution. In this study, ARISEBA-Tech is positioned as an automatic recording system integrated with the implementation of standardized shooting instruments. In this study, ARISEBA-Tech can be fully integrated with the implementation of BJSAT and SST. In CBST, the function of ARISEBA-Tech is used to record shooting accuracy and completion time, while the manual penalty system in the original CBST protocol (e.g., wrong ball selection: +4 seconds, wrong hand lay-up: +2 s, loss of ball control: +5 s, moving before stimulus: +3 s) is omitted, due to limitations in the functionality of ARISEBA-Tech.

Procedures

Measurement Reliability Test

Evaluation of the consistency of ARISEBA-Tech automatic recording was conducted through reliability testing using the test–retest method. Participants performed the same series of shooting tests on two separate occasions with a one-week interval to minimize fatigue effects and short-term learning.

Training Intervention

The first test in the reliability test (test–retest) was designated as the initial measurement result (pre-test), then all participants followed a structured shooting training program for eight weeks, with a frequency of 3–4 sessions per week and a duration of approximately 60 minutes per session. This duration and frequency were selected because they have been reported to be adequate to facilitate physiological adaptations, improvements in movement coordination, and enhancements in motor control related to basketball shooting performance (Xue, 2024; Zacharakis et al., 2020; Gong et al., 2025). All training sessions were conducted under the supervision of licensed coaches to ensure adherence to the training protocol and participant safety. Post-test measurements were conducted after all participants completed the training program.

ARISEBA-Tech enables the regulation of repetitions, rest intervals, training duration, and the number of sets through a web-based platform, either manually or automatically. The automatic mode allows adaptive adjustment of training variables based on objective data obtained during standardized tests integrated with ARISEBA-Tech. The system also features automatic determination of training volume based on the maximum repetition principle (50–100%), aimed at maintaining an optimal balance between training load and gradual performance improvement. All parameters are displayed in real time on a digital scoreboard, providing immediate visual feedback.

Data Analysis

The reliability of shooting performance recording using ARISEBA-Tech was analyzed using the Intraclass Correlation Coefficient (ICC) to assess the consistency of measurement results over time, as well as the Coefficient of Variation (CV) to assess the relative stability of the data, complemented by descriptive statistics in the form of mean

Table 1. Test–Retest Reliability of ARISEBA-Tech–Based Shooting Measurements

Instrument / Variable	Mean ± SD Test 1	Mean ± SD Test 2	Cronbach's α	ICC (3,1)	95% CI	Interpretation
BJSAT (Accuracy)	3.77 ± 0.74	4.04 ± 0.76	0.984	0.911	0.147 – 0.977	Very good
CBST Lay-up (Accuracy)	2.52 ± 0.95	2.31 ± 0.89	0.923	0.840	0.670 – 0.924	Good
CBST Lay-up (Time)	23.02 ± 0.95	22.57 ± 0.93	0.987	0.871	–0.029 – 0.970	Good
CBST Reverse Lay-up (Accuracy)	2.07 ± 0.92	1.86 ± 0.83	0.942	0.869	0.701 – 0.941	Good
CBST Reverse Lay-up (Time)	23.60 ± 0.84	23.19 ± 0.80	0.982	0.858	–0.026 – 0.965	Good
CBST Jump Shot 2 Point (Accuracy)	2.79 ± 0.98	2.69 ± 1.17	0.910	0.836	0.683 – 0.919	Good
CBST Jump Shot 2 Point (Time)	22.45 ± 1.15	22.00 ± 1.11	0.990	0.908	0.009 – 0.979	Very good
SST Free Throw	26.66 ± 5.53	23.59 ± 8.97	0.697	0.501	0.178 – 0.728	Moderate
SST Jump Shot 2 Point	3.83 ± 1.49	4.07 ± 1.75	0.981	0.955	0.887 – 0.980	Very good
SST Jump Shot 3 Point	2.83 ± 1.44	3.03 ± 1.57	0.968	0.929	0.843 – 0.967	Very good

and standard deviation. Analysis of training effectiveness began with descriptive statistics (mean and standard deviation), normality testing using the Shapiro–Wilk test ($p > 0.05$). Differences between pretest and posttest were analyzed using a paired-sample t-test ($p < 0.05$) if the data were normally distributed, or the Wilcoxon Signed-Rank Test ($p < 0.05$) if normality was not met. Analysis of intervention effects used Cohen's d (small: 0.20, medium: 0.50, and large: 0.80).

Results

Measurement Reliability Test

Table 1 shows that most shooting instruments have ICC values in the good to very good categories ($ICC > 0.80$), which indicates consistency of measurement results over time. The instruments with the highest ICC values are the SST two-point jump shot and SST three-point jump shot, while the lowest ICC value is found in the SST free throw, which indicates moderate consistency.

Table 2 presents the coefficient of variation (CV) as an indicator of the level of performance variation among participants. Time-based instruments in the CBST show low CV values ($<10\%$), both at pre-test and post-test, which indicates performance stability among participants. In contrast, accuracy score-based instruments show higher CV values, particularly in shooting tasks with higher levels of difficulty, which reflects heterogeneity of shooting ability among beginner athletes.

Effectiveness of ARISEBA-Tech

Table 3 shows that descriptively all shooting variables experienced performance improvements at post-test, indicated by increases in mean accuracy scores (BJSAT, SST, and CBST) and decreases in task completion time for time-based CBST variables. The range of minimum and maximum values indicates that performance improvements occurred relatively consistently among most participants, without prominent extreme outliers.

The results of the Shapiro–Wilk test in Table 4 show that most variables are normally distributed ($p > 0.05$), particularly BJSAT scores, all SST subtests, and time-based

Table 2. Coefficient of Variation (CV) of Shooting Measurement Results

Instrument / Variable	Test	Mean	SD	CV (%)	Level of Variation
BJSAT	Test 1	3.77	0.74	19.6	Moderate
	Test 2	4.04	0.76	18.9	
CBST Lay-up (Outcome)	Test 1	2.52	0.95	37.7	High
	Test 2	2.31	0.89	38.5	
CBST Lay-up (Time)	Test 1	23.02	0.95	4.1	Low
	Test 2	22.57	0.93	4.1	
CBST Reverse Lay-up (Outcome)	Test 1	2.07	0.92	44.4	High
	Test 2	1.86	0.83	44.6	
CBST Reverse Lay-up (Time)	Test 1	23.60	0.84	3.6	Low
	Test 2	23.19	0.80	3.4	
CBST Jump Shot 2 Point (Outcome)	Test 1	2.79	0.98	35.1	High
	Test 2	2.69	1.17	43.5	
CBST Jump Shot 2 Point (Time)	Test 1	22.45	1.15	5.1	Low
	Test 2	22.00	1.11	5.0	
SST Free Throw	Test 1	26.66	5.53	20.7	Moderate–High
	Test 2	23.59	8.97	38.0	
SST Jump Shot 3 Point	Test 1	2.83	1.44	50.9	Very high
	Test 2	3.03	1.57	51.8	
SST Jump Shot 2 Point	Test 1	3.83	1.49	38.9	High
	Test 2	4.07	1.75	43.0	

CBST variables. In contrast, score-based CBST variables (lay-up, reverse lay-up, and two-point jump shot) show non-normal distributions ($p < 0.05$). Based on these findings, analysis of pre-test and post-test differences was conducted using paired-sample t-tests for normally distributed data and Wilcoxon signed-rank tests for non-normally distributed data, in accordance with principles of inferential statistical analysis.

The results of the paired-sample t-test in Table 5 show that there are significant differences between pre-test and post-test scores for all normally distributed variables ($p < 0.05$). These findings indicate that the use of ARISEBA-

Table 3. Descriptive statistics of pre-test and post-test shooting scores

Variable	Pre-test (Mean $\pm$ SD)	Post-test (Mean $\pm$ SD)
BJSAT	3.77 $\pm$ 0.74	4.64 $\pm$ 0.93
SST – Free Throw	26.66 $\pm$ 5.53	29.24 $\pm$ 7.57
SST – Jump Shot 3 Point	2.83 $\pm$ 1.44	3.45 $\pm$ 1.70
SST – Jump Shot 2 Point	3.83 $\pm$ 1.49	4.76 $\pm$ 1.41
CBST – Lay-up (score)	4.62 $\pm$ 0.73	5.38 $\pm$ 0.56
CBST – Reverse Lay-up (score)	4.10 $\pm$ 0.77	5.03 $\pm$ 0.60
CBST – Jump Shot 2 Point (score)	4.34 $\pm$ 0.61	4.79 $\pm$ 0.63
CBST – Lay-up (time, seconds)	23.02 $\pm$ 0.95	22.46 $\pm$ 0.94
CBST – Reverse Lay-up (time, seconds)	23.60 $\pm$ 0.84	23.09 $\pm$ 0.80
CBST – Jump Shot 2 Point (time, seconds)	22.45 $\pm$ 1.15	21.91 $\pm$ 1.08

Table 4. Results of the normality test

Variable	Shapiro-Wilk (W)	Sig. (p)	Decision
BJSAT	0.962	0.412	Normal
SST – Free Throw	0.955	0.276	Normal
SST – Jump Shot 3 Point	0.967	0.521	Normal
SST – Jump Shot 2 Point	0.971	0.603	Normal
CBST – Lay-up (score)	0.903	0.018	Not normal
CBST – Reverse Lay-up (score)	0.892	0.011	Not normal
CBST – Jump Shot 2 Point (score)	0.918	0.032	Not normal
CBST – Lay-up (time)	0.969	0.548	Normal
CBST – Reverse Lay-up (time)	0.973	0.621	Normal
CBST – Jump Shot 2 Point (time)	0.961	0.401	Normal

Table 5. Results of the paired-sample t-test

Variable	Mean Difference	t	df	Sig. (p)
BJSAT	-0.87	-15.74	28	< 0.001
SST – Free Throw	-2.58	-3.02	28	0.005
SST – Jump Shot 3 Point	-0.62	-5.38	28	< 0.001
SST – Jump Shot 2 Point	-0.93	-7.70	28	< 0.001
CBST – Lay-up (time)	0.56	10.05	28	< 0.001
CBST – Reverse Lay-up (time)	0.51	11.36	28	< 0.001
CBST – Jump Shot 2 Point (time)	0.54	9.13	28	< 0.001

Tech significantly increases shooting accuracy while also accelerating task completion time in beginner basketball athletes.

The Wilcoxon signed-rank test in Table 6 shows significant increases in scores for all score-based CBST variables ($p < 0.05$). These results confirm that the integration of ARISEBA-Tech not only improves movement efficiency, but also has a positive impact on the quality and accuracy of shooting execution in dynamic situations.

Table 6. Results of the Wilcoxon signed-rank test

CBST Variable	Z	P (2-tailed)	Decision
CBST – Lay-up (score)	-3.606	< 0.001	Significant
CBST – Reverse Lay-up (score)	-4.185	< 0.001	Significant
CBST – Jump Shot 2 Point (score)	-2.121	< 0.001	Significant

The analysis of effect size in Table 7 shows that the ARISEBA-Tech-based training intervention provides moderate to large effects on improving shooting performance in beginner basketball athletes. The largest effects are found in score-based CBST variables, particularly lay-up and reverse lay-up skills ($d > 1.00$), which reflect improvements in the quality of shooting execution under dynamic conditions. Meanwhile, SST and time-based CBST variables show moderate effects, indicating that the intervention not only improves accuracy, but also movement efficiency and task completion speed.

Table 7. Effect size (Cohen's d) of the ARISEBA-Tech intervention

Variable	Cohen's d	Effect Category
BJSAT	1.05	Large
SST – Free Throw	0.38	Small-Moderate
SST – Jump Shot 3 Point	0.40	Moderate
SST – Jump Shot 2 Point	0.65	Moderate
CBST – Lay-up (score)	1.18	Large
CBST – Reverse Lay-up (score)	1.33	Large
CBST – Jump Shot 2 Point (score)	0.73	Moderate
CBST – Lay-up (time)	0.59	Moderate
CBST – Reverse Lay-up (time)	0.63	Moderate
CBST – Jump Shot 2 Point (time)	0.49	Moderate

Discussion

This study is a pilot study aimed at evaluating the initial effectiveness of ARISEBA-Tech in improving shooting performance among beginner basketball athletes, as well as the feasibility of integrating standardized basketball shooting instruments into a sensor-based measurement system.

Measurement Reliability

The reliability analysis demonstrated that most shooting measurements implemented through ARISEBA-Tech

showed good to very good consistency, as indicated by high ICC values. These findings confirm that the system is capable of producing stable and repeatable performance data across repeated measurements, which is essential for longitudinal monitoring in skill training contexts (Hove et al., 2022).

The use of a two-way mixed-effects ICC model with absolute agreement further indicates that ARISEBA-Tech ensures not only consistency in performance ranking among athletes but also equivalence of absolute measurement scores. This is particularly important in training evaluation, where small performance changes must be detected with high precision. The automated recording mechanism of ARISEBA-Tech likely contributed to this stability by minimizing human error and procedural variability commonly associated with manual observation, which is a known advantage of sensor-based performance assessment systems (Schneikart & Mayrhofer, 2022; Li et al., 2025).

Complementary analysis using the coefficient of variation (CV) provided additional insight into performance stability. Low CV values observed in time-based variables suggest homogeneous execution speed among participants, whereas higher CV values in accuracy-related variables reflect expected variability in shooting ability among beginner athletes. Such variability is characteristic of early stages of motor skill acquisition, where performance fluctuations represent functional motor variability associated with exploration and adaptation rather than measurement inconsistency (Vidal & Lacquaniti, 2021; Moreno et al., 2023).

The slightly lower reliability observed in the SST free-throw task may be attributed to the high precision demands of closed-skill performance, which require consistent execution of fixed movement patterns. Small deviations in technique can therefore produce larger score variations compared with more dynamic shooting tasks (Goldschmied et al., 2022). Overall, these findings indicate that integrating standardized shooting instruments with ARISEBA-Tech produces objective, stable, and reliable measurements, supporting its suitability for repeated performance monitoring and evaluation in beginner basketball training contexts.

Effectiveness of ARISEBA-Tech

The results demonstrated significant improvements across all shooting accuracy and time-based performance variables following the ARISEBA-Tech-based intervention. The consistent direction of change across multiple standardized shooting instruments indicates that the system is capable of producing measurable short-term performance gains in beginner basketball athletes.

These improvements may be partly explained by two key features of ARISEBA-Tech: real-time visual performance feedback and individualized automatic regulation of training repetitions. The visual scoreboard provides augmented knowledge-of-results feedback, which is widely recognized as an important factor in early stages of motor skill acquisition by helping learners interpret performance outcomes and adjust subsequent attempts (Sigrist et al., 2013; Wulf et al., 2010).

In addition, the system's automatic adjustment of training repetitions based on individual performance

capacity likely contributed to more consistent practice exposure among participants. Motor learning theory emphasizes that structured control of practice variables, including practice volume and task difficulty, plays a critical role in facilitating skill acquisition (Magill & Anderson, 2014; Moreno & Ordoño, 2015; Debatin et al., 2023). In this context, ARISEBA-Tech appears to support a more individualized and structured training process compared with conventional repetitive practice.

However, given the pilot nature of this study, these findings should be interpreted as preliminary evidence rather than definitive proof of causal learning mechanisms. The quasi-experimental design, relatively small sample size, and absence of direct measurements of movement technique or retention limit the ability to determine the underlying processes responsible for the observed performance improvements.

Furthermore, because the sample size was determined based on pilot-study conventions rather than formal statistical power calculations, the results should be interpreted as exploratory and primarily intended to estimate preliminary effect sizes for future confirmatory research.

Overall, the results suggest that ARISEBA-Tech has practical potential as a technology-assisted training system capable of supporting short-term improvements in shooting performance while providing structured and objective performance monitoring in beginner basketball training contexts.

Contribution, practical implications, limitations, and future research

This study provides an important contribution by demonstrating the feasibility of integrating standardized basketball shooting assessment instruments with a sensor-based training and measurement system. Unlike conventional approaches that primarily focus on outcome evaluation, ARISEBA-Tech enables simultaneous performance measurement and structured regulation of practice variables. In this way, the study helps bridge the conceptual gap between performance assessment and motor learning process control in technology-assisted skill training.

From a practical perspective, ARISEBA-Tech offers a structured and objective approach to shooting training for beginner athletes. The system allows coaches to monitor performance in real time, regulate training repetitions based on individual ability, and provide standardized feedback without relying solely on manual observation. These features may help improve training efficiency, consistency of evaluation, and athlete engagement during repetitive skill practice.

Despite these promising findings, several limitations should be acknowledged. First, the study employed a quasi-experimental design without a control group, which limits causal interpretation of training effects. Second, the relatively small sample size restricts generalizability of the findings. Third, the study focused exclusively on performance outcomes without assessing movement technique, learning retention, or cognitive processes underlying motor skill acquisition. Therefore, the results should be interpreted as preliminary evidence within a pilot-study framework.

Therefore, future studies should incorporate larger samples with formal statistical power analysis to validate

the magnitude and stability of the observed effects. Future studies should employ randomized controlled designs with larger samples to establish stronger causal evidence regarding the effectiveness of ARISEBA-Tech-based training. Further research is also needed to integrate movement technique analysis, examine long-term retention effects, and investigate how technology-assisted feedback influences motor learning processes across different stages of skill development.

Conclusions

The findings of this pilot study indicate that ARISEBA-Tech demonstrates good to very good reliability in automatically recording basketball shooting performance and is suitable for repeated performance monitoring in beginner athletes. The eight-week training intervention incorporating real-time visual feedback and automatic regulation of training repetitions was associated with significant improvements in shooting accuracy and execution efficiency, with moderate to large effect sizes.

These results should be interpreted as preliminary empirical evidence rather than definitive proof of causal learning mechanisms. Nevertheless, the findings suggest that integrating standardized shooting assessment instruments with sensor-based technology may support more structured regulation of motor learning processes during training. Therefore, this study contributes to bridging the gap between performance measurement and motor learning process control in technology-assisted basketball training.

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Conflict of interest

No Conflicts of interest.

AI Transparency Statement

The authors declare that no artificial intelligence (AI) tools were used to generate data, perform analyses, or produce the scientific content of this manuscript. AI-assisted language tools were used only for grammar refinement and language editing, and all final content remains the responsibility of the authors.

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Надійність вимірювань і ефективність тренування кидків у баскетболістів-початківців на основі ARISEBA-Tech

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Реферат. Стаття: 10 с., 7 табл., 1 рис., 44 джерела.

Обґрунтування. Результативність кидків у баскетболі визначається множинними фізичними, технічними та перцептивно-моторними чинниками, що зумовлює акцент сучасних досліджень на ролі технологічно підтримуваного тренування та об'єктивного вимірювання результатів. Водночас стандартизовані інструменти оцінювання кидків значною мірою залишаються залежними від ручного спостереження та рідко інтегруються з системами, здатними забезпечити структуроване керування процесом навчання рухів.

Мета. Це пілотне дослідження мало на меті оцінити надійність вимірювань ARISEBA-Tech та дослідити ефективність восьмижневої програми тренування кидків із використанням технологічної підтримки у баскетболістів-початківців.

Матеріали і методи. Було застосовано квазіекспериментальний дизайн «до-після», поєднаний з аналізом надійності за схемою «тест-ретест». Двадцять дев'ять студентів-баскетболістів початкового рівня виконали стандартизовані тести кидків (BJSAT, SST та CBST), які автоматично реєструвалися за допомогою ARISEBA-Tech. Надійність оцінювали за допомогою внутрішньокласових коефіцієнтів кореляції (ICC) та коефіцієнтів варіації (CV). Зміни показників аналізували за допомогою парного t-тесту або критерію знакових рангів Вілкоксона з розрахунком розмірів ефекту за Коеном (*d*).

Результати. Більшість показників результативності кидків продемонстрували добру та дуже добру надійність (ICC > 0,80). Часові показники характеризувалися нижчою варіабельністю порівняно з показниками точності. Після втручання зафіксовано статистично значущі покращення точності кидків та ефективності їх виконання ($p < 0,05$) із помірними та великими розмірами ефекту ($d = 0,38-1,33$).

Висновки. ARISEBA-Tech забезпечує надійне автоматизоване вимірювання результатів і демонструє потенціал для підтримки структурованого керування процесами навчання рухів у підготовці кидків у початківців. Як пілотне дослідження, отримані результати мають попередній емпіричний характер і не можуть бути узагальнені, що зумовлює необхідність подальших досліджень із більшими вибірками та контрольованими дизайнами, а також інтеграції аналізу техніки рухів.

Ключові слова: баскетбол, тренування, результативність кидків, сенсорно-орієнтоване оцінювання.

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Differential Neuromuscular Adaptations to Skill-Integrated versus Sprint-Based HIIT: Implications for Match-Specific Performance in Racket Sports

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Abstract

Background. Effective badminton performance requires sustaining a high level of physical effort while maintaining precise technical execution under fatigue. However, there is limited research comparing sprint-based high-intensity interval training (HIIT) and skill-integrated HIIT in terms of their physiological effects and transfer to match performance. HIIT is well established as an effective method for improving aerobic capacity and recovery.

Objectives. This study aimed to examine the effects of sprint-based HIIT and skill-integrated HIIT on aerobic capacity, autonomic recovery, metabolic clearance, smash accuracy, and smash speed in trained badminton players.

Materials and Methods. Thirty-six regional-level badminton players (aged 18–25 years) were stratified by age and baseline VO_2max and then randomly assigned to one of three groups: sprint-based HIIT (HSB; $n = 12$), skill-integrated HIIT (HSI; $n = 12$), or a control group (CON; $n = 12$). Both HIIT interventions followed an 8-week periodized program conducted three times per week, targeting 80–95% of maximal heart rate (HR_{max}). VO_2max was assessed using graded treadmill testing; heart rate recovery (HRR) was measured using Polar H10 monitors; and blood lactate concentration was determined using Accutrend Plus[®] analyzers at 5 and 10 minutes post-exercise. Smash accuracy was evaluated using a validated point-based target protocol, and smash speed was measured using radar. Data were analyzed using two-way repeated-measures ANOVA with Bonferroni post hoc corrections ($p < 0.05$). Effect sizes were calculated using Cohen's d .

Results. Both HSB and HSI groups demonstrated significant improvements in VO_2max (HSB: +6.7; HSI: +6.8 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, $p < 0.001$), HRR (HSB: +6.1; HSI: +6.5 bpm, $p < 0.001$), and metabolic clearance rate ($p < 0.01$), with effects exceeding those observed in the CON group ($p < 0.05$). Smash speed increased similarly in both HIIT groups (approximately +10 km/h, $p < 0.001$). However, HSI resulted in significantly greater improvements in smash accuracy compared to HSB (HSI: +8.1 vs. HSB: +4.7 points; $p = 0.002$), while the control group showed minimal changes across all variables.

Conclusions. Both sprint-based and skill-integrated HIIT effectively enhance physiological parameters in badminton players; however, only skill-integrated HIIT leads to substantial improvements in technical performance. Therefore, integrating high-intensity training with sport-specific skill execution appears to be optimal for competitive readiness.

Keywords: high-intensity interval training, badminton performance, neuromuscular adaptation, sport-specific conditioning, smash accuracy.

Introduction

Badminton is a high-intensity, intermittent sport characterized by rapid directional changes, forceful lower-

body movements, repeated overhead strokes, and decision-making under fatigue (Ma et al., 2025; Rusdiana et al., 2023). These biomechanical and physiological requirements necessitate that athletes possess optimal aerobic capacity, rapid autonomic recovery, precise neuromuscular coordination, and the ability to maintain technical accuracy during high-intensity rallies (Rusdiana et al., 2020).

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Traditional badminton training, generally defined by consistent conditioning, repetitive multi-shuttle drills, and non-periodized technical exercises, often fails to develop the integrated physiological and technical skills necessary for modern competitive performance (Alvarez-Dacal et al., 2025; Raibowo et al., 2024). This discrepancy highlights the urgent need for training frameworks that simultaneously enhance physiological readiness and performance capabilities within the constraints of match-specific conditions. The increasing emphasis on evidence-based conditioning in racket sports highlights the importance of interventions that can promote sport-specific adaptations while maintaining ecological validity.

Recent advancements in high-intensity interval training (HIIT) have offered a strategic alternative to conventional conditioning methods. Meta-analyses and empirical studies in racket sports, including tennis, squash, and badminton, indicate that HIIT leads to significant enhancements in VO_2max , heart rate recovery, metabolic efficiency, and anaerobic tolerance within brief training durations (Alibrahim & Hassan, 2024; Liu et al., 2024; Wiesinger et al., 2024). HIIT also helps the body reactivate autonomously and clear lactate more quickly, which are both important for keeping up rally performance and stroke quality (Kafrawi et al., 2025; Torma et al., 2019). Nonetheless, the majority of HIIT applications in badminton are non-specific, predominantly sprint-oriented and deficient in technical integration, consequently restricting the transference of physiological improvements to on-court performance (Bumrung et al., 2025). This limitation constitutes a significant deficiency in the existing literature.

To fill this gap, new research on skill-integrated HIIT suggests combining high-intensity workloads with technical and tactical elements that are specific to each sport. Research in tennis and squash demonstrates that the incorporation of stroke execution, footwork patterns, and decision-making into HIIT protocols markedly enhances racket velocity, accuracy, and movement efficiency more effectively than physical HIIT alone (Nugroho et al., 2024; Salem & Ismail, 2025; Zemková et al., 2024). In theory, this training specificity corresponds with ecological dynamics and motor learning principles, which assert that performance adaptation is optimized when training mirrors the perceptual-action couplings encountered in real match scenarios (Araújo et al., 2023). Despite this encouraging evidence, there is still a lack of controlled experimental studies evaluating the relative effects of sprint-based HIIT and skill-integrated HIIT on both physiological and performance outcomes pertinent to badminton matches.

This study's originality is in its direct comparison of sprint-based HIIT and skill-integrated HIIT through an 8-week periodized intervention and comprehensive outcome measures, including VO_2max , heart rate recovery, metabolic clearance rate, smash speed, and smash accuracy. This research rigorously analyzes both modalities within a quasi-experimental design employing well-trained regional-level athletes, unlike previous studies that examine one mode in isolation, hence ensuring high ecological validity. Moreover, technical performance metrics, especially smash accuracy have infrequently been assessed alongside physiological indicators within HIIT-based paradigms. This integrative assessment offers a novel comprehension of the role of

neuromuscular coordination under fatigue in facilitating successful performance transfer.

Consequently, this study aimed to compare the effects of sprint-based and skill-integrated high-intensity interval training on physiological and match-relevant performance adaptations in trained badminton players. Based on principles of training specificity and ecological dynamics, it was hypothesized that both HIIT modalities would significantly improve aerobic capacity (VO_2max), heart rate recovery, and metabolic clearance compared to traditional training; however, skill-integrated HIIT would produce superior improvements in smash accuracy due to enhanced neuromuscular specificity and perceptual-action coupling under fatigue. Furthermore, it was expected that improvements in physiological recovery indices would be positively associated with changes in smash performance outcomes, reflecting a functional transfer of physiological adaptation to sport-specific technical execution.

Materials and Methods

The study's methodological framework is described in detail to guarantee openness and reproducibility. The ensuing subsections cover the participant characteristics, the intervention program's structure, the measurement protocols, and the statistical techniques used.

Study Participants

This quasi-experimental study involved thirty-six badminton players from East Java, aged 18 to 25, who participated at the regional level. Each player actively participates in competitive regional competitions and has at least five years of formal training experience. Invitations were disseminated via local badminton clubs to recruit participants, and interested individuals were assessed for eligibility.

Any prior musculoskeletal injuries within the last six months, a cardiovascular or metabolic disorder diagnosis, or current participation in a structured HIIT program were also criteria for exclusion. To guarantee the equilibrium of physiological profiles among the groups, individuals were segregated by age (18–21 versus 22–25 years) and baseline VO_2max quartiles before randomization. An independent research assistant executed stratified block randomization (block size = 6) via a computerized random number generator (Random.org).

Using the stratified block randomization technique, participants were randomly divided into three experimental groups. With no sport-specific technical components, the first group, the HIIT sprint-based group (HSB; $n = 12$), participated in high-intensity interval training that included general physical activities. The second group, the HIIT skill-integrated group (HSI; $n = 12$), engaged in training sessions tailored to badminton that combined technical and tactical elements such as multi-phase shot patterns, footwork drills, and smash execution with high-intensity intervals. The third group (CON; $n = 12$) was used as a control and carried on with their usual, traditional training regimens devoid of organized HIIT intervention. All participants gave written informed consent before data collection after being briefed on the study's methods, advantages, and possible risks. The

Universitas Negeri Semarang Research Ethics Committee examined and approved the study protocol (200/KEPK/FK/KLE/2025). Except for lactate analysis, which needed direct and instant post-exercise access, outcome assessors were blinded to group allocation during pre-test and post-test evaluations to reduce assessment bias.

Study Organization

The design of both the sprint-based and skill-integrated HIIT interventions was grounded in a periodization framework that aligns physiological overload with sport-specific neuromuscular demands. Rather than applying uniform high-intensity stimuli, the intervention structure was intentionally divided into progressive phases (foundation, intensification, power, and competition transfer) to ensure adaptive continuity and minimize neuromuscular redundancy. The sprint-based HIIT protocol was conceptualized to primarily target central and peripheral cardiovascular adaptations through repeated maximal locomotor actions, while the skill-integrated HIIT protocol was designed to elicit task-specific neuromuscular coordination under fatigue by embedding technical execution, perceptual–decision demands, and temporal pressure within the high-intensity framework.

This conceptual distinction was critical to the study's experimental logic, as it allowed for a direct comparison between non-specific physiological loading and ecologically valid, skill-oriented overload while maintaining comparable internal training intensity (80–95% HRmax). The intervention architecture therefore reflects a deliberate methodological choice to examine not only physiological adaptations but also the transferability of these adaptations to match-relevant technical performance.

A quasi-experimental pretest-posttest control group design was used for the 8-week intervention, which involved three weekly supervised sessions. Polar H10 heart rate monitors were used to carefully track training intensity, guaranteeing that target intensities (80–95% HRmax) were met. Attendance had to be higher than 80% to be included in the final analyses. The experimental groups adhered to

programs that were periodized and divided into successive stages (Table 1).

The HIIT sprint-based protocol (Table 1) was meticulously periodized to maximize neuromuscular adaptations through progressive overload and phase-specific bioenergetic targeting. The four-phase structure—Foundation, Intensification, Power, and Tapering—systematically changed volume (reps/sets), intensity (80→95% HRmax), and rest periods to create different physiological stressors.

In contrast to the non-specific physiological demands of sprint-based HIIT, the skill-based intervention (Table 2) specifically targeted task-specific neuromuscular coordination under fatigue by integrating badminton's technical-tactical aspects into high-intensity frameworks.

Badminton-specific technical components were methodically incorporated into the high-intensity interval framework of the HIIT skill-based program. The development of basic movement patterns and technical proficiency was the main focus of the first half of the intervention (Weeks 1-4). To enhance agility, proprioception, and decision-making under fatigue, athletes engaged in cognitive-reaction exercises, shadow play with resistance bands, and six-point footwork circuits. Smash biomechanics training, which included kinematic chain drills and deception-based shot practices, came next. It aimed to improve upper-body power and stroke execution at 85–90% HRmax.

In the later phases (Weeks 5–8), the program progressed into match-representative scenarios. To replicate real-game intensity and tactical variation, drills featured rally-based shot sequences, high-pressure point play, and fatigue-induced decision-making. The final phase concentrated on competition transfer using full-sequence rally simulations, randomized shuttle anticipation tasks, and differential learning drills. These increasingly demanding sessions, which reached >95% HRmax, aimed to improve the neuromuscular coordination and physiological resilience needed for competitive badminton play.

Without being exposed to high-intensity interval structures, the control group trained in badminton according to a traditional regimen that mirrored preparation at the

Table 1. 8-week HIIT Sprint-based program

Weeks	Phase	Training Protocol	Intensity	Rest between sets	Rest between drills	Total Duration
1-2	Foundation	Dynamic warm-up (10 min) Shuttle run 20m: 5 sets x 10 repetitions Box jumps: 5 sets x 8 repetitions Burpees: 5 sets x 20 repetitions	80-85% HR max	60 sec	5 min	~80 min
3-4	Intensifikasi	Plyometric ladder drills: 10 sets (without interval rest) Sprint resisted 20m: 5 sets x 6 repetitions Medicine ball slams: 5 sets x 12 repetitions	85-90% HR max	60 sec	5 min	~90 min
5-6	Power	Depth jumps: 5 sets x 10 repetitions Sled pushes: 10 sets x 15m Tuck jumps: 5 sets x 20 repetitions	90-95% HR max	60 sec	5 min	~90 min
7-8	Tapering	Sport-specific agility drills: 5 sets Overspeed training: 5 sets x 20m Explosive starts: 5 sets x 10 repetitions	>95% HR max	60 sec	5 min	~80 min

Table 2. 8-week HIIT Skill-based program

Weeks	Phase	Training Protocol	Intensity	Rest between sets	Rest between drills	Total Duration
1-2	Footwork mastery	6-point footwork circuit: 5 sets x 60 s Shadow play with resistance bands (netting) Cognitive reaction drills (with tennis ball)	80-85% HR max	60 sec	5 min	~80 min
3-4	Smash biomechanics	Kinematic chain sequencing drills (Split-step to overhead smash) 25 min Deception skill practice (Cross-court drop shot disguised as smash) 25 min Smash power training: 10 sets x 15 repetitions	85-90% HR max	60 sec	5 min	~90 min
5-6	Match simulation	High-pressure point play (Targeted pressure drill): 5 sets x 4 min Fatigue-decision making drills (Smash-run-return drill) 5 sets x 20 repetitions Combination shot sequences (Smash-Net Partner Rally) 25 min	90-95% HR max	60 sec	5 min	~90 min
7-8	Competition transfer	Differential learning drills (Adaptive Smash Target Drill) 10 x 15 set Anticipation training (Random Shuttle Drill) 10 x 15 set Simulated tournament scenarios (clear → drop → netting → lift → smash) 25 min	>95% HR max	60 sec	5 min	~80 min

regional level. Under the guidance of the coach, training sessions were held three times a week and mostly comprised moderate-intensity technical drills, such as multishuttle drills, shuttlecock feeding, fundamental footwork patterns, and exercises involving stroke repetition. Physical conditioning was restricted to steady-state aerobic exercises like jogging and general dynamic stretching without any set intensity thresholds or performance evaluations. During the eight weeks, neither progressive overload nor periodization was used. To isolate the effects of HIIT, the control program purposefully did not include the structured work-rest ratios and sport-specific fatigue exposure found in the experimental groups. This method guaranteed ecological validity by simulating the standard procedure frequently employed by amateur badminton coaches in regional settings.

The Sport and Exercise Research Center (SERC) Laboratory and official indoor badminton courts approved by the Indonesian Badminton Federation served as the venues for all training and testing sessions. Participants were advised to avoid strenuous activity and caffeine for at least 24 hours before data collection and to keep regular sleep schedules during the study. Testing times were standardized for the morning (08:00–10:00 AM) to reduce circadian effects. All assessors adhered to a standard testing protocol, and calibration sessions before data collection helped establish interrater reliability among assessors. Participants were also asked to record their daily dietary intake and physical activity to track potential confounding factors.

Measurement

The selection of physiological outcome measures in this study was based on their sensitivity to high-intensity

intermittent exercise and their relevance to recovery dynamics in badminton performance. Maximal oxygen uptake (VO_2max) was employed as an index of aerobic capacity underpinning repeated high-intensity rally participation, while heart rate recovery (HRR) was selected as a marker of autonomic reactivation and cardiovascular efficiency following maximal exertion. Blood lactate concentration and metabolic clearance rate (MCR) were included to capture post-exercise metabolic recovery, which is known to influence technical precision and movement stability under fatigue.

Importantly, these measures were not interpreted in isolation but as complementary indicators representing central (VO_2max), autonomic (HRR), and peripheral metabolic (MCR) adaptations. This integrative measurement rationale allowed for a multidimensional interpretation of training-induced adaptations and supported the examination of how physiological recovery capacity relates to technical performance outcomes such as smash accuracy and smash speed.

Every outcome measure was evaluated twice: once at baseline (pre-test) and once after the 8-week intervention (post-test). To reduce circadian variation, both tests were performed simultaneously (08:00–10:00 AM) in a standardized laboratory or on-court setting. For at least 24 hours before the test, participants were told not to engage in physically demanding activities or consume any caffeine or alcohol. A standardized dynamic warm-up preceded each measurement session, and all participants underwent the same testing procedures.

Heart rate recovery, maximal oxygen uptake (VO_2max), and blood lactate concentration were among the physiological parameters. The Accutrend Plus® portable analyzer (Roche

Diagnostics, Germany) was used to measure the amount of lactate in the blood. At the first and third minutes following the completion of an exercise regimen tailored to badminton and intended to elicit maximal effort, capillary blood samples were drawn from the fingertip. The findings were used as metabolic response indicators and reported in millimoles per liter (mmol/L).

Under laboratory conditions, a graded treadmill test (Bruce protocol) was used to determine maximal oxygen uptake ($\text{VO}_{2\text{max}}$). A calibrated breath-by-breath metabolic system (Cosmed Quark CPET, Italy) was used to measure oxygen consumption, and the highest 30-second rolling average was measured in $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. After encouraging each athlete to reach volitional exhaustion, the test was stopped based on accepted clinical standards.

In the $\text{VO}_{2\text{max}}$ treadmill test, heart rate recovery (HRR) was defined as the one-minute decrease in heart rate after maximal exertion. A Polar H10 heart rate sensor continuously measured heart rate, and readings were recorded in beats per minute (bpm). This measure served as a gauge for autonomic recovery ability (Bonato et al., 2018) and contrasted it with the smallest worthwhile change (SWC).

Smash accuracy and smash speed were among the performance outcomes. A badminton court fitted with rackets, shuttlecocks, a net, and a court marked with target zones for various scoring was used for the test. Participants received an explanation, examples, and two opportunities to try before the test. They then moved to their assigned positions, and after the tester delivered a long serve, they hit ten smashes into the opponent's court target area. The following rules apply to the assessment, which is based on where the shuttlecock lands: The shuttlecock scores 1 point if it lands on the single sideline 1.98 meters from the net with a width of 35 cm; 4 points if it lands 1.32 meters from the short service line; 5 points if it lands between 1.32 and 2.64 meters from the short service line; 3 points if it lands between 2.64 and 3.96 meters from the short service line; and 2 points if it lands directly on the long service line for singles. The highest score is awarded if the shuttlecock lands on the line between the two targets; if it lands outside the field or outside the target, the score is zero. After completing all smashes, the total scores from each attempt is used to determine the final score, indicating the participant's smash accuracy (Edmizal et al., 2022).

A Stalker ATS II radar gun (Stalker Radar, USA) was used to measure smash speed. It was positioned at shuttlecock height, two meters behind the player, to guarantee accurate velocity capture. Following a standardized warm-up, each player executed five maximal smashes; the fastest speed (km/h) was saved for analysis. Before data collection, test-retest reliability was established through pilot testing, and the same qualified staff gave all assessments to guarantee consistency.

Statistical Analysis.

All statistical procedures were conducted using IBM SPSS Statistics (Version 26.0; IBM Corp., Armonk, NY, USA). Data are presented as mean $\pm$ standard deviation (SD). Assumptions of normality and homogeneity of variance were evaluated using the Shapiro-Wilk and Levene's tests, respectively. For repeated-measures analyses, sphericity was

assessed using Mauchly's test, with Greenhouse-Geisser corrections applied when necessary.

Training effects were examined using a two-way repeated-measures ANOVA with time (pre vs. post) as the within-subject factor and group (HSB, HSI, CON) as the between-subject factor. The primary parameter of interest was the time $\times$ group interaction, indicating differential training-induced adaptations. Significant interactions were followed by Bonferroni-adjusted post hoc comparisons. When distributional assumptions were violated, appropriate non-parametric alternatives were applied.

Effect sizes for ANOVA were expressed as partial eta squared (η^2_p), interpreted as small (0.01–0.05), medium (0.06–0.13), and large (≥ 0.14). Pairwise comparisons were quantified using Cohen's *d*. Associations between physiological and performance adaptations were explored using Pearson correlation coefficients. Statistical significance was set at $p < 0.05$.

An a priori power analysis was conducted using G*Power (Version 3.1.9.7) for a repeated-measures ANOVA (within-between interaction), assuming a large effect size ($f = 0.40$), $\alpha = 0.05$, and statistical power $(1 - \beta) = 0.80$. The minimum required total sample size was estimated at 30 participants.

To provide a more precise estimation aligned with the observed data, a post-hoc achieved power analysis was performed based on the interaction effect of the primary outcome ($\text{VO}_{2\text{max}}$). Based on the observed between-group differences and the significant time $\times$ group interaction ($p = 0.005$), the effect size was conservatively estimated at $f \approx 0.50$ ($\eta^2_p \approx 0.20$), corresponding to a large interaction effect. With $N = 36$, three groups, two measurement points, $\alpha = 0.05$, and an estimated correlation among repeated measures of 0.60, the achieved statistical power was calculated to be approximately 0.94.

Results

The following tables summarize the study's findings, starting with the performance and physiological adaptations observed in pre- and post-test assessments. The participant cohort was relatively homogeneous, consisting of 36 regional-level badminton players aged 18 to 25 (average age = 21.4 ± 2.1 years). Each player had at least five years of structured training experience. All groups' players displayed similar physiological and performance profiles at baseline: mean $\text{VO}_{2\text{max}}$ values ranged from 47.1 ± 2.4 to $48.4 \pm 3.2 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, resting heart rates were within the expected range for trained athletes, and initial smash performance was comparable (smash accuracy = 28.3 ± 4.4 to 28.8 ± 4.6 points; smash speed = 263.3 ± 5.0 to $269.6 \pm 4.3 \text{ km/h}$). By clarifying the interpretability of later findings, these baseline similarities allow for greater confidence in attributing the observed adaptations to the intervention protocols rather than to pre-existing participant differences.

Sprint-based HIIT induced significant improvements in aerobic capacity, autonomic recovery, and metabolic clearance compared to baseline. Large effect sizes were observed for $\text{VO}_{2\text{max}}$ and HRR, accompanied by meaningful improvements in smash speed and moderate gains in smash accuracy. Peak heart rate remained unchanged, indicating that performance gains were primarily driven by recovery and metabolic adaptations rather than maximal exertion capacity.

Skill-integrated HIIT produced comparable physiological improvements to sprint-based HIIT,

Table 3. Physiological and Performance Adaptations Following 8-Week Sprint-Based HIIT in Badminton Players

Variable		Mean±SD	Min	Max	Shapiro-Wilk test	Paired t-test	ES Cohen's d
VO ₂ max (ml/kg/min)	Pre	47.14±2.39	42.16	49.94	0.241	0.000	2.192
	Post	53.89±3.64	49.8	61.48	0.159		
	Δpre-post	6.74±3.38	2.08	13.07	0.428		
Heart rate (bpm)	Peak HR_ Pre	195.17±3.41	191	202	0.671	0.574	0.242
	Peak HR_ Post	196.00±3.44	189	201	0.098		
	After 1 min_Pre	172.67±4.75	166	182	0.101		
	After 1 min_Post	167.42±6.20	156	181	0.174	0.000	0.951
	HRR_Pre	22.5±4.27	11	27	0.792		
	HRR_Post	28.58±4.29	20	35	0.777		
	ΔHRR pre-post	6.08±2.87	1	11	0.542		
Blood Lactate (mmol/L)	5_min after exercise_Pre	12.29±1.45	10.15	14.32	0.837	0.010	1.029
	5_min after exercise_Post	11.07±0.84	9.07	11.89	0.426		
	10_min after exercise_Pre	11.63±1.07	10.18	13.85	0.402		
	10_min after exercise_Post	9.03±0.74	7.86	10.16	0.531	0.000	2.826
	MCR_Pre	0.66±1.09	-1.88	1.98	0.198		
	MCR_Post	2.04±1.22	-0.97	3.82	0.768		
	ΔMCR pre-post	1.38±1.37	-0.81	4.91	0.280		
Smash Accuracy	Pre	28.67±3.47	23	36	0.081	0.000	1.312
	Post	33.33±3.63	27	39	0.685		
	Δpre-post	4.67±2.35	2	9	0.668		
Smash Speed (km/h)	Pre	263.29±4.99	256.43	273.32	0.305	0.000	1.883
	Post	273.19±5.51	261.14	280.81	0.777		
	Δpre-post	9.89±2.39	4.71	12.92	0.542		

HRR is heart rate recovery; MCR is Metabolic Clearance Rate; Δ is the difference between pre and post

Table 4. Physiological and Performance Adaptations Following 8-Week Skill-Integrated HIIT in Badminton Players

Variable		Mean±SD	Min	Max	Shapiro-Wilk test	Paired t-test	ES Cohen's d
VO ₂ max (ml/kg/min)	Pre	48.36±3.16	44.54	55.96	0.129	0.000	2.264
	Post	55.13±2.81	50.94	59.66	0.193		
	Δpre-post	6.77±2.62	1.84	9.72	0.293		
Heart rate (bpm)	Peak HR_ Pre	197.75±7.28	180.00	208.00	0.064	0.564	0.188
	Peak HR_ Post	196.67±3.60	191.00	203.00	0.236		
	After 1 min_Pre	171.67±7.44	158.00	181.00	0.485		
	After 1 min_Post	164.08±5.66	157.00	176.00	0.972	0.000	1.148
	HRR_Pre	26.08±3.82	19.00	33.00	0.652		
	HRR_Post	32.58±3.91	24.00	40.00	0.206		
	ΔHRR pre-post	6.5±2.58	0.00	10.00	0.740		
Blood Lactate mmol/L	5_min after exercise_Pre	12.79±0.99	10.64	14.27	0.493	0.091	0.529
	5_min after exercise_Post	12.32±0.77	11.10	13.63	0.255		
	10_min after exercise_Pre	11.46±0.71	9.90	12.70	0.309		
	10_min after exercise_Post	9.58±0.86	8.13	10.91	0.645	0.000	2.384
	MCR_Pre	1.33±0.48	0.54	2.03	0.493		
	MCR_Post	2.74±1.25	0.96	5.50	0.890		
	ΔMCR pre-post	1.41±1.25	0.18	4.19	0.583		
Smash Accuracy	Pre	28.25±4.43	21.00	36.00	0.564	0.000	2.110
	Post	36.33±3.11	32.00	42.00	0.066		
	Δpre-post	8.08±2.54	3.00	12.00	0.581		
Smash Speed (km/h)	Pre	269.59±4.26	263.65	274.94	0.853	0.000	2.201
	Post	279.58±4.80	273.25	286.93	0.129		
	Δpre-post	9.99±2.86	4.01	13.63	0.193		

HRR is heart rate recovery; MCR is Metabolic Clearance Rate; Δ is the difference between pre and post

Table 5. Physiological and Performance Outcomes in the Control Group After 8 Weeks of Traditional Training

Variable		Mean±SD	Min	Max	Shapiro-Wilk test	Paired t-test	ES Cohen's d
VO ₂ max (ml/kg/min)	Pre	48.23±3.27	43.62	54.06	0.747	0.109	0.656
	Post	50.51±3.67	45.29	55.69	0.245		
	Δpre-post	2.28±4.54	-4.69	12.07	0.809		
Heart rate (bpm)	Peak HR_Pre	193.83±6.46	186.00	205.00	0.311	0.635	0.184
	Peak HR_Post	195±6.28	185.00	205.00	0.664		
	After 1 min_Pre	166.33±9.54	151.00	182.00	0.571		
	After 1 min_Post	164.58±9.02	152.00	180.00	0.813	0.512	0.189
	HRR_Pre	27.5±6.65	12.00	40.00	0.087		
	HRR_Post	30.42±6.85	17.00	43.00	0.335		
	ΔHRR pre-post	2.92±2.84	-3.00	7.00	0.567		
Blood Lactate mmol/L	5_min after exercise_Pre	12.85±0.99	11.26	14.27	0.071	0.097	0.319
	5_min after exercise_Post	12.54±0.95	11.32	13.72	0.793		
	10_min after exercise_Pre	11.50±0.93	10.12	12.52	0.552	0.078	0.530
	10_min after exercise_Post	11.02±0.88	9.73	12.67	0.521		
	MCR_Pre	1.35±0.46	0.68	1.98	0.071		
	MCR_Post	1.52±0.72	0.12	2.60	0.603		
	ΔMCR pre-post	0.17±0.67	-0.87	1.58	0.273		
Smash Accuracy	Pre	28.83±4.59	21.00	35.00	0.062	0.000	0.661
	Post	31.75±4.24	24.00	39.00	0.268		
	Δpre-post	2.92±1.72	0.00	6.00	0.420		
Smash Speed (km/h)	Pre	265.03±4.49	259.90	275.26	0.751	0.000	1.143
	Post	270.41±4.91	264.85	279.27	0.747		
	Δpre-post	5.37±3.50	1.63	11.04	0.245		

HRR is heart rate recovery; MCR is Metabolic Clearance Rate; Δ is the difference between pre and post

Table 6. Between-Group Comparisons of Physiological and Performance Changes Across Sprint-Based HIIT, Skill-Integrated HIIT, and Control Conditions

Variable	Anova test	Group	p (sig.)	ES Cohen's d
ΔVO ₂ max (ml/kg/min)	0.005	HSB	HSI	1.000
			CON	0.014*
		HSI	CON	0.013*
ΔHeart rate HRR (bpm)	0.006	HSB	HSI	1.000
			CON	0.025*
		HSI	CON	0.010*
ΔLactic acid MCR (mmol/L)	0.018	HSB	HSI	1.000
			CON	0.043*
		HSI	CON	0.036*
ΔSmash Accuracy	0.000	HSB	HSI	0.002*
			CON	0.191
		HSI	CON	0.000
ΔSmash Speed (km/h)	0.001	HSB	HSI	1.000
			CON	0.002*
		HSI	CON	0.002*

*Significant difference at p<0.05; Post hoc test using the Bonferroni test; ES refers to Effect Size.

particularly in VO₂max and HRR, but demonstrated a more pronounced enhancement in smash accuracy. The magnitude of technical improvement suggests a stronger transfer of training stimulus to match-relevant motor execution.

The control group exhibited only modest changes across physiological and performance variables, with substantially smaller effect sizes compared to both HIIT interventions, indicating limited adaptation under traditional training conditions.

Between-group comparisons confirmed that both HIIT modalities elicited superior physiological adaptations compared to the control condition. However, only skill-integrated HIIT demonstrated significantly greater improvements in smash accuracy relative to sprint-based HIIT, whereas no between-HIIT differences were observed for VO₂max, HRR, MCR, or smash speed.

Figure 1 visually illustrates the magnitude and trajectory of pre-to-post changes across all outcome variables. Both HIIT groups demonstrate steeper improvement slopes compared to the control condition for physiological markers and performance measures. Notably, the divergence between skill-integrated HIIT and sprint-based HIIT is most evident in smash accuracy, where the skill-integrated protocol shows a more pronounced upward shift. In contrast, physiological adaptations appear comparable between the two HIIT modalities, reinforcing the statistical findings presented in Table 6.

Discussion

The present study demonstrates that both sprint-based and skill-integrated HIIT significantly enhanced aerobic capacity, autonomic recovery, and metabolic clearance compared to traditional training. The magnitude of VO₂max

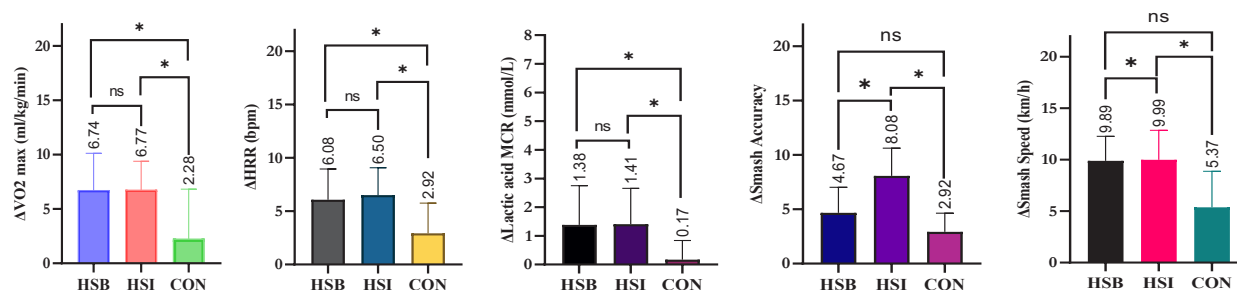


Fig 1. Graphical Representation of Pre-to-Post Intervention Changes in $VO_2 \text{ max}$, Heart Rate Recovery, Lactate Clearance, Smash Accuracy, and Smash Speed Among Groups. *significantly different; ns is not significantly different

improvement observed in both intervention groups is consistent with previous systematic reviews and meta-analyses reporting robust cardiorespiratory adaptations following HIIT in racket sport athletes (Alibrahim & Hassan, 2024; Liu et al., 2024; Wiesinger et al., 2024) while hemoglobin (Hb). Given the intermittent and high-intensity nature of badminton, improvements in aerobic capacity are particularly relevant for sustaining repeated high-intensity rallies and minimizing performance decrement across match duration (Cádiz Gallardo et al., 2023).

Both HIIT modalities also produced significant improvements in heart rate recovery (HRR), reflecting enhanced post-exercise autonomic reactivation. Faster HRR has been associated with improved cardiorespiratory fitness and competitive readiness (Plaza-Florido et al., 2019) HR has recently shown to be a stronger predictor of CRF than HRV in healthy young adults, yet these findings need to be replicated, in other age groups such as children. Therefore, this study aimed: (1, supporting the physiological relevance of the present findings. Similarly, the observed increases in metabolic clearance rate (MCR) indicate enhanced post-exercise lactate regulation, which is consistent with prior evidence suggesting that HIIT improves peripheral metabolic efficiency (Torma et al., 2019; Wiesinger et al., 2024). However, it is important to emphasize that molecular mechanisms such as monocarboxylate transporter upregulation were not directly assessed in this study; therefore, mechanistic explanations remain inferential rather than empirically confirmed.

Although physiological adaptations were comparable between HIIT formats, skill-integrated HIIT resulted in significantly greater improvements in smash accuracy compared to sprint-based HIIT. This finding aligns with the principle of training specificity, which posits that performance adaptations are optimized when training stimuli closely resemble competitive task demands (Araújo et al., 2023; Gabbett, 2006). Previous research in tennis and squash has shown that integrating technical execution within high-intensity training enhances stroke precision and performance transfer more effectively than non-specific conditioning alone (Irvan et al., 2024; Salem & Ismail, 2025). The present results extend this evidence to badminton, suggesting that embedding technical and decision-making components within high-intensity contexts may facilitate superior transfer to match-relevant motor execution.

Importantly, no significant differences were observed between the two HIIT modalities in $VO_2 \text{ max}$, HRR, MCR, or smash speed. This indicates that both training structures

are similarly effective in eliciting central and peripheral physiological adaptations, likely through shared overload mechanisms characteristic of high-intensity interval stimuli (Astorino et al., 2017; Liu et al., 2024). The added benefit of skill-integrated HIIT appears to be performance-specific rather than physiological. However, this interpretation should remain within the limits of the measured variables. The present study did not include biomechanical motion analysis, electromyography, or perceptual-cognitive assessments; therefore, conclusions regarding neuromuscular coordination pathways or perceptual-action coupling mechanisms cannot be definitively established.

Taken together, these findings suggest that while structured HIIT effectively enhances physiological readiness in badminton athletes, the integration of sport-specific technical demands within high-intensity training may provide additional advantages for precision-dependent skills such as smash accuracy. Future investigations incorporating biomechanical and neurophysiological measurements are warranted to clarify the mechanisms underlying this performance transfer.

Conclusions

Both sprint-based and skill-integrated HIIT significantly enhanced aerobic capacity, autonomic recovery, metabolic clearance, and smash performance compared to traditional training. No meaningful differences were observed between HIIT modalities for physiological adaptations. However, skill-integrated HIIT resulted in superior improvements in smash accuracy, indicating a greater transfer to sport-specific technical performance.

These findings suggest that while high-intensity interval training is effective for improving physiological readiness in badminton players, integrating technical components within high-intensity contexts may provide additional performance-specific benefits. Future studies incorporating biomechanical and neuromuscular analyses are warranted to clarify the mechanisms underlying these adaptations.

Data and AI Transparency Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. Due to ethical considerations and the protection of participant confidentiality, individual-level raw data are not publicly accessible. All aggregated data supporting the findings of this study are presented within the article.

The authors further declare that artificial intelligence (AI)-assisted tools were used solely for language editing and manuscript refinement. Specifically, QuillBot and Grammarly were utilized to improve grammatical accuracy, clarity, and academic writing style. No AI tools were used in study conception, methodological design, data collection, statistical analysis, data interpretation, or the generation of scientific conclusions. All scientific content and analytical decisions were independently developed and verified by the authors, who assume full responsibility for the integrity and accuracy of the manuscript.

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Conflict of Interest

All researchers declare that there is no conflict of interest in this research

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Диференційовані нейром'язові адаптації до високоінтенсивного інтервального тренування, інтегрованого з технічними діями, порівняно зі спринт-орієнтованим: наслідки для ігрової результативності у ракеткових видах спорту

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 11 с., 6 табл., 1 рис., 22 джерела.

Обґрунтування. Ефективна гра в бадмінтон вимагає підтримання високого рівня фізичного навантаження при одночасному збереженні точного технічного виконання в умовах втоми. Водночас існує обмежена кількість досліджень, що порівнюють спринт-орієнтований високоінтенсивний інтервальный тренінг (НІІТ) та НІІТ, інтегрований із технічними діями, з точки зору їх фізіологічного впливу та перенесення на ігрову діяльність. Відомо, що НІІТ є ефективним засобом підвищення аеробної працездатності та відновлення.

Мета. Вивчити вплив спринт-орієнтованого НІІТ та НІІТ, інтегрованого з технічними діями, на аеробну працездатність, автономне відновлення, метаболічний кліренс, точність і швидкість смєша у тренуваних гравців у бадмінтон.

Матеріали і методи. У дослідженні взяли участь 36 гравців у бадмінтон регіонального рівня (18–25 років), яких стратифіковано за віком і базовим рівнем VO₂max та випадково розподілено на три групи: спринт-орієнтований НІІТ (HSB; n = 12), НІІТ, інтегрований з технічними діями (HSI; n = 12), і контрольна група (CON; n = 12). Обидві НІІТ-програми реалізовано протягом 8 тижнів за періодизованою схемою з частотою три рази на тиждень та інтенсивністю 80–95% від максимального серцевого ритму (HRmax). VO₂max оцінювали за допомогою градуйованого тесту на біговій доріжці; відновлення частоти серцевих скорочень (HRR) — з використанням моніторів Polar H10; концентрацію лактату в крові визначали за допомогою аналізаторів Accutrend Plus® через 5 і 10 хв після навантаження. Точність смєша оцінювали за валідованим протоколом із цільовою системою балів, швидкість смєша — за допомогою радару. Дані аналізували методом двохфакторного дисперсійного аналізу з повторними вимірюваннями (ANOVA) із поправкою Бонферроні (p < 0,05). Розміри ефекту визначали за коефіцієнтом d Коена.

Результати. У групах HSB і HSI виявлено статистично значуще підвищення VO₂max (HSB: +6,7; HSI: +6,8 мл·кг⁻¹·хв⁻¹, p < 0,001), HRR (HSB: +6,1; HSI: +6,5 уд/хв, p < 0,001) та швидкості метаболічного кліренсу (p < 0,01), причому ці зміни перевищували показники контрольної групи (p < 0,05). Швидкість смєша зросла подібною мірою в обох НІІТ-групах (приблизно +10 км/год, p < 0,001). Водночас у групі HSI зафіксовано значно більші покращення точності смєша по-

рівняно з HSB (HSI: +8,1 проти HSB: +4,7 бала; $p = 0,002$), тоді як у контрольній групі зміни були мінімальними за всіма показниками.

Висновки. Спринт-орієнтований та інтегрований із технічними діями HIIT ефективно покращують фізіологічні показники гравців у бадмінтон. Водночас лише HIIT, інтегрований із технічними діями, забезпечує суттєве підвищення технічної результативності. Поєднання високоінтенсивного тренування зі специфічним виконанням технічних дій є оптимальним підходом до підготовки спортсменів до змагальної діяльності.

Ключові слова: високоінтенсивний інтервальний тренінг, результативність у бадмінтоні, нейром'язова адаптація, специфічна спортивна підготовка, точність смеша.

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The Impact of Functional Movement Strength Training on Core Muscle Activation and Trunk Kinematics During Jumping Heading in Adolescent 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. Functional Movement Strength Training (FMST) integrates functional, strength, and plyometric exercises to enhance neuromuscular coordination and movement performance. Although these training modalities have been investigated individually in soccer, their combined effects on core muscle activation and trunk kinematics during jumping heading in adolescent players remain unclear.

Objectives. This study aimed to examine the effects of an eight-week FMST program on core muscle activation and trunk kinematics during jumping heading in adolescent male soccer players.

Materials and Methods. A quasi-experimental pretest–posttest design with a control group was employed. Thirty adolescent soccer players were allocated into an Experimental Group (EG; $n = 16$), which completed an eight-week FMST program (three sessions per week), and a Control Group (CG; $n = 14$), which continued regular training. Muscle activity was assessed using surface electromyography, and kinematic variables of the neck, trunk, hip, knee, and ankle were analyzed during the preparation, take-off, and ball-contact phases of jumping heading. Data were analyzed using Linear Mixed Model analysis.

Results. A significant Group $\times$ Time interaction was observed for rectus abdominis (RA) activation ($p < 0.05$), with greater increases in the EG compared to the CG. Furthermore, significant interactions were also found for hip angle during the preparation phase, and for neck angle and trunk tilt during the take-off phase ($p < 0.05$). No significant differences were identified during the ball-contact phase.

Conclusions. Using FMST was associated with increased RA activation and phase-specific modifications in trunk-related kinematics during jumping heading. These findings suggest that integrated training approaches may enhance trunk control and neuromuscular coordination in adolescent soccer players.

Keywords: soccer, heading, functional training, kinematics, electromyography and muscle activity.

Introduction

Among adolescents, soccer is a popular sport in Africa, America, the Eastern Mediterranean, and Europe, with a prevalence of approximately 30% (Hulteen et al., 2017). Soccer is a unique sport because it can use the head to contact the ball, which is called heading (Bonn et al., 2021). Heading can be used to score goals, defense and offense, control, or pass the ball, which is an integral part of football (Sandmo et al., 2020). At the 2018 World Cup in Russia,

heading contributed 18.9% of all goals scored (Mićović et al., 2023).

Heading is a complex and multidimensional component of soccer involving mechanical demands across all parts of the body (Mehnert et al., 2005; Shewchenko et al., 2005). The kinematics heading were preparation, ball contact and follow-through (Rusdiana et al., 2020; Sekine et al., 2022). The greater hyperextension of the trunk during the preparation phase, the greater the speed at which the trunk comes into contact with the ball, thus providing which has been associated with greater trunk velocity and force generation (Kirkendall & Garrett, 2001; Rusdiana et al., 2020). The trunk flexes forward to contact the ball (Doewes et al., 2023; Rusdiana et al., 2020; Sekine et al., 2022) while the head

and shoulders move in unison with the trunk (Doewes et al., 2023; Rusdiana et al., 2020). Stability and stiffness in the cervical region are essential to minimize unwanted angular movements, enabling the head–neck–trunk unit to function as a single, complex unit (Caccese et al., 2018).

Core muscles are muscles critically involved in and play an important role during activities such as jumping, heading (Becker et al., 2018; Eckner et al., 2018; Kristensen et al., 2004). Defined as the muscles around the hips and trunk, the core muscles are vital. The abdominal muscles, in particular, are strongly activated before and during ball contact to maintain body stability throughout the preparation and contact phases (Sekine et al., 2022). Core muscles are needed to support the jump (Kumahara et al., 2021; Sasaki et al., 2019) and to maintain balance when dynamic motion (Lifshitz et al., 2020). In a jumping heading, the core musculature is essential, not only to provide kinetic momentum but also to stabilize and ready the lower limbs (Sasaki et al., 2019).

Previous research has examined various training interventions to enhance heading performance. Plyometric training has been shown to improve jump height in heading contexts (Matsuda et al., 2024). Neck strengthening protocols have produced inconsistent findings: no significant effects on neck and head kinematics (Doewes et al., 2023), whereas improvements in head kinematics following combined neck and trunk strengthening (Müller & Zentgraf, 2021). Trunk-focused interventions have also been shown to modify abdominal muscle activation patterns during heading (Sekine et al., 2022). Beyond heading-specific interventions, functional training has been widely investigated for general soccer performance enhancement (Carvutto et al., 2021; Jia, 2023; Philip et al., 2022).

Despite these findings, several important gaps remain. First, previous studies have typically examined functional training, strength training, and plyometric training as isolated or partially combined interventions. To date, no study has integrated these three components within a single structured program specifically targeting jumping heading performance in adolescent soccer players. Second, prior investigations have generally focused on either muscle activation patterns or kinematic variables independently, with limited studies simultaneously evaluating both neuromuscular activation and segmental kinematics during distinct phases of jumping heading. Third, most biomechanical and intervention studies on heading have involved adult or collegiate populations (Müller & Zentgraf, 2021; Sekine et al., 2022), whereas evidence specific to adolescent players remains scarce. Considering that neuromuscular maturation and motor control strategies are still developing during adolescence (Sonesson et al., 2022), training adaptations in this population may differ from those observed in adults.

Functional Movement Strength Training (FMST) represents an integrative training approach that combines elements of functional training, resistance-based strength development, and plyometric exercise within a structured program. Such an approach is theoretically aligned with the biomechanical demands of jumping heading, which requires coordinated trunk stabilization, lower-limb force production, and efficient energy transfer between body segments. By simultaneously targeting neuromuscular control, force-generating capacity, and explosive movement

characteristics, FMST may provide a comprehensive stimulus relevant to sport-specific performance adaptations.

Therefore, the purpose of this study was to investigate the effects of an eight-week Functional Movement Strength Training (FMST) program on core muscle activation patterns and trunk kinematics during jumping heading in adolescent soccer players. We hypothesized that FMST would be associated with (1) greater core muscle activation during jumping heading and (2) phase-specific modifications in trunk kinematics compared with regular training alone.

Materials and Methods

Study Design and Participant

The present study employed a quasi-experimental pretest–posttest design with a control group. Two soccer schools (SSB) affiliated with the local football association (ASKOT) were purposively selected for participation. Both SSBs competed at the same regional level and followed comparable regular training schedules (three sessions per week), ensuring a relatively similar training background prior to the intervention. Group allocation was performed at the cluster level, whereby one SSB was assigned to the experimental group and the other to the control group. This cluster-based assignment was implemented to prevent contamination between training programs and to maintain ecological validity within a real-world youth soccer training environment.

A total of 30 Indonesian male adolescent soccer players with a minimum of one year of playing experience were recruited for the study. Players from the SSB assigned to the experimental group comprised 16 participants (EG; $n = 16$), while players from the other SSB formed the control group (CG; $n = 14$). All participants were actively engaged in regular soccer training at their respective SSBs throughout the study period. The EG had a mean age of 16.00 ± 0.86 years, height of 166.81 ± 5.63 cm, body mass of 58.81 ± 6.75 kg, and body mass index (BMI) of 21.11 ± 2.00 kg/m². The CG had a mean age of 15.64 ± 0.71 years, height of 164.92 ± 6.81 cm, body mass of 49.92 ± 10.51 kg, and BMI of 18.22 ± 2.99 kg/m². Exclusion criteria included (1) failure to obtain written parental or guardian consent, (2) the presence of a current musculoskeletal injury or ongoing injury rehabilitation, and (3) playing in the goalkeeper position.

Prior to data collection, all participants and their parents or legal guardians were informed about the study objectives, procedures, potential benefits, and risks, and written informed consent was obtained. The study protocol was reviewed and approved by the Ethical Clearance Committee of Dr. Soetomo General Hospital (RSUD Dr. Soetomo), Surabaya, Indonesia (Reference No: 1250/KEPK/III/2025), and all procedures were conducted in accordance with the Declaration of Helsinki.

FMST Intervention

The EG completed an eight-week FMST program in addition to their regular soccer training, whereas the CG continued their usual soccer training without additional intervention. The FMST program was implemented over eight consecutive weeks, with three sessions per week (total:

Table 1. Program Design FMST

Week	Modul	Exercise	Sets × Repetitions	Rest
1-2	Mobility & Motor Control	90/90 hip stretch; Spiderman Stretch; Straight-leg adductor Rocking; Half-kneeling hip flexor Stretch; Nordic Hamstring; Squat; Unassisted Leg Lower; squats; Lunge	2–3 sets × 8–12 reps	30-45 s
3-4	Strength & Power (Neck And Core Muscle)	Head Ball Isometric Partner-assisted; Neck Resistance; Neck Band (Flexi & Extension); Quadruped hip extension on elbows; Quadruped alternating arm and leg; Sit-Up; Push Up; Russian Twist; Reach-Through Tug of War; Throw Ball	3 sets × 8–12 reps	60 s
5-6	Strength & Power (Core And Leg Muscle)	Plank; Abdominal Cruch; Single Leg Squat; Sprint 20 meter; Glute bridge; Glute bridge—one leg lift; V-up; Oblique bridge; Trunk stability Rotation Knee flexed; Lunges; Sit Up	3 sets × 10–12 reps	90 s
7-8	Plyometrics	Cone Hop; Hurdle Jump (10-30 cm); Box jump; Single leg hop Zig zag;	3 sets × 6–8 reps	90-120s

24 sessions). Each session lasted approximately 60 minutes and followed a progressive periodized structure.

Weeks 1–2 (Foundation Phase): Emphasis was placed on mobility, postural alignment, and fundamental motor control exercises to establish movement quality and trunk stabilization. Weeks 3–6 (Strength Development Phase): Training focused on progressive resistance exercises targeting the neck, trunk, and lower-limb musculature through multi-joint functional movements. External resistance and exercise complexity were gradually increased. Weeks 7–8 (Power and Plyometric Phase): Plyometric and explosive movement drills were incorporated to stimulate stretch–shortening cycle activity and inter-segmental coordination relevant to jumping tasks. Exercise intensity and task complexity were progressively increased across phases to ensure overload and adaptation. A detailed description of the FMST protocol, including specific exercises and volume parameters, is presented in Table 1.

Data Measurement and Experimental Task

Data collection was conducted at the Gait and Motion Laboratory of Dr. Soetomo General Hospital, Surabaya. Participants performed a standardized jumping heading without a run-up, starting from a stationary position and barefoot to ensure consistent ground interaction. The ball was suspended at a height corresponding to each participant's standing height to standardize task demands. Participants performed a forward jumping header (not lateral), and arm swing was permitted to replicate natural movement. Two successful trials were recorded for each participant, and the mean values were used for analysis.

Muscle Activation

Core and lower-extremity muscle activity was assessed using surface electromyography (sEMG) with an eight-channel system (HW-SYSTEM 8CH, Mega Electronics Ltd., Finland) and Peak Module 2000 software. Electrodes were placed on the dominant side, defined as the preferred side for daily activities; when dominance was unclear, the right side was selected for consistency. Skin preparation included shaving (if necessary), cleaning, and drying to reduce impedance.

Muscles analyzed included the sternocleidomastoid (SCM), rectus abdominis (RA), erector spinae (ES), gluteus maximus (GMax), biceps femoris (BF), vastus medialis (VM),

and gastrocnemius (GC). EMG signals were also recorded from the hip flexor region corresponding anatomically to the psoas major (PM); however, this signal represents activity of the superficial hip flexor region rather than the deep psoas major muscle specifically. Bipolar electrode configurations were applied according to SENIAM recommendations.

EMG signals were sampled at 1000 Hz and band-pass filtered between 20 and 450 Hz. Signals were full-wave rectified and processed using a root mean square (RMS) algorithm with a 100-ms moving window using MATLAB software. Raw EMG data were processed by laboratory personnel, and only RMS amplitude outputs were provided for analysis.

EMG amplitudes were not normalized to maximal voluntary contraction (MVC). Therefore, RMS values were analyzed as non-normalized amplitudes to examine relative changes in muscle activation patterns across the preparation, take-off, and ball-contact phases. Findings were interpreted in terms of relative neuromuscular activation changes rather than absolute muscle activation levels.

Kinematics Analysis

Jumping heading kinematics were recorded and analyzed using an AMTI ORG 05 motion analysis system in conjunction with CMAX (Clinical Motion Analysis System) software version 2016 and using a Basler acA2000-50gc camera operating at 100 Hz. All kinematic variables were analyzed in the sagittal plane. The kinematic variables analyzed included joint angles of the neck, trunk, hip, knee, and ankle. Joint angle definitions were adapted from previously published studies (Wojtusch & Von Stryk, 2015). Reflective markers were placed on specific anatomical landmarks to calculate segmental angles. The neck angle was defined using the tragus, seventh cervical vertebra (C7), and acromion. The trunk angle was defined using the seventh cervical vertebra (C7), eighth thoracic vertebra (T8), and fifth lumbar vertebra (L5). The hip angle was determined using the acromion, greater trochanter, and lateral knee joint line. The knee angle was defined by the greater trochanter, lateral knee joint line, and lateral malleolus. The ankle angle was defined using the lateral knee joint line, lateral malleolus, and the second metatarsophalangeal (MTP) joint.

The jumping heading movement was divided into three phases: preparation, take-off, and ball contact. The preparation

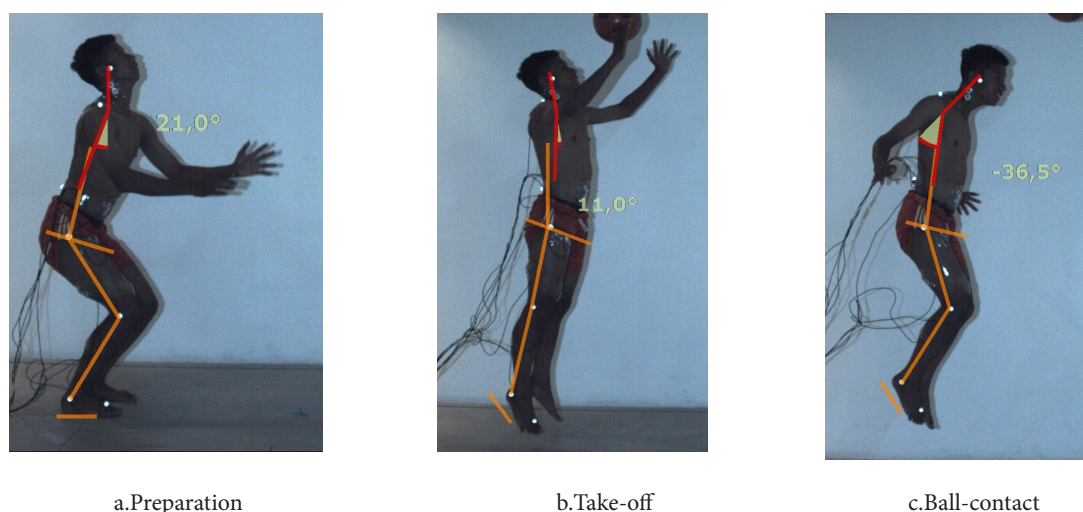


Fig. 1. Kinematics jumping heading

phase was defined as the period from the initiation of trunk extension to the onset of knee flexion. The take-off phase was defined from peak knee flexion to toe-off, and the ball-contact phase was defined as the interval surrounding initial head-ball contact, as illustrated in Figure 1. Mean joint angles for each phase were extracted for statistical analysis. Each participant completed two successful trials, and the average values were used for subsequent analyses.

Statistical analysis

Descriptive statistics (mean and standard deviation) were calculated for all variables. Baseline differences between groups were examined prior to intervention. Statistical analysis was performed using a Linear Mixed Model (LMM) to account for the repeated-measures design. Group (Experimental vs. Control), Time (Pre-test vs. Post-test), and the Group $\times$ Time interaction were included as fixed effects, with participants specified as random effects. The primary outcome of interest was the Group $\times$ Time interaction, which examined whether changes in muscle activation and kinematic variables during the jumping heading task differed between groups over time. All analyses were two-tailed, with statistical significance set at $p < 0.05$. Statistical analyses were conducted using SPSS version 27 (IBM Corp., Armonk, NY, USA).

Results

Figure 2 and Figure 3 illustrate the temporal patterns and RMS amplitude of muscle activity across the preparation, take-off, and ball-contact phases of the jumping heading task. Following the FMST intervention, the Experimental Group (EG) demonstrated higher RMS EMG amplitudes across all analyzed muscles during the post-test compared with the pre-test. In contrast, the Control Group (CG) showed minimal changes in EMG amplitude across testing sessions.

In the EG, the activation of the sternocleidomastoid (SCM), rectus abdominis (RA), erector spinae (ES), and gastrocnemius (GC) muscles occurred earlier during the post-test compared with the pre-test. No notable changes in activation were observed in the CG.

Across both groups, during the preparation phase, increased activation was observed in trunk and hip-related musculature, particularly the erector spinae (ES). During the take-off phase, activation of lower-limb muscles, including the gastrocnemius (GC), biceps femoris (BF), vastus medialis (VM), and gluteus maximus (GMax), became more pronounced. In the ball-contact phase, concurrent activation of the sternocleidomastoid (SCM) and rectus abdominis (RA) was observed. ES activity peaked prior to ball contact and gradually decreased thereafter.

Table 2 presents the results of the LMM for RMS muscle activity during the jumping heading. A significant Group $\times$ Time interaction was observed for the rectus abdominis (RA) muscle ($F = 6.12$, $p = 0.02$). The EG demonstrated higher RMS EMG values at post-test compared with pre-test, whereas no significant changes were observed in the Control Group. No significant Group $\times$ Time interactions were found for the remaining muscles ($p > 0.05$), indicating that changes in RMS EMG amplitude over time did not differ significantly between groups for these muscles.

Table 3 summarizes the LMM results for kinematic variables during the jumping heading. Significant Group $\times$ Time interactions were identified in specific movement phases. During the preparation phase, a significant interaction was observed for the hip angle ($F = 7.29$, $p = 0.01$), indicating greater pre-post changes in the EG compared with the CG.

During the take-off phase, significant Group $\times$ Time interactions were found for the neck angle ($F = 5.48$, $p = 0.02$) and trunk tilt angle ($F = 11.43$, $p < 0.01$). No significant Group $\times$ Time interactions were observed for any kinematic variables during the ball-contact phase ($p > 0.05$).

Discussion

This study investigated the effects of an eight-week FMST program on core muscle activation and trunk kinematics during jumping heading in male adolescent soccer players. LMM analysis revealed significant Group $\times$ Time interactions for RA activation and selected trunk-related kinematic variables, indicating that temporal changes differed between the EG and CG. Given the anatomical and functional role of the trunk in integrating core musculature

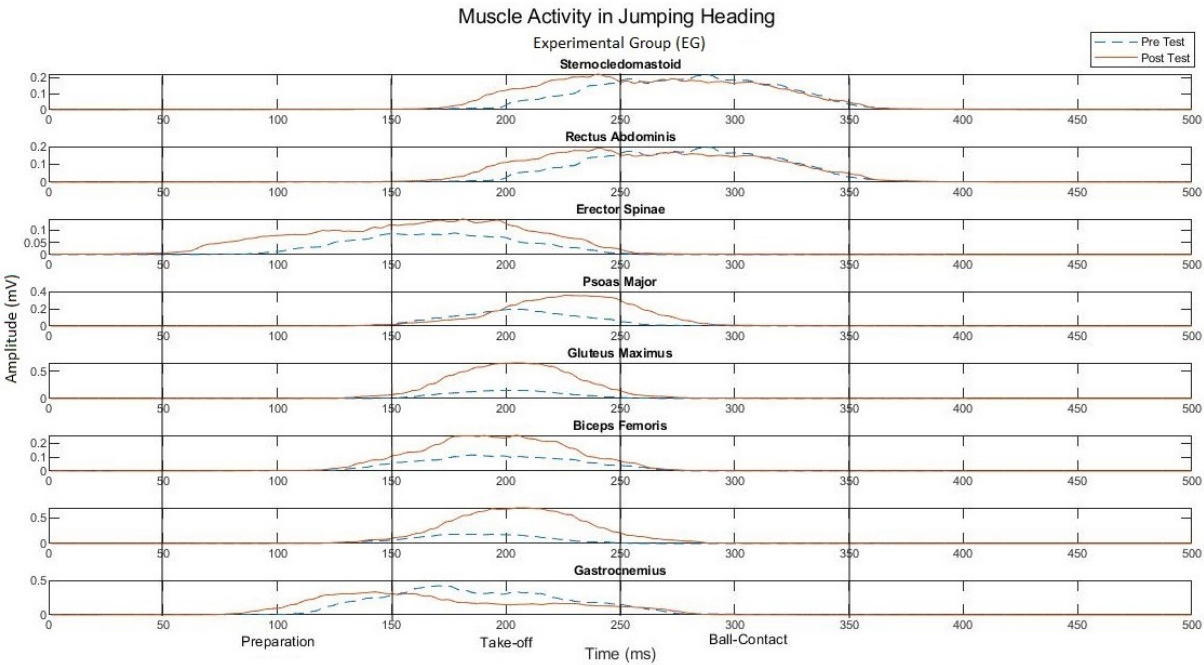


Fig. 2. Muscle activity during jumping heading was measured in the experimental group (EG)

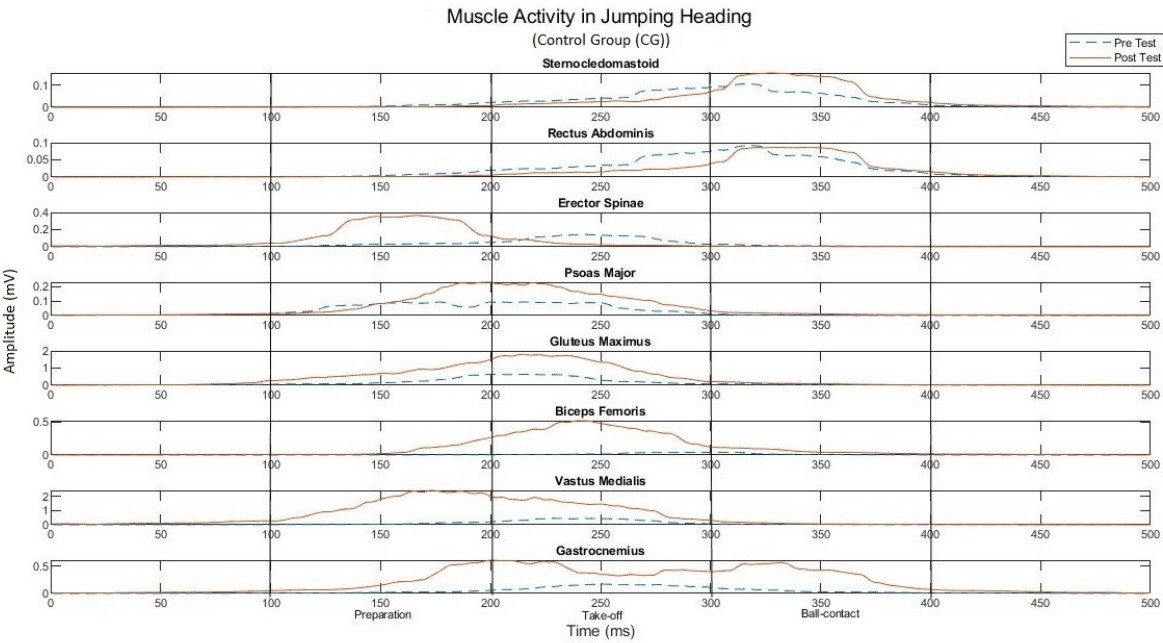


Fig.3. Muscle activity during jumping heading was measured in the control group (CG)

and coordinating multi-segmental movement, these findings suggest that FMST may induce alterations in neuromuscular activation magnitude and trunk movement characteristics during jumping heading.

The FMST program was associated with altered muscle activation patterns, characterized by increased RMS EMG amplitude during jumping heading. These changes in activation magnitude may reflect improved neuromuscular efficiency and altered motor unit recruitment strategies. Efficient neuromuscular function is governed by motor unit recruitment patterns (Aslam et al., 2025), with key

adaptations including elevated firing rates, changes in recruitment thresholds, and enhanced motor neuron responsiveness to synaptic inputs (Del Vecchio et al., 2019).

The ES demonstrated descriptively higher RMS amplitudes following the intervention, although these changes were not statistically significant. This adaptation suggests enhanced trunk engagement during the preparatory and propulsive phases of jumping heading. Specifically, greater ES activity facilitates trunk extension during take-off, optimizing body positioning prior to ball contact. Concurrently, lower-limb musculature, including the GC,

Table 2. LMM results for root mean square (RMS) electromyography (EMG) activity during the jumping heading

RMS (mV)		EG		CG		Linear Mixed Model					
		Pre	Post	Pre	Post	Group		Time		Group x Time	
						F	p	F	p	F	p
SCM	M	0.48	0.52	0.30	0.25	19.45	<0.01	0.01	0.95	2.97	0.09
	SD	0.17	0.18	0.15	0.07						
RA	M	0.39	0.44	0.27	0.21	15.91	<0.01	0.26	0.60	6.12	0.02*
	SD	0.14	0.16	0.13	0.05						
ES	M	0.28	0.46	0.19	0.19	4.04	0.05	1.28	0.26	1.26	0.27
	SD	0.13	0.61	0.06	0.08						
PM	M	0.29	0.33	0.23	0.23	4.28	0.04	2.44	0.12	1.85	0.18
	SD	0.13	0.13	0.06	0.11						
GMax	M	0.42	0.51	0.49	0.54	0.21	0.64	2.12	0.15	0.25	0.61
	SD	0.24	0.28	0.43	0.37						
BF	M	0.18	0.21	0.27	0.21	1.55	0.22	0.27	0.60	3.34	0.07
	SD	0.08	0.07	0.2	0.09						
VM	M	0.47	0.52	0.50	0.40	0.97	0.33	0.40	0.52	3.77	0.06
	SD	0.14	0.15	0.16	0.14						
GC	M	0.49	0.51	0.49	0.50	0.01	0.93	0.16	0.68	0.20	0.88
	SD	0.13	0.14	0.18	0.29						

Note: *) p-value<0.05; M: Mean; SD: Standard Deviation; SCM: Sternocleidomastoid; RA: Rectus Abdominis; ES: Erector Spinae; PM: Psoas Major; GMax: Gluteus Maximus; BF: Biceps Femoris; VM: Vastus Medialis; GC: Gastrocnemius; EG: Experimental Group; CG: Control Group.

Table 3 The results LMM on kinematic jumping heading

Kinematics (°)		EG		CG		Linear Mixed Model					
		Pre	Post	Pre	Post	Group				Group x Time	
						F	p	F	p	F	p
Preparation											
Neck Angle	M	11.53	16.97	16.72	18.77	2.61	0.11	11.13	0.00	2.46	0.12
	SD	5.5	8.31	5.08	6.79						
Trunk Tilt	M	7.58	11.7	8.45	9.64	0.01	0.89	2.54	0.12	0.64	0.42
	SD	7.43	7.93	7.72	7.92						
Hip Angle	M	32.98	35.71	42.44	38.43	2.46	0.12	0.02	0.88	7.29	0.01*
	SD	11.5	12.46	9.69	7.29						
Knee Angle	M	59.62	59.94	72.64	69.96	7.05	0.01	0.36	0.55	0.84	0.36
	SD	12.28	15.33	12.59	10.25						
Ankle Angle	M	21.26	17.68	27.28	26.48	6.40	0.01	1.24	0.27	0.36	0.55
	SD	10.1	9.37	4.65	8.63						
Take-off											
Neck Angle	M	41.82	32.33	41.15	35.52	7.60	0.01	1.2	0.28	5.48	0.02*
	SD	11.72	13.71	13.89	8.77						
Trunk Tilt	M	17.47	24.16	11.31	9.75	15.58	<0.01	4.74	0.03	11.43	<0.01*
	SD	9.17	9.69	5.77	6.82						
Hip Angle	M	3.63	6.2	7.97	7.9	5.39	0.02	1.68	0.20	1.83	0.18
	SD	3.31	2.8	7.07	3.7						
Knee Angle	M	5.83	7.77	10.78	11.1	4.26	0.04	0.61	0.43	0.26	0.60
	SD	5.85	6.41	8.34	5.62						
Ankle Angle	M	32.5	40.63	31.16	36.85	0.59	0.44	14.45	<0.00	0.51	0.47
	SD	7.68	13.22	10.41	11.13						
Ball-contact											
Neck Angle	M	41.82	32.33	41.15	35.52	0.08	0.77	14.18	<0.01	0.83	0.37
	SD	11.72	13.71	13.89	8.77						
Trunk Tilt	M	6.16	8.12	8.34	5.72	0.75	0.39	1.34	0.25	1.34	0.25
	SD	6.01	5.68	6.57	3.36						
Hip Angle	M	20.65	21.84	21.68	20.4	0.03	0.85	0.03	0.85	1.80	0.19
	SD	7.23	7.1	7.14	7.74						
Knee Angle	M	11.91	11.47	12.42	17.56	0.38	0.54	1.96	0.17	0.43	0.51
	SD	10.01	8.87	6.87	15.55						
Ankle Angle	M	32.13	38.43	32.12	37.56	0.01	0.99	8.02	0.01	0.01	0.99
	SD	10.81	16.24	10.08	8.88						

Note: *) p<0.05; M: Mean; SD: Standart Deviation; EG: Experimental Group; CG: Control Group.

exhibited increased activation during preparation, reflecting enhanced readiness for vertical propulsion.

The RA exhibited elevated activation during the take-off phase, with temporal patterns synchronous with the SCM. This coordination suggests integrated recruitment of trunk and neck musculature during movement preparation. Notably, RA activity increased markedly at ball contact, likely contributing to trunk stabilization during impact. Biomechanically, the core musculature functions as the primary stabilizer and mobilizer during jumping heading, controlling trunk motion to ensure appropriate extension and forward progression toward the ball (Sekine et al., 2022). The observed increases in muscle activation magnitude following FMST support the notion of improved trunk control and inter-muscular coordination.

The significant Group $\times$ Time interaction for RA activation indicates greater increases in RMSEMG amplitude in the EG compared with the CG. These changes should be interpreted as neuromuscular adaptations rather than direct indicators of muscle hypertrophy or maximal strength gains. Previous research has demonstrated that functional and strength-based training interventions can modify neuromuscular activation and inter-muscular coordination during sport-specific tasks (Khazaei et al., 2023; Wang et al., 2024; Xiao et al., 2021).

Increased RMS EMG amplitude is commonly associated with altered motor unit recruitment strategies, enhanced neural drive, or improved motor unit synchronization (Aslam et al., 2025; Del Vecchio et al., 2019). In the present context, higher RA activation in the EG likely reflects improved recruitment efficiency and enhanced muscle coordination rather than absolute force production capacity. Functional training emphasizes multi-planar movements, multi-joint coordination, and dynamic postural demands, which may facilitate adaptations in postural control and movement coordination during complex actions such as jumping heading (Xiao et al., 2025).

FMST demonstrated a significant Group $\times$ Time interaction ($p < 0.05$) for trunk tilt during the take-off phase. This kinematic change aligns with the observed increases in ES and RA activation amplitudes, suggesting coordinated adaptations in trunk musculature recruitment and positioning strategy. Alterations in preparatory trunk positioning may reflect improved trunk control and modified movement strategies following training.

During take-off, the capacity to achieve greater trunk extension or increased tilt angle is biomechanically advantageous, as this enhanced range of motion generates greater momentum upon ball contact (Kirkendall & Garrett, 2001). Functional training induces kinematic adaptations by emphasizing the integration of upper and lower body motion alongside improvements in motor control (Khazaei et al., 2023). Such approaches focus on coordinated movement patterns across multiple body segments, which may facilitate phase-specific trunk kinematic adjustments during complex sport-specific tasks (Tomljanović et al., 2011). Collectively, these findings suggest that FMST may elicit phase-specific modifications in trunk kinematics, particularly during the preparatory stage of jumping heading.

Several limitations should be acknowledged. First, the sample was restricted to male adolescent players; future research should incorporate broader age ranges and

female athletes to enhance generalizability. Second, EMG measurements were limited to the dominant side and assessed RMS amplitude only; future studies should incorporate onset timing analysis and bilateral assessment to provide comprehensive insight into neuromuscular timing and potential inter-limb asymmetries. Third, the experimental paradigm did not include actual ball delivery, potentially limiting ecological validity. Finally, objective performance outcomes—such as ball velocity and heading accuracy—were not assessed and should be incorporated in subsequent investigations to determine the functional significance of these neuromuscular and kinematic adaptations.

Conclusions

This study demonstrates that an eight-week FMST program is associated with changes in core muscle activation patterns and phase-specific trunk kinematics during jumping heading in male adolescent soccer players. Notably, FMST was linked to greater RA activation and modifications in preparatory trunk positioning, which may reflect adaptations in neuromuscular control and movement strategy. These findings suggest that FMST may be a practical and time-efficient training approach to support the development of soccer-specific movement mechanics, particularly jumping heading, in adolescent players.

Ethics Approval

This study was approved by the Ethical Clearance Committee of RSUD Dr. Soetomo Surabaya East Java Indonesian (Reference No: 1250/KEPK/III/2025)

Informed Consent

Written informed consent was obtained from all participant and their legal guardians.

Data Availability Statement

Data are not publicly available due to ethical or privacy restrictions.

AI Transparency Statement

The authors used AI-assisted (DeepL and ChatGPT) tools for language editing only and take full responsibility for the content.

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Conflict of interest

The authors declare no conflict of interest.

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Вплив функціонального силового тренування рухів на активацію м'язів кору та кінематику тулуба під час виконання удару головою у стрибку у футболістів підліткового віку

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 10 с., 3 табл., 3 рис., 22 джерела.

Обґрунтування. Функціональне силове тренування рухів (ФСТР) поєднує в собі функціональні, силові та пліометричні вправи для покращення нервово-м'язової координації та результативності рухів. Попри наявність досліджень цих методів тренування у футболі як окремих компонентів, їхній комбінований вплив на активацію м'язів кору та кінематику тулуба під час удару головою у стрибку у гравців підліткового віку залишається недостатньо вивченим.

Мета. Це дослідження мало на меті вивчити вплив восьми тижневої програми функціонального силового тренування рухів на активацію м'язів кору та кінематику тулуба під час удару головою у стрибку у футболістів підліткового віку.

Матеріали та методи. У дослідженні застосовано квазіекспериментальний претест-посттестовий дизайн із контрольною групою. Тридцять футболістів підліткового віку були розподілені на експериментальну групу (ЕГ; n = 16), яка виконувала восьми тижневу програму ФСТР (три заняття на тиждень), та контрольну групу (КГ; n = 14), що продовжувала регулярні тренування. Активність м'язів оцінювали за допомогою поверхневої електроміографії, а кінематичні показники шиї, тулуба, стегна, колінного та гомілковостопного суглобів аналізували під час фаз підготовки, відштовхування та контакту з м'ячем при ударі головою у стрибку. Аналіз даних проводився з використанням лінійної змішаної моделі.

Результати. Спостерігалася значуща взаємодія Група $\times$ Час для активації прямого м'яза живота (ПМЖ) ($p < 0.05$), причому в експериментальній групі (ЕГ) встановлено суттєвіше зростання порівняно з контрольною групою (КГ). Крім того, значущі взаємодії було виявлено для кута згинання стегна під час фази підготовки, а також для кута нахилу шиї та тулуба під час фази відштовхування ($p < 0.05$). Під час фази контакту з м'ячем значущих відмінностей виявлено не було.

Висновки. Застосування програми ФСТР асоційоване з підвищеною активацією прямого м'яза живота та фазово-специфічними модифікаціями кінематичних показників тулуба під час удару головою у стрибку. Отримані результати свідчать про те, що підходи на основі інтегрованого тренування сприяють покращенню контролю тулуба (стабільності корпусу) та нервово-м'язової координації у футболістів підліткового віку.

Ключові слова: футбол, удар головою, функціональне тренування, кінематика, електроміографія, м'язова активність.

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Determining the Structure and Integral Assessment of Technical and Tactical Activity in Highly Qualified Football Players across Different Playing Positions

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Abstract

Objectives. The study aimed to determine the structure and integral assessment of technical and tactical activity in highly qualified football players across different playing positions based on a systematic approach.

Materials and Methods. The study was conducted during the UEFA European Football Championships in 2021 and 2024. The competitive activity of football players representing the national teams of England, Spain, Italy, Denmark, the Netherlands, Belgium, Romania, Slovenia, Austria, Switzerland, Sweden, North Macedonia, Serbia, and Ukraine was analyzed. The following research methods were applied: theoretical analysis of scientific sources and literature, pedagogical observation, video analysis of competitive activity, and methods of mathematical statistics.

Results. The technical and tactical activity structure in highly qualified football players across different playing positions — full-backs, central defenders, defensive midfielders, central midfielders (inside midfielders), wide midfielders (wingers), and forwards — was determined. It was established that the performance of ball control actions, passes, dribbling, feints, tackles, interceptions, and shots on goal differs significantly across playing positions, which reflects the specific characteristics of their competitive activity.

Conclusions. The findings suggest that the identified structural indicators and integral assessment of technical and tactical activity in highly qualified football players across various playing positions allow for more effective managerial decision-making in both training and competitive processes of football teams.

Keywords: UEFA European Championship, systematic approach, coordination complexity modes, specific coefficients, managerial influence.

Introduction

Effective management of a football team is determined by a rational approach to monitoring and analyzing competitive activity, both at the team level and with regard to players occupying different playing positions. During a match, depending on the tactical system applied, football players perform various functional roles characterized by specific features. This primarily concerns the execution

of technical and tactical actions during the phases of ball possession and ball recovery, areas that have been extensively studied by researchers (Papadopoulos et al., 2023; Soroka et al., 2023; Goranović et al., 2024). However, competitive activity in football is highly complex due to the large number of technical actions involved, the constant change of game situations, the high level of coordination demands, and intense psychological pressure, all of which complicate comprehensive analysis. Quantitative and qualitative indicators of technical and tactical activity differ significantly depending on playing position, which makes it impossible to apply a single set of indicators to all players (Arjol-Serrano et al., 2021; Karpa et al., 2021; Perepelytsia et al., 2026). Consequently, the problem arises of determining

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the structure and integral assessment of the technical and tactical activity of highly qualified football players.

Scientific research aimed at identifying the structure of technical and tactical activity of athletes in team sports, including football, has been conducted by both domestic scholars (Oliinyk et al., 2021; Mezhvynskyi, 2024; Bezmylov et al., 2025) and international researchers (Ferrari et al., 2022; Tojo et al., 2023; Sitti & Rangubhet, 2025). In particular, studies by Solovey et al. (2020), Shchepotina et al. (2021), Mitova (2022), and Kostyukevych (2025) focused on developing general principles for monitoring and analyzing technical and tactical activity in team sports. As for determining the structure of technical and tactical activity of players occupying different positions, this issue has been investigated in basketball (Doroshenko et al., 2020; Hatem et al., 2020), handball (Pueo et al., 2022; Nagy et al., 2025), volleyball (Shchepotina et al., 2019; Lima et al., 2021), and field hockey (Kostiukevych et al., 2020, 2025; Konnov, 2021). These studies examined the structure of technical and tactical activity with consideration of the execution of key game actions specific to each team sport.

In football, the structure of technical and tactical activity of both players and teams has been analyzed in studies by Kostiukevych et al. (2022, 2023) and Mezhvynskyi (2024). It should be noted that these authors investigated the structure of competitive activity while taking into account the integral assessment of technical and tactical performance.

A review and synthesis of scientific literature indicate that this issue remains highly relevant. A significant gap persists between the need for position-specific assessments of football players' technical and tactical activity and the limitations of current unified, position-independent approaches.

First and foremost, there is a need to identify indicators of the structure and integral assessment of the technical and tactical activity of highly qualified football players occupying different playing positions who represent European national teams. This is due to the necessity of determining model (benchmark) values that could serve as reference points for athlete training (Shchepotina et al., 2021; Sobol et al., 2024; Shlonska et al., 2024). The purpose of integral assessment is not merely to state empirical facts but, in the long term, to use it for effective management of the training process and adjustment of its content and structure based on the obtained data (Leibo et al., 2021; Adamchuk et al., 2023; Wang et al., 2025). Thus, the development of a scientific and methodological approach to the integral assessment of technical and tactical activity that takes into account the individual specificity of each playing position is a relevant task for improving the effectiveness of training highly qualified football players.

Research Hypothesis. It was hypothesized that identifying differences in the structure and integral assessment of the technical and tactical activity of highly qualified football players would make it possible to determine model values for each playing position, which, in turn, would allow the identification of prospects for adjusting the training process and individual player preparation.

The purpose of the study was to determine the structure and integral assessment of the technical and tactical activity of highly qualified football players of different playing positions based on a systematic approach.

Materials and Methods

Participants

The study involved pedagogical observation and video recording of the competitive activity of national football teams during the UEFA European Football Championships in 2021 and 2024. The competitive performance of football players representing the national teams of England, Spain, Italy, Denmark, the Netherlands, Belgium, Romania, Slovenia, Austria, Switzerland, Sweden, North Macedonia, Serbia, and Ukraine was analyzed. In total, the competitive activity of 206 players was examined, including 45 full-backs, 38 central defenders, 29 defensive midfielders, 38 wide midfielders (wingers), 35 central midfielders (inside midfielders), and 21 forwards.

Study Design

Pedagogical observation was applied in combination with video analysis of the competitive activity of national football teams during the UEFA European Football Championships in 2021 and 2024 in order to record the main technical and tactical actions performed by players, namely ball control actions, passes, ball carrying, dribbling, tackles, interceptions, and shots on goal, taking into account three modes of coordination complexity (MCC). The first mode of coordination complexity (MCC 1) included technical and tactical actions performed while stationary or at a comfortable movement speed. Actions executed in motion under spatial and temporal constraints were classified as MCC 2. The third mode of coordination complexity (MCC 3) comprised technical and tactical actions performed under active opposition from the opponent. Ball passes were classified as possession-retaining, progressive, and penetrative.

The integral evaluation of the technical and tactical activity of football players consisted of three quantitative and three qualitative specific coefficients (Table 1).

Statistical Analysis

The statistical analysis of the research results was conducted using methods of descriptive mathematical statistics (Byshevets et al., 2019; Bai & Bai, 2021; Jones, 2022). The indicators characterizing the sample were determined, including the arithmetic mean ($\bar{x}$), the standard deviation (S) and the coefficient of variation (V).

The ten-point scale for the integral assessment of the technical and tactical activity of football players was developed based on the three-sigma rule (Vincent, 2005) according to the following algorithm:

Step 1 – determination of the arithmetic mean value of a specific coefficient ($\bar{x}$);

Step 2 – determination of the standard deviation (S);

Step 3 – determination of the range (the difference between the values ($\bar{x}+3S$));

Step 4 – determination of the inter-score interval (ISI):

$$ISI = \frac{(\bar{x}+3S) - (\bar{x}-3S)}{9}, (8)$$

where 9 is the number of intervals in the ten-point scale (from the 2nd to the 10th score). The value ($\bar{x} - 3S$) is assigned to the first column of the scale.

Table 1. Integral Evaluation of Football Players' technical and tactical activity

Nº	Performance-specific coefficients	Formulas	Notes
Quantitative			
1	Intensity Coefficient	$IC = \frac{\sum_{i=1}^n TTA}{t}, (1)$	TTA – technical and tactical actions t – playing time
2	Mobility Coefficient	$MC = \frac{\sum_{i=1}^n TTA(2\text{-nd MMC} + 3\text{-rd MMC})}{t} \times 2, (2)$	2 – index of coordination complexity and match intensity
3	Aggression Coefficient	$AC = \frac{\sum_{i=1}^n TTA(3\text{-rd MMC})}{t} \times 3, (3)$	3 – indicator of coordination complexity and game intensity
Qualitative			
4	Effectiveness Coefficient	$EC = \frac{\sum_{i=1}^n \text{executed TTA}}{\sum_{i=1}^n \text{all TTA}}, (4)$	-
5	Duel Effectiveness Coefficient	$DEC = \frac{\sum_{i=1}^n \text{executed TTA, in 3-rd MMC}}{\sum_{i=1}^n \text{all TTA, in 3-rd MMC}}, (5)$	-
6	Creativity Coefficient	$CC = \frac{\sum_{i=1}^n \text{executed TTA} (DP \times 1 + PP \times 2 + A \times 5 + SG \times 5 + G \times 10)}{t}, (6)$	DP – developmental passes; PP – penetrative passes; A – assists (goal-scoring passes); SG – shots on goal; G – goals
7	Integral assessment of a field player's technical tactical activity	$IATTA = IC + MC + AC + EC + DEC + CC, (7)$	-

Step 5 – construction of the ten-point scale: 1 point – value ($\bar{x} - 3S$); 2 points – value ($\bar{x} - 3S$) plus one inter-score interval, and so on.

Mathematical processing of the research results was performed using the Data Analysis package of the MS Office Excel software, as well as the Statistica software package.

Results

Modern football tactics involve the classification of players into seven playing positions: goalkeeper, full-back, central defender, defensive midfielder, central midfielder (inside), wide midfielder (winger), and forward (Fig. 1).

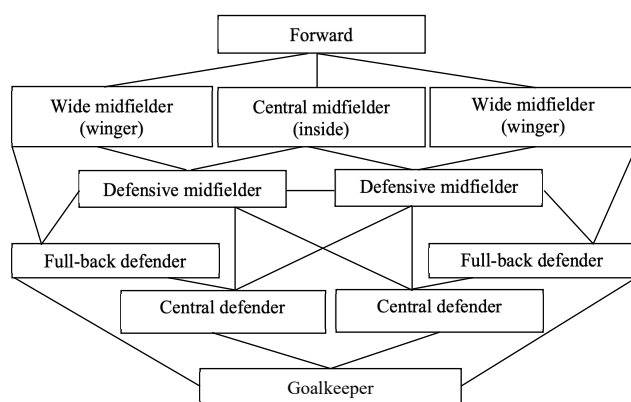


Fig. 1. Tactical formation of a football team (one of the possible variants)

As shown in Table 2, the technical and tactical activity of football players includes ball stops, passes, dribbling, maneuvers, tackles, interceptions, and shots on goal. Ball stops are predominantly performed by full-backs (35.6%) and forwards (35.7%). The highest proportion of passes in the technical and tactical activity structure is contributed by central defenders (47.3%), defensive midfielders (45.3%), wide midfielders/wingers (37.6%), and central midfielders/inside players (33.3%). Dribbling is most frequently performed by central defenders (6.5%), wide midfielders/wingers (5.9%), and central midfielders/inside players (6.1%).

As expected, dribbling is predominantly performed by wide midfielders/wingers (9.9%), central midfielders/inside players (9.4%), and forwards (10.7%).

The analysis of Table 2 highlights the need to specifically characterize the technical and tactical activity of players performing as central defenders. On the one hand, central defenders execute the fewest ball tackles (3.0%), yet on the other hand, they achieve the highest number of interceptions (10.5%). Overall, the greatest involvement in ball tackles is observed among defensive midfielders (8.1%), wide midfielders/wingers (7.1%), and central midfielders/inside players (7.8%).

Interceptions, aside from central defenders, are primarily performed by full-backs (10.1%) and defensive midfielders (9.5%).

Regarding shots on goal, the highest proportion in the technical and tactical activity structure belongs to forwards (4.8%), followed by wide midfielders/wingers (2.1%) and central midfielders/inside players (1.7%).

The primary structural element of a football team's tactical play is passing. Depending on tactical objectives—

Table 2. Structure of technical and tactical activity of highly skilled football players across different playing positions, %

Playing positions	Technical and tactical activity, %						
	ball stops	passes	dribbling	maneuvers	tackles	interception	shots on goal
Full-back defender (n=45)	35.6	39.7	4.1	3.3	6.8	10.1	0.3
Central defender (n=38)	32.1	47.5	5.5	1.5	3.0	10.5	0.1
Defensive midfielder (n=29)	29.1	45.3	3.5	3.1	8.1	9.5	1.4
Wide midfielder (winger) (n=38)	34.8	37.6	5.9	9.9	7.1	2.6	2.1
Central midfielder (inside) (n=35)	29.2	39.3	6.1	9.4	7.8	5.8	1.7
Forward (n=21)	35.7	34.2	4.7	10.7	6.2	3.7	4.8

ball retention, development of attacking actions, and intensification of game situations—passes in this study were categorized as retention, development, and intensifying passes. Figure 2 presents the distribution of these types of passes among highly skilled outfield players across different playing positions.

As shown in Fig. 2, during a football match, the highest proportion of development passes is performed by central defenders (75.7%), defensive midfielders (65.6%), and central midfielders/inside players (61.2%). Undoubtedly, the effectiveness of a football team's play largely depends on intensifying passes, which lead to shots on goal. Among all playing positions, the most intensifying passes are executed by central defenders (9.6%), wide midfielders/wingers (16.5%), central midfielders/inside players (9.7%), and forwards (13.0%).

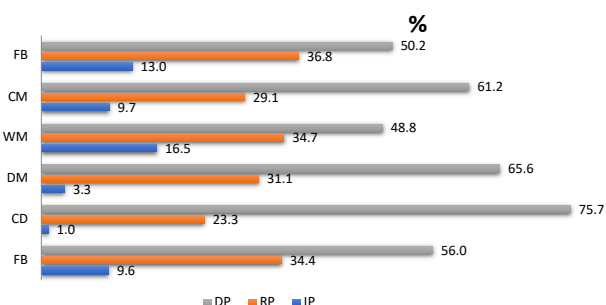


Fig. 2. Distribution of retention (RP), development (DP), and intensifying passes (IP) among highly skilled football players across different playing positions: F – Forward; CM – Central Midfielder (Inside); WM – Wide Midfielder (Winger); DM – Defensive Midfielder; CD – Central Defender; FB – Full-Back

Regarding retention passes, Fig. 2 shows that the largest share is attributed to full-backs (34.4%), wide midfielders/wingers (34.7%), and forwards (36.8%).

During a match, players perform technical and tactical actions under different modes of coordination complexity (MCC). The 1st MCC mainly includes ball stops and retention and development passes. The 2nd MCC involves stops, passes, dribbling, interceptions, and shots on goal. Technical and tactical actions are most challenging for players in the 3rd MCC, which occurs under active opposition pressure or constrained spatial-temporal conditions. These primarily include dribbling, tackles, interceptions, and shots on goal.

As illustrated in Fig. 3, the overall execution of technical and tactical actions considering MCC varies across different positions. The highest share of actions under complex conditions (3rd MCC) is performed by wide midfielders/

wingers (34.7%), central midfielders/inside players (33.6%), and forwards (49.9%). Overall, forwards execute almost 50% of their technical and tactical actions in the 3rd MCC, reflecting the specific competitive conditions faced by players in this position.

A considerable share of technical and tactical actions in the 3rd MCC is performed by wide midfielders/wingers (34.2%) and central midfielders/inside players (33.6%). The execution of technical and tactical actions in the 2nd MCC ranges from 61.4% for wide midfielders/wingers to 73.2% for full-backs.

The structure of technical and tactical activity of highly skilled football players across different positions was assessed in conjunction with an integral assessment of their technical and tactical activity (IATTA). The IATTA consists of three quantitative and three qualitative specific coefficients. The quantitative specific coefficients include the intensity coefficient (IC), mobility coefficient (MC), and aggressiveness coefficient (AC). The qualitative specific coefficients comprise the effectiveness coefficient (EC), duel effectiveness coefficient (DEC), and creativity coefficient (CC). The methodology for determining the IATTA is described above (see Table 1).

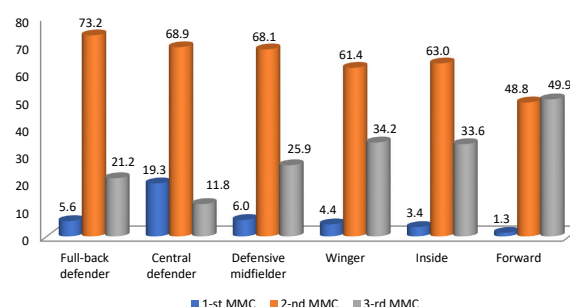


Fig. 3. Distribution of technical and tactical actions performed by highly skilled football players across different playing positions in the 1st, 2nd, and 3rd modes of coordination complexity (MCC)

Each of these specific coefficients characterizes particular aspects of players' technical and tactical performance. Specifically, IC reflects overall player activity and the total number of technical and tactical actions performed. MC indicates player mobility, particularly their execution of technical and tactical actions in the 2nd and 3rd MCC; among all specific coefficients, MC contributes the largest share to the IATTA. AC characterizes player involvement in duels, i.e., technical and tactical actions performed in the 3rd MCC.

Regarding the qualitative indicators of the IATTA, they are determined by the ratio of successfully executed technical and tactical actions to the total number performed.

Table 3. Ten-point scale of integral assessment values of technical and tactical activity of highly skilled football players across different playing positions

Playing positions	Specific coefficients	Level of manifestation of specific indicators									
		low		below average		average		above average		high	
		1	2	3	4	5	6	7	8	9	10
Full back defender, n=76	IC	0.67	0.76	0.84	0.93	1.02	1.11	1.19	1.28	1.37	1.45
	MC	1.39	1.54	1.68	1.83	1.98	2.13	2.27	2.42	2.57	2.71
	AC	0.41	0.45	0.49	0.53	0.57	0.61	0.65	0.69	0.73	0.77
	EC	0.70	0.73	0.76	0.79	0.83	0.86	0.89	0.92	0.95	0.99
	DEC	0.36	0.40	0.44	0.48	0.52	0.56	0.60	0.64	0.68	0.72
	CC	0.19	0.23	0.27	0.32	0.36	0.40	0.44	0.48	0.53	0.57
	IATTA	3.85	4.17	4.49	4.80	5.12	5.44	5.76	6.08	6.39	6.71
Central defender, n=48	IC	0.84	0.93	1.02	1.11	1.21	1.29	1.39	1.48	1.57	1.67
	MC	1.24	1.40	1.56	1.73	1.89	2.05	2.21	2.37	2.54	2.69
	AC	0.29	0.34	0.39	0.44	0.49	0.55	0.60	0.66	0.71	0.77
	EC	0.81	0.83	0.85	0.87	0.89	0.91	0.93	0.95	0.97	0.99
	DEC	0.39	0.44	0.49	0.53	0.58	0.63	0.68	0.73	0.78	0.82
	CC	0.29	0.32	0.35	0.38	0.41	0.44	0.47	0.50	0.53	0.56
	IATTA	3.69	4.13	4.57	5.00	5.46	5.90	6.34	6.78	7.21	7.65
Defensive midfielder, n=31	IC	0.56	0.67	0.78	0.89	1.00	1.12	1.23	1.34	1.45	1.56
	MC	1.39	1.53	1.67	1.80	1.94	2.08	2.22	2.36	2.49	2.63
	AC	0.52	0.59	0.66	0.73	0.79	0.86	0.93	0.99	1.07	1.14
	EC	0.67	0.70	0.74	0.77	0.81	0.84	0.87	0.91	0.94	0.98
	DEC	0.37	0.42	0.47	0.52	0.57	0.62	0.66	0.71	0.76	0.81
	CC	0.24	0.27	0.29	0.32	0.35	0.38	0.41	0.44	0.46	0.49
	IATTA	3.95	4.34	4.72	5.11	5.49	5.89	6.27	6.66	7.04	7.43
Wide midfielder (winger) n=49	IC	0.58	0.67	0.76	0.86	0.95	1.04	1.14	1.23	1.32	1.41
	MC	1.34	1.48	1.61	1.75	1.88	2.02	2.15	2.29	2.42	2.56
	AC	0.46	0.57	0.68	0.79	0.90	1.01	1.12	1.23	1.34	1.45
	EC	0.69	0.72	0.76	0.79	0.82	0.86	0.89	0.92	0.95	0.99
	DEC	0.46	0.51	0.56	0.60	0.65	0.69	0.74	0.79	0.83	0.88
	CC	0.22	0.26	0.31	0.35	0.39	0.44	0.48	0.52	0.56	0.61
	IATTA	4.04	4.43	4.82	5.21	5.60	5.99	6.38	6.77	7.16	7.55
Central midfielder (inside) n=39	IC	0.68	0.75	0.82	0.89	0.97	1.05	1.12	1.19	1.27	1.34
	MC	1.22	1.41	1.60	1.79	1.98	2.17	2.36	2.55	2.74	2.93
	AC	0.49	0.59	0.70	0.79	0.91	1.01	1.11	1.21	1.31	1.42
	EC	0.65	0.69	0.72	0.76	0.79	0.83	0.87	0.90	0.94	0.97
	DEC	0.33	0.38	0.43	0.47	0.52	0.57	0.62	0.66	0.71	0.76
	CC	0.24	0.28	0.32	0.37	0.41	0.45	0.49	0.53	0.58	0.62
	IATTA	4.21	4.53	4.85	5.17	5.49	5.82	6.14	6.46	6.78	7.11
Forward	IC	0.40	0.45	0.49	0.54	0.58	0.63	0.68	0.72	0.77	0.81
	MC	0.74	0.85	0.97	1.08	1.19	1.31	1.42	1.54	1.65	1.77
	AC	0.50	0.61	0.72	0.84	0.95	1.06	1.17	1.28	1.39	1.50
	EC	0.50	0.54	0.56	0.62	0.66	0.70	0.74	0.78	0.82	0.86
	DEC	0.35	0.40	0.45	0.55	0.56	0.61	0.66	0.71	0.76	0.82
	CC	0.16	0.19	0.22	0.25	0.28	0.31	0.34	0.37	0.40	0.42
	IATTA	2.59	3.03	3.46	3.89	4.33	4.77	5.21	5.64	6.08	6.51

These qualitative specific coefficients of the IATTA reflect the level of a player's sporting mastery.

To establish a hierarchy among players in different positions, a ten-point scale of IATTA values for highly skilled football players across various playing positions was developed in this study (Table 3).

The ten-point scale enables the development of graphical models of the IATTA for players in specific positions during a match.

For example, Fig. 4 presents the graphical models of the IATTA for the defensive midfielder of the England national

team, Declan Rice, during the final matches of the UEFA European Championship: England vs. Italy in 2021 and England vs. Spain in 2024.

Discussion

The study of specific aspects of athletes' preparedness is determined by the structure of their training within the framework of organized training processes (Kostiukevych et al., 2020; Leibo et al., 2021; Adamchuk et al., 2023). Analyzing the competitive performance of highly skilled athletes

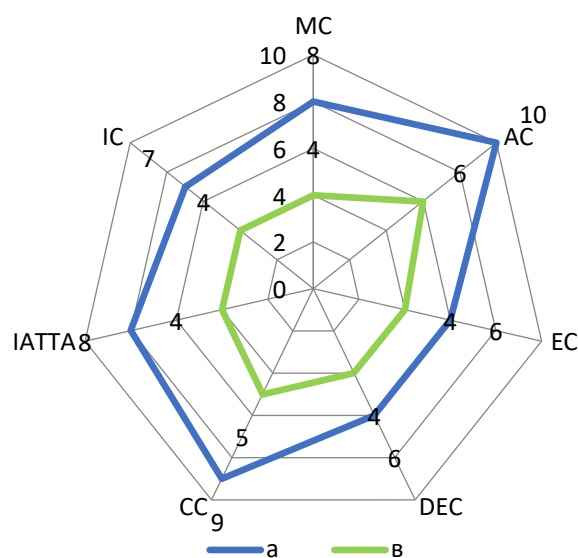


Fig. 4. Graphical model of technical and tactical activity of the defensive midfielder of the England national team in the UEFA European Championship finals: England vs. Italy (a) and England vs. Spain (b): IC – Intensity Coefficient; MC – Mobility Coefficient; AC – Aggressiveness Coefficient; EC – Effectiveness Coefficient; DEC – Duel Effectiveness Coefficient; CC – Creativity Coefficient; IATTA – Integral Assessment of Technical and Tactical Activity

allows for targeted training interventions that account for their specific technical and tactical actions. For team sport athletes, including football players, it is essential to consider functional responsibilities depending on their playing positions (Shchepotina et al., 2019; Hatem et al., 2020; Lima et al., 2021).

Our research was conducted over two UEFA European Championships in 2021 and 2024. This allowed us to determine the structure and integral assessment of technical and tactical activity of highly skilled football players in different playing positions during the most prestigious competitions. Moreover, the results are based on a sufficiently large number of observations ($n > 40$), which allows the derived indicators of technical and tactical activity structure and integral assessment to be considered as model benchmarks (Shchepotina et al., 2021; Mitova, 2022; Perepelytsia et al., 2026). These indicators can serve as a basis for comparative analysis of the competitive performance of highly skilled players in different positions across both club and national teams.

It is noteworthy that our study not only supplements previous findings on this topic (Kostiukevych et al., 2022, 2023) but also presents new results.

Primarily, this concerns the ten-point scale of specific coefficients of the integral assessment of technical and tactical activity for highly skilled football players in various positions. Based on this scale, both the level of players' technical and tactical activity and graphical models of technical and tactical activity can be constructed (Kononov, 2021; Mezhvynskyi, 2024).

The considerable share of technical and tactical actions performed in the 3rd MCC by wide midfielders/wingers and central midfielders/inside players is explained by the

fact that players in these positions, along with forwards, primarily perform technical and tactical actions in the third zone of the pitch, which is characterized by limited playing space (Arjol-Serrano et al., 2021; Karpa et al., 2021).

In the 2nd MCC, the majority of technical and tactical actions are executed during the match. This reflects the competitive level of the football team: the higher the match tempo, the fewer actions are performed in the 1st and 3rd MCC (Kostiukevych et al., 2022, 2023).

According to the results, ball stops, as one of the main components in the structure of technical and tactical activity, are predominantly performed by full-backs and forwards. For full-backs, this is associated with the need for quick ball reception during flank attacks or intercepting passes, whereas for forwards, it is related to ball control in the attacking zone or aerial duels. The primary role of passes in the technical and tactical activity structure for central defenders, defensive midfielders, wide midfielders, and central midfielders reflects their key function in constructing and organizing game schemes. The central and defensive midfielders' role aligns with modern football concepts, where ball distribution often begins from deep positions. Regarding dribbling, its share in the technical and tactical activity structure depends on players' specific game tasks. For defenders, dribbling often serves as the initiation of an attack or repositioning for a better passing option, whereas for wingers and inside midfielders, it is an important tool to overcome opponents, create numerical superiority on the flank, or advance the ball into the penalty area. These results correspond with the general principles of positional play and can serve as a foundation for further studies examining the effectiveness of technical and tactical actions execution in various game situations and match phases (Papadopoulos et al., 2023; Soroka et al., 2023; Goranović et al., 2024).

In conclusion, this study provides a timely response to theoretical and practical demands in football regarding the preparation of highly skilled players.

Conclusions

1. The structure of technical and tactical activity of highly skilled football players in different playing positions—full-back, central defender, defensive midfielder, central midfielder (inside), wide midfielder (winger), and forward—has been established. In particular, ball stops are most characteristic of full-backs (35.6%), wide midfielders/wingers (34.8%), and forwards (35.7%). Passes are predominantly executed by central defenders (47.5%) and defensive midfielders (45.3%).

The proportions of dribbling, maneuvers, tackles, and interceptions for each playing position are significantly lower than those of ball stops and passes. Dribbling ranges from 3.5% for defensive midfielders to 6.1% for central midfielders (inside). Maneuvers are most frequently performed by wide midfielders/wingers (9.9%), central midfielders/inside players (9.4%), and forwards (10.7%). Tackles are primarily executed by defensive midfielders (8.1%), wide midfielders/wingers (7.1%), and central midfielders/inside players (7.8%). Interceptions are most common among full-backs (10.1%), central defenders (10.5%), and defensive midfielders (9.5%). Shots on goal are mainly performed by central midfielders/inside players (1.7%), wide midfielders/wingers (2.1%), and forwards (4.8%).

2. The developed integral assessment of technical and tactical activity enables a targeted analysis of players' performance during both ball possession and ball recovery phases. It comprises three quantitative coefficients—intensity, mobility, aggressiveness—and three qualitative coefficients—effectiveness, duel effectiveness, and creativity.

3. Based on the ten-point scale of technical and tactical activity for highly skilled players in various positions, the level of sporting mastery exhibited during the game can be determined, and graphical models of their competitive performance can be constructed.

The prospects for further research are linked to determining the structure and integral assessment of technical and tactical activity in both club and national teams of high competitive level.

Ethics Approval

The study was approved by the Ethics Committee of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, and all procedures were conducted in accordance with the Declaration of Helsinki.

Informed consent

Not applicable.

Data Availability Statement

Data are available from the authors upon reasonable request.

AI Transparency Statement

The authors did not use artificial intelligence-based tools in the preparation of this manuscript.

Acknowledgements

Not applicable.

Conflict of Interest

The authors declare no conflict of interest.

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Структура та інтегральна оцінка техніко-тактичної діяльності висококваліфікованих футболістів різних ігрових амплуа

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; Е – збір коштів

Реферат. Стаття: 9 с., 3 табл., 4 рис., 36 джерел.

Мета дослідження – на основі системного підходу визначити структуру й інтегральну оцінку техніко-тактичної діяльності висококваліфікованих футболістів різних ігрових амплуа.

Матеріал і методи. Дослідження проводилося упродовж чемпіонатів Європи з футболу 2021 та 2024 років. Аналізувалася змагальна діяльність футболістів, які входили до складу національних збірних команд Англії, Іспанії, Італії, Данії, Нідерландів, Словаччини, Бельгії, Румунії, Словенії, Австрії, Швейцарії, Швеції, Північної Македонії, Сербії та України. У дослідженні використовувалися такі методи: теоретичний аналіз джерел та літератури, педагогічне спостереження, відеоаналіз змагальної діяльності, методи математичної статистики.

Результати. Визначено структуру техніко-тактичної діяльності висококваліфікованих футболістів різних ігрових амплуа – крайнього захисника, центрального захисника, опорного півзахисника, центрального півзахисника (інсайда), крайнього півзахисника (вінгера) та нападника. Встановлено, що виконання зупинок, передач, введення, обведення, відборів, перехватів м'яча та ударів у ворота для цих ігрових амплуа є нерівнозначним, що характеризує специфічні особливості їх змагальної діяльності.

Висновки. Визначені показники структури та інтегральної оцінки техніко-тактичної діяльності висококваліфікованих футболістів різних ігрових амплуа дозволяють більш ефективно здійснювати управлінські впливи у тренувальному та змагальному процесах футбольних команд.

Ключові слова: чемпіонат Європи з футболу, системний підхід, режими координаційної складності, специфічні коефіцієнти, управлінські впливи.

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Combination Training Improves Leptin Regulation, Reduces Body Fat, and Increases Skeletal Muscle Mass in Obese Females

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Abstract

Background. Leptin dysregulation and unfavorable body composition are central features of obesity in women. Although combined aerobic and resistance training is commonly prescribed to improve adiposity and muscle mass, evidence integrating changes in serum leptin concentration with detailed body composition outcomes in this population remains limited.

Objectives. The present randomized controlled trial aimed to examine the effects of an eight-week combined training intervention on leptin concentration, fat mass, and skeletal muscle mass in obese women.

Materials and Methods. Thirty obese women were allocated to either a combined training group or a non-exercising control group. The intervention consisted of moderate-intensity aerobic and resistance exercise performed five times per week for eight weeks. Body composition included body fat percentages (BFP), fat mass (FM), Free Fat Mass (FFM) and skeletal muscle mass (SMM) was assessed using bioelectrical impedance analysis, and serum leptin concentration was determined by enzyme-linked immunosorbent assay. Pre-post and between-group differences were analyzed using parametric statistical tests (independent sample t test and paired t test) with a significance threshold of $p < 0.05$.

Results. Participants who completed the combined training program exhibited significant reductions in serum leptin concentration and adiposity indices (specifically BFP and FM), alongside significant increases in FFM and SMM, compared to the control group ($p < 0.05$).

Conclusions. Using short-term moderate-intensity combined aerobic and resistance training was associated with favorable changes in leptin concentration. These findings support the potential role of structured combination training as an exercise-based approach for improving metabolic and musculoskeletal profiles within the limits of the present study.

Keywords: body composition, combination training, leptin, muscle mass, obesity.

Introduction

Obesity remains a major public health challenge worldwide, with a rapidly increasing prevalence among adult populations, particularly women, and is closely linked to a

broad range of metabolic and cardiovascular complications (GBD 2021 Adult BMI Collaborators, 2025; Martin et al., 2025). According to data from Survei Kesehatan Indonesia (SKI) 2023, the prevalence of obesity in Indonesian adults (aged 18 years and older) rose from 21.8% in 2018 to 23.4% in 2023 (Kepmenkes 2025). Beyond excessive fat accumulation, obesity is characterized by dysregulation of adipose tissue function, including changes in the secretion of adipokines like leptin, which are essential for controlling hunger, energy

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balance, and metabolic homeostasis (Sakers et al., 2022; Klein et al., 2022). In individuals with obesity, chronically elevated leptin levels are often accompanied by impaired leptin signaling, contributing to persistent energy imbalance and metabolic dysfunction (Lee et al., 2022; Fahed et al., 2022). At the same time, obesity is frequently associated with reduced skeletal muscle mass and function, a condition increasingly recognized as sarcopenic obesity, which further exacerbates metabolic risk and limits functional capacity, particularly in women (Donini et al., 2022; Petermann-Rocha et al., 2022; Yuan & Larsson, 2023). Although clinical and public health guidelines consistently emphasize physical activity as a cornerstone of obesity management (Rock et al., 2022; American Diabetes Association Professional Practice Committee, 2025), there remains a gap between theoretical recommendations and empirical evidence regarding how specific exercise modalities simultaneously influence leptin regulation, fat mass reduction, and muscle mass preservation in obese female populations.

Combined aerobic and resistance training has been proposed as an effective exercise strategy to address the multifaceted nature of obesity by targeting both adiposity and muscle tissue. Previous intervention studies and systematic reviews have shown that combination training can improve body composition, reduce body fat, and favorably modify adipokine profiles in individuals with overweight and obesity (Rejeki et al., 2023; Oh et al., 2023; Sugiharto et al., 2024; Hejazi et al., 2023; Tan et al., 2024). However, existing evidence remains heterogeneous with respect to training protocols, participant characteristics, and outcome measures, and relatively few randomized controlled trials have focused specifically on obese women while concurrently assessing leptin levels alongside detailed body composition indicators. Moreover, many studies emphasize weight loss or inflammatory outcomes without adequately addressing the combined dynamics of leptin regulation, fat mass reduction, and skeletal muscle mass accretion within a single intervention framework (González-Jurado et al., 2020; Gil-Cosano et al., 2024; Hintze et al., 2021). As a result, the specific contribution of moderate-intensity combination training to integrated metabolic and musculoskeletal adaptations in obese females remains insufficiently clarified.

From a theoretical perspective, combining aerobic and resistance exercise offers a complementary stimulus that may promote favorable changes in energy balance while preserving or increasing muscle mass, thereby addressing key physiological challenges associated with obesity. Rather than focusing on isolated outcomes, an integrated approach that simultaneously evaluates leptin concentrations, body fat, and skeletal muscle mass may provide a more comprehensive understanding of exercise-induced adaptations relevant to obesity management.

Various previous intervention studies have shown that physical exercise, both aerobic and resistance training, can reduce circulating leptin levels (González-Jurado et al., 2020; Hintze et al., 2021; Li et al., 2022; Gil-Cosano et al., 2024; Sugiharto et al., 2024). However, most of these studies only assessed the effects of exercise on leptin regulation and body composition changes separately, without evaluating the physiological adaptations of both simultaneously in an integrated exercise program. Furthermore, these studies used diverse populations ranging from children to obese

adults so that evidence in the Indonesian population, especially in obese women is still limited. To the best of our knowledge, research related to the combination of aerobic and resistance training is still limited. One of the studies that identified related topic in Indonesia was by Rejeki et al. (2023) which showed that 4 weeks of combined training improved body composition and adipokine levels in obese women. Accordingly, this randomized controlled trial investigated whether an eight-week moderate-intensity aerobic–resistance exercise regimen could modulate serum leptin levels alongside changes in adiposity and lean tissue indices in women living with obesity. We hypothesized that combination training would lead to a significant reduction in leptin concentration and body fat, accompanied by an increase in skeletal muscle mass, compared with a non-exercising control group.

Materials and Methods

Study Design

This study used a pretest–posttest control-group study and a true experimental design, with participants being obese adults females. Purposive sampling was used to choose participants based on the inclusion criteria as follows: BMI of 28 kg/m² or higher, sedentary lifestyle for at least 6 months, non-smoker, and no history of metabolic, cardiovascular, endocrine, or orthopedic disorders. Before being enrolled as participants, eligible individuals gave written informed permission. The intervention was conducted over an 8-week period. This study was approved by the Health Research Ethics Committee, Faculty of Medicine, Universitas Airlangga (Approval No. 203/EC/KEPK/FKUA/2025).

Sample Size and Power Calculation

G*Power was used to determine the sample size (Version 3.1.9.7). A paired mean difference model was selected based on expected pre–post change in leptin and body composition parameters. The minimum sample size required was 27 people with a medium effect size (Cohen's $d = 0.50$), $\alpha = 0.05$, and statistical power ($1 - \beta$) = 0.80. Accounting for an estimated 10–15% attrition, a total of 30 subjects were targeted for enrollment.

Randomization and Allocation

After baseline assessments were performed, individuals were randomized using computer-generated basic randomization sequence to either the intervention or control group. To ensure allocation concealment, sealed opaque envelopes were prepared by an independent researcher who was not involved in testing or analysis. Moreover, those assessing outcome and laboratory staff were blinded to the group allocations.

Training Protocol

The intervention group performed combination training five sessions per week. Each session began with moderate intensity aerobic activity on a motorized treadmill (60–70% HRmax) followed by resistance training with Cybex fitness

equipment that targeted the main muscle groups in the upper and lower bodies. The resistance was set at about 60-70% of their one-repetition maximum, two to 4-6 sets per exercise, 10-12 repetitions per set, with 60-90 seconds of rest between sets. The average duration of each session was around 60 minutes, and their exercise intensity was monitored using heart rate. Participants in the control group, on the other hand, received instructions to carry on with their regular activities without adding any organized exercise.

Diet and Physical Activity Control

Before participated in the intervention programs, the researcher thoroughly explained about the recommended diet during the research. The recommendation diet was based on the balanced nutritional guidelines, including limiting the consumption of foods high in sugar, salt, and fat. To avoid contamination effects, participants were prohibited from engaging in structured exercise outside the study protocol. Light daily activity was tracked using smartphone-based pedometer step counts and weekly activity checklists to verify compliance.

Biochemical and Body Composition Analysis

Blood samples (10-12 hours after fasting) were collected at baseline and after intervention. Serum leptin concentration was analyzed using enzyme-linked immunosorbent assay (ELISA) in accordance with manufacturer instructions Human LEP (Leptin) ELISA Kit (Cat.No.: E-EL-H6017; Elabscience, Inc. USA) with sensitivity = 9.38 pg/mL; detection range = 15.63-1000 pg/mL; inter-assay variability = < 10%. Body composition variables including body fat percentage, fat mass (FM), free fat mass (FFM), and skeletal muscle mass were assessed using TANITA DC-360 bioelectrical impedance analysis (TANITA Corp. Inc., Arlington Heights, IL, USA).

Statistical Analysis

By using the Shapiro-Wilk test, the normality of the data distribution was evaluated. The normality of data distribution was assessed using the Shapiro-Wilk test. We used independent sample t-test and to assess differences within group, and to evaluate differences within the group, we used paired sample t-test. Correlation between changes in leptin concentration and body composition were also analyzed using the Pearson's correlation. Additionally, statistical significance was set at $p < 0.05$. Effect size (ES) estimates were calculated using Cohen's to quantify the magnitude of observed effects. According to Cohen's classification, effect sizes (Cohen's d) were interpreted as small ($d = 0.2$), medium ($d = 0.5$), large ($d = 0.8$), and very large ($d \geq 1.3$) to evaluate the magnitude of changes following the exercise intervention (Sullivan & Feinn, 2012).

Results

Participant Flow and Baseline Characteristics

Thirty people in all were recruited and randomly assigned into training group and control group with each group consists of 15 participants. All participants completed

the 8-week intervention and post-testing (attrition = 0%). Age, blood pressure, resting heart rate, oxygen saturation, body temperature, fasting blood glucose, hemoglobin, height, weight, and body mass index were not significantly difference between the groups at baseline. It shows that the characteristics of participants in the training and control group is similar ($p > 0.05$) (Table 1).

Table 1. Baseline Characteristics of Participants

Characteristics	Control (n = 15)	Training (n = 15)	p-value
Age (yrs)	25.53 $\pm$ 1.85	26.33 $\pm$ 1.92	0.254
SBP (mmHg)	116.53 $\pm$ 3.16	116.07 $\pm$ 3.06	0.684
DBP (mmHg)	72.87 $\pm$ 5.14	72.93 $\pm$ 4.27	0.969
RHR (bpm)	75.93 $\pm$ 4.51	74.53 $\pm$ 2.45	0.302
SpO2 (%)	97.73 $\pm$ 0.88	98.27 $\pm$ 0.89	0.110
BT (°C)	36.41 $\pm$ 0.31	36.31 $\pm$ 0.27	0.316
FBG (mg/dL)	97.53 $\pm$ 7.59	98.20 $\pm$ 4.69	0.775
Hb (g/dL)	14.14 $\pm$ 1.48	13.97 $\pm$ 1.35	0.749
Height (m)	1.55 $\pm$ 0.07	1.56 $\pm$ 0.06	0.788
Weight (kg)	76.14 $\pm$ 7.57	77.99 $\pm$ 9.95	0.572
BMI (kg/m ²)	31.70 $\pm$ 2.75	32.20 $\pm$ 3.34	0.659

Note: SBP: Systolic blood pressure, DBP: Diastolic blood pressure, RHR: Resting heart rate, SpO2: Oxygen saturation, BT: Body temperature, FBG: Fasting blood glucose, Hb: Hemoglobin, BMI: Body mass index. All data are presented as mean $\pm$ SD. The p-value was obtained using the independent samples t-test.

Effects on Serum Leptin

In comparison to baseline, the training group showed a significantly decrease in leptin concentration after eight week intervention. While there was no significant change in leptin level of the control group ($p=0.399$), the decreasing of leptin level in training group after intervention showed significantly reduction ($p=0.001$; ES: 2.163) (Figure 1).

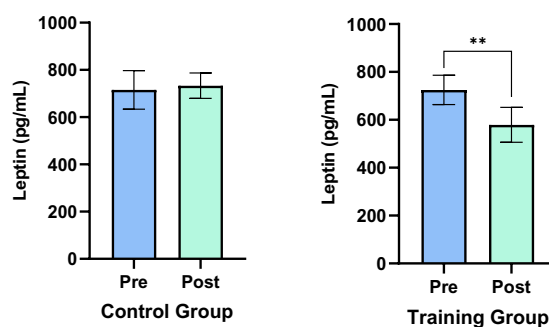


Fig. 1. Changes in Leptin Concentrations After an 8-Week Intervention. Note: (**) Significant at pre ($p < 0.001$). The p-value was obtained using the paired samples t-test

Effects on Body Composition

Based on the Figure 2, it can be seen that in the intervention group, combination training led to increase free fat mass (FFM) and decrease body fat percentage. Within-group improvements were statistically significant (body fat percentage $p = 0.001$, effect size (ES) = 0.683; fat mass $p = 0.001$, ES = 0.663; free fat mass $p = 0.001$, ES = 0.645; skeletal

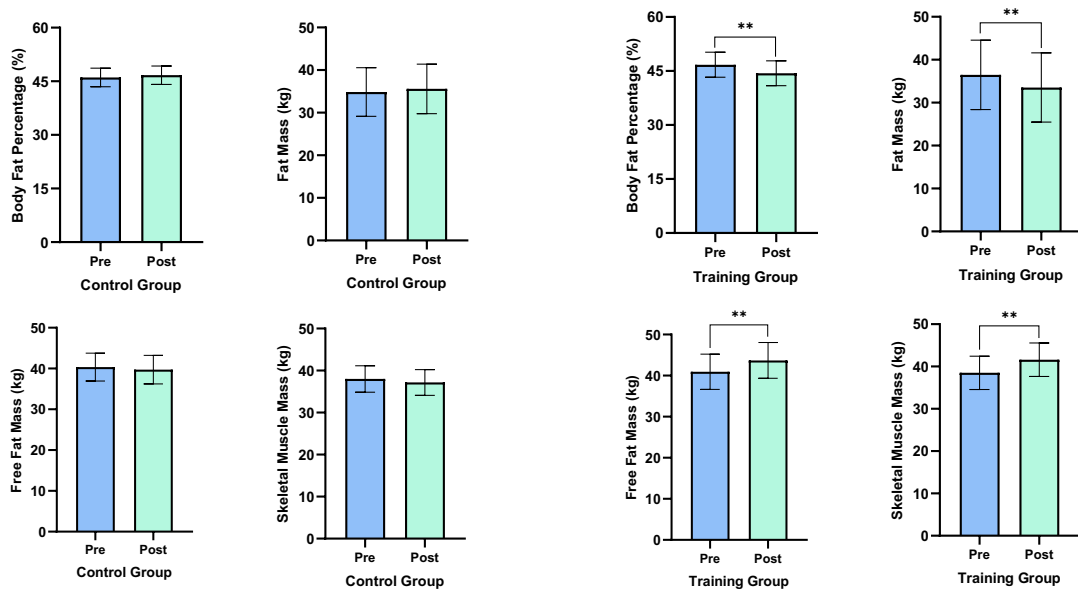


Fig. 2. Changes in Body Composition After an 8-Week Intervention.

Note: (**) Significant at pre ($p < 0.001$). All data are presented as mean $\pm$ standard deviation (SD). The p-value was obtained using the paired samples t-test

muscle mass $p = 0.001$, ES = 0.785), whereas the control group did not exhibit significant changes ($p > 0.05$).

Between-Group Differences

Between-group comparisons confirmed greater improvements in leptin and body composition in the training group compared to control group (all key outcomes $p < 0.05$)

(Table 2). Table 3 showed the association between changes in leptin levels and the body composition. As shown in Table 2, the training program significantly reduced leptin level by $-19.27 \pm 14.24\%$ (95%CI: 13.28-31.91, $p < 0.001$, ES: 1.814). Moreover, combined training also significantly reduced the body composition namely BFP by $-5.01 \pm 3.81\%$ (95%CI: 4.31-8.52, $p < 0.001$, ES: 2.283), and FM by $-8.36 \pm 2.09\%$ (95%CI, 9.34-11.72, $p < 0.001$, ES: 2.535), alongside significant

Table 2. Between-Group Differences in Leptin and Body Composition Improvements

Parameters	Control (n = 15)	Training (n = 15)	95% CI		p-value	ES
			Lower	Upper		
Pre-Leptin (pg/mL)	715.09 $\pm$ 81.66	724.91 $\pm$ 61.28	-63.81	44.19	0.713	0.135
Post-Leptin (pg/mL)	732.99 $\pm$ 53.79	579.11 $\pm$ 72.99††	105.92	201.83	0.001	2.400
Δ -Leptin (pg/mL)	17.89 $\pm$ 79.69	-145.79 $\pm$ 110.48††	91.64	235.73	0.001	1.699
Change-Leptin (%)	3.33 $\pm$ 10.36	-19.27 $\pm$ 14.24††	13.28	31.91	0.001	1.814
Pre-BFP (%)	46.06 $\pm$ 2.59	46.75 $\pm$ 3.46	-2.98	1.61	0.544	0.224
Post-BFP (%)	46.70 $\pm$ 2.55	44.39 $\pm$ 3.45†	0.05	4.58	0.047	0.763
Δ -BFP (%)	0.64 $\pm$ 0.49	-2.36 $\pm$ 1.70††	2.06	3.94	0.001	2.396
Change-BFP (%)	1.41 $\pm$ 1.11	-5.01 $\pm$ 3.81††	4.31	8.52	0.001	2.283
Pre-FM (kg)	34.84 $\pm$ 5.71	36.47 $\pm$ 8.09	-6.86	3.61	0.530	0.232
Post-FM (kg)	35.59 $\pm$ 5.82	33.53 $\pm$ 8.07	-3.19	7.32	0.429	0.292
Δ -FM (kg)	0.75 $\pm$ 0.31	-2.93 $\pm$ 0.49††	3.38	3.99	0.001	1.871
Change-FM (%)	2.17 $\pm$ 0.84	-8.36 $\pm$ 2.09††	9.34	11.72	0.001	2.535
Pre-FFM (kg)	40.37 $\pm$ 3.42	40.92 $\pm$ 4.29	-3.46	2.35	0.699	0.142
Post-FFM (kg)	39.73 $\pm$ 3.52	43.71 $\pm$ 4.35†	-6.94	-1.03	0.010	1.007
Δ -FFM (kg)	-0.64 $\pm$ 0.46	2.79 $\pm$ 0.35††	-3.73	-3.12	0.001	1.456
Change-FFM (%)	-1.61 $\pm$ 1.18	6.87 $\pm$ 1.09††	-9.33	-7.63	0.001	2.186
Pre-SMM (kg)	38.01 $\pm$ 3.14	38.51 $\pm$ 3.94	-3.16	2.16	0.704	0.141
Post-SMM (kg)	37.17 $\pm$ 3.08	41.61 $\pm$ 3.95††	-7.09	-1.79	0.001	1.253
Δ -SMM (kg)	-0.84 $\pm$ 0.37	3.10 $\pm$ 0.34††	-4.21	-3.68	0.001	1.648
Change-SMM (%)	-2.21 $\pm$ 0.95	7.51 $\pm$ 0.99††	-10.44	-8.99	0.001	2.231

Note: (†) Significant at control group ($p < 0.05$). (††) Significant at control group ($p < 0.001$). ES: Effect Size. Δ : Delta (Post - Pre). All data are presented as mean $\pm$ standard deviation (SD). The p-value was obtained using the independent samples t-test.

increases in FFM by $6.87 \pm 1.09\%$ (95%CI: -9.33-(-7.63), $p < 0.001$, ES: 2.186) and skeletal muscle mass by $7.51 \pm 0.99\%$ (95%CI: -10.44-(-8.99), $p < 0.001$, ES: 2.231), compared with the control group ($p < 0.05$).

On the other hand, correlation analysis showed that changes in leptin concentration before and after training program significantly associated with changes in all body composition parameters namely BFP ($r: 0.554$), FM ($r: 0.659$), FFM ($r: -0.661$), and SMM ($r: -0.601$) (Table 3). The r value of BFP, FM, and FFM showed positive value and for SMM showed negative value. It means that the decrease in leptin concentration significantly inline with reduction of the BFM, FM, and FFM; meanwhile, reduction in leptin concentration significantly increase the SMM.

Table 3. Shows the correlations between leptin concentrations and body fat and skeletal muscle mass.

Parameter	Δ -Leptin (pg/mL)	
	r	p-value
Δ -BFP (%)	0.554	0.001
Δ -FM (kg)	0.659	0.001
Δ -FFM (kg)	-0.661	0.001
Δ -SMM (kg)	-0.601	0.001

Note: BFP: body fat percentage, FM: fat mass, FFM: fat free mass, SMM: skeletal muscle mass. The p-value was obtained using the Pearson's correlation test.

Discussion

This study evaluated changes in leptin levels, body composition, and skeletal muscle mass in obese women with ages ranging from 25.53 ± 1.85 in the control group and 26.33 ± 1.92 in the intervention group. In the present study, we observed that an eight-week moderate-intensity combined aerobic-resistance training program significantly reduced serum leptin concentrations by almost 19.5% ($-19.27 \pm 14.24\%$, 95%CI: 13.28-31.91, $p < 0.001$, ES: 1.814), reduced body fat percentage by 5% ($-5.01 \pm 3.81\%$, 95%CI: 4.31-8.52, $p < 0.001$, ES: 2.283), and FM by 8% ($-8.36 \pm 2.09\%$, 95%CI: 9.34-11.72, $p < 0.001$, ES: 2.535), while increasing FFM by $6.87 \pm 1.09\%$ (95%CI: -9.33-(-7.63), $p < 0.001$, ES: 2.186) and SMM by $7.51 \pm 0.99\%$ (95%CI: -10.44-(-8.99), $p < 0.001$, ES: 2.231), in obese women compared with the control group (Table 2). These findings are consistent with previous randomized and controlled studies reporting favorable effects of concurrent training on body composition and adipokine profiles in obese populations (Rejeki et al., 2023; Oh et al., 2023; Sugiharto et al., 2024). Providing aerobic and resistance training for 8 weeks with a frequency 5 times a week for 60 minutes in this study also can improve leptin levels and body composition. Leptin levels before intervention in both groups were not significantly different. After intervention program, there was a significant difference in leptin levels with the training group showing lower leptin levels than the control group. Changes in leptin concentration also significantly associated with body composition (Table 3).

Obesity is characterized by the body mass index (BMI) $\geq 25 \text{ kg/m}^2$ by criteria from the World Health Organization (WHO). Obese individuals have an excessive accumulation

of adipose tissue, which functions as an endocrine organ through the secretion of adipokines, which play a role in regulating food intake, lipid and glucose metabolism, insulin action, and energy balance is shown in obesity people. Adipokine dysfunction contributes to the development of obesity, primarily through impaired regulation of leptin and adiponectin, key regulators of metabolic homeostasis (Park & Shimokawa 2024). Leptin, a product of the obesity gene, plays a role in weight control by regulating appetite and energy expenditure and also influences neuroendocrine function (Landecheo et al., 2019). In obesity, hyperleptinemia occurs due to leptin resistance triggered by excessive energy intake and low physical activity, resulting in persistently high circulating leptin levels. This condition not only reflects metabolic disturbances but also plays a role in the pathogenesis of cardiometabolic complications, inflammation, and malignancy. Therefore, intervention like combination program that can reduce hyperleptinemia have the potential to reduce obesity-related morbidity (Rostas et al., 2017). Combination training in this study significantly reduced leptin levels in training groups. It has been suggested that exercise might increase energy expenditure and inhibit leptin secretion (Murawska-Ciałowicz et al., 2022).

Leptin, glucagon-like peptide 1 (GLP-1), ghrelin, peptide YY (PYY), glucose dependent insulinotropic polypeptide (GIP), and cholecystokinin (CCK) are among the hormones that regulate appetite and satiety behaviors. All the mentioned hormones above are released and produced by intestine and adipocytes which interact with hypothalamus to regulate eating and satiety behaviors (Zouhal et al., 2019). Exercise inhibits the production of ghrelin via attaching to the its receptor namely G-protein coupled receptor 81 (GPCR81) in gastric cell (Vanderheyden et al., 2020). On the other hand, exercise also can lower leptin levels and increase leptin sensitivity in the brain. After doing exercise, the hypothalamus becomes more sensitive to leptin, which improves its capability to control hunger and energy balance. It also reduces inflammation, increases insulin sensitivity, and stimulates neurogenesis and synaptic plasticity (Augusto-Oliveira et al., 2023; de Assis et al., 2023). Leptin starts to initiate signaling pathways after binding to its hypothalamic receptor, long isoform receptor (ObRb) with the most notable being the JAK2/STAT3 pathway, which leads to the transcription of genes such as POMC, suppressor of cytokine signaling 3 (SOCS3), and brain-derived neurotrophic factor (BDNF) that promote satiety and reduce food intake (Kwon et al., 2016; Liu et al., 2021).

In this study, body composition such as FM, FFM, and SMM significantly improved by intervention of combination training. Exercise activates the cardiovascular, respiratory, endocrine, and metabolic systems, triggering key signaling pathways such as adenosine monophosphate (AMP)-activated protein kinase (AMPK), calcium/calmodulin-dependent protein kinase (CaMK), protein kinase A (PKA), protein kinase C (PKC), and mammalian target of rapamycin (mTOR) (Hoffman et al., 2015). Specifically, AMPK activates peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC-1 α) to sense energy deficit and promote mitochondrial biogenesis (Hoffman et al., 2015; Gowans et al., 2013). Another crucial kinase, namely CaMK-II promotes lipid oxidation and increases glucose absorption via glucose transporter-4 (GLUT-4), supports lipid oxidation

(Yong & Song 2024). Resistance training typically activates the phosphatidylinositol 3-kinase (PI3K)- protein kinase B(Akt)-mTOR (PAM) signaling pathway, which regulates synthesis and degradation of protein, resulting in higher lean body mass and muscle hypertrophy (Plaza-Diaz et al., 2022). Aerobic exercise, on the other hand, mainly stimulates the AMPK-MAPK-PGC-1 α pathway, which leads to increased mitochondrial biogenesis, improved oxidative metabolism, a change in fiber phenotype from rapid glycolytic to more oxidative, and angiogenesis (Ashcroft et al., 2024). The physiological changes that affect body composition are highlighted by these molecular process. Together, aerobic and resistance training can contribute to long-term improvements not only body composition but also health and performance.

Comparable benefits have been reported across pediatric, adolescent, and adult populations presenting with excess body weight, although the extent of these adaptations appears to depend on exercise modality, training dose, and individual characteristics (González-Jurado et al., 2020; Gil-Cosano et al., 2024; Hintze et al., 2021; Headid & Park, 2021). In addition, evidence from broader exercise interventions suggests that combination training is consistently associated with favorable adaptations in muscle mass and functional capacity across different age groups (Wu et al., 2021). Taken together, the present results reinforce the notion that combination training is an effective exercise modality for simultaneously targeting excess adiposity and muscle mass deficits, which are central features of obesity in women.

Although the present study did not directly assess molecular or inflammatory pathways, the observed reductions in leptin levels and fat mass, alongside increases in skeletal muscle mass, may be explained by previously described exercise-induced adaptations. Prior studies suggest that combined aerobic and resistance training can modulate adipokine secretion, reduce low-grade inflammation, and enhance metabolic flexibility through coordinated adaptations in adipose and skeletal muscle tissue (Makarewicz et al., 2022; Sanchis et al., 2024). Exercise-induced myokines and exerkines have also been proposed to facilitate crosstalk between muscle and adipose tissue, thereby influencing leptin sensitivity and energy balance (Chow et al., 2022). In addition, changes in endocrine mediators such as insulin-like growth factor-1 and fibroblast growth factor-21 have been reported following concurrent training interventions, which may support muscle hypertrophy and lipid metabolism (Colleluori et al., 2025; Fiorenza et al., 2024). Broader systemic hormonal and metabolic adaptations to regular exercise, including age- and lifestyle-related endocrine responses, have also been suggested to contribute to favorable changes in body composition, with exercise intensity and prescription playing an important role in shaping these responses (Pataky et al., 2021; Hansen et al., 2022). These mechanisms should be interpreted as plausible explanations rather than direct causal pathways, given that they were not directly measured in the present study.

From a practical perspective, the present findings support the application of moderate-intensity combination training as a non-pharmacological strategy for improving metabolic and musculoskeletal health in obese women. Compared with single-modality exercise, concurrent training offers a time-efficient approach that addresses both

fat reduction and muscle preservation, which is particularly relevant for female populations at risk of sarcopenic obesity (Donini et al., 2022). The benefits of combined exercise modalities have also been demonstrated in other clinical and functional contexts, including improvements in muscle strength, balance, and overall functional performance (Sadeghi et al., 2021), as well as in structured rehabilitation settings following disease-related deconditioning (Jimeno-Almazán et al., 2022). The main contribution of this study lies in its integrated evaluation of leptin regulation, detailed body composition parameters, and skeletal muscle mass within a randomized controlled design. By focusing on obese women and employing a structured training protocol, this study extends previous evidence and provides novel empirical support for the role of combination training in comprehensive obesity management.

It is important to recognize that there were several limitations of this present findings. First, the results' generalizability may be limited by the comparatively small sample size and brief intervention period. Second, bioelectrical impedance analysis was used to measure body composition instead of imaging-based techniques, which may introduce measurement variability. Third, dietary intake was monitored but not strictly controlled, and additional biomarkers related to inflammation, insulin sensitivity, or muscle metabolism were not assessed. These limitations should be considered when extrapolating the findings beyond the study context.

Further research should prioritize the inclusion of more heterogeneous cohorts, prolonged training durations, and multidimensional assessments of metabolic, inflammatory, and hormonal pathways to better elucidate the biological processes underlying exercise-induced alterations in leptin regulation and body composition. The integration of molecular, transcriptomic, or gut microbiota analyses may further clarify the pathways through which combination training exerts its effects (Pillon et al., 2020; Quiroga et al., 2020; Brunelli et al., 2024; Estébanez et al., 2023). Additionally, comparative trials examining exercise training alongside pharmacological interventions for obesity may help to define optimal multimodal treatment strategies (Melson et al., 2025; Jastreboff et al., 2025).

Notwithstanding these limitations, the present results suggest that combined aerobic-resistance exercise promotes favorable short-term changes in leptin homeostasis alongside improvements in body composition profiles among women with obesity. Beyond metabolic outcomes, previous research indicates that regular exercise—particularly when combining aerobic and resistance components—can also support broader systemic and neurophysiological health benefits, including cognitive and neurotrophic adaptations (Ruiz-González et al., 2021; Kao et al., 2025; Dhahbi et al., 2025). The findings align with broader evidence supporting exercise as a cornerstone of obesity management and metabolic disease prevention (Rahmati et al., 2025; Batrakoulis et al., 2022). Given the increasing burden of obesity-related comorbidities, including cardiovascular and hepatic complications (Packer et al., 2025; Younossi et al., 2025; European Association for the Study of the Liver, 2025), the present results justify the inclusion of structured combination training programs as part of evidence-based lifestyle interventions.

Conclusion

The findings of this randomized controlled study indicate that eight weeks of moderate-intensity combined aerobic–resistance training elicit favorable changes in leptin levels alongside improvements in body composition profiles in women living with obesity. Compared with a non-exercising control group, participants who completed the combination training intervention exhibited reduced leptin levels and adiposity alongside increased muscle mass, indicating favorable short-term adaptations in metabolic and musculoskeletal health. Taken together, the present evidence underscores the relevance of combined aerobic–resistance exercise as a non-pharmacological approach to addressing fundamental physiological aspects of obesity, especially in female populations at risk of unfavorable body composition profiles. However, the results should be interpreted within the context of the study's scope, including the relatively small sample size, short intervention duration, and the use of indirect body composition assessment methods. Overall, the present study provides evidence that moderate-intensity combined aerobic–resistance training may contribute to improved leptin regulation and body composition in obese women. While the findings strengthen existing evidence on the benefits of concurrent exercise, further large-scale and long-term studies incorporating comprehensive metabolic assessments are warranted to confirm these effects and clarify their underlying mechanisms.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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Data Availability Statement

Data are available from the corresponding author upon reasonable request (dwicahyo@unesa.ac.id)

AI Transparency Statement

The authors used AI-assisted tools for language editing only and take full responsibility for the content.

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Комбіновані тренування покращують регуляцію лептину, знижують вміст жиру в організмі та збільшують масу скелетних м'язів у жінок із ожирінням

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Реферат. Стаття: 11 с., 3 табл., 2 рис., 62 джерела.

Обґрунтування. Порушення регуляції лептину та несприятливий склад тіла є ключовими ознаками ожиріння у жінок. Попри те, що для покращення показників кількості жиру в організмі (адипозності) та м'язової маси зазвичай призначають комбіновані аеробно-силові тренування, дані щодо взаємозв'язку між змінами концентрації лептину в сироватці крові та детальними параметрами складу тіла у цієї категорії осіб залишаються обмеженими.

Цілі. Це рандомізоване контрольоване дослідження мало на меті вивчити вплив восьмижильневої програми комбінованих тренувань на концентрацію лептину, жирову масу та масу скелетних м'язів у жінок із ожирінням.

Матеріали та методи. Тридцять жінок із ожирінням були розподілені на групу з використанням методу комбінованих тренувань або контрольну групу без фізичних навантажень. Програма інтервенції включала аеробні та силові вправи

помірної інтенсивності, які виконувалися п'ять разів на тиждень протягом восьми тижнів. Склад тіла, зокрема відсоток жиру в організмі (ВЖО), жирову масу (ЖМ), безжирову масу (БЖМ) та масу скелетних м'язів (МСМ), оцінювали за допомогою біоімпедансного аналізу (БІА). Концентрацію лептину в сироватці крові визначали методом імуноферментного аналізу (ІФА). Аналіз відмінностей у показниках перед та після інтервенції, а також між групами проведено за допомогою параметричних статистичних тестів (t-критерій для незалежних вибірок та t-критерій для парних вибірок) із порогом значущості $p < 0.05$.

Результати. В учасниць, які пройшли програму комбінованих тренувань, спостерігалось значуще зниження концентрації лептину в сироватці крові та показників адипозності (зокрема ВЖО та ЖМ), а також суттєве збільшення БЖМ та МСМ порівняно з контрольною групою ($p < 0.05$).

Висновки. Використання методу короткострокового комбінованого аеробно-силового тренування помірної інтенсивності асоційовано з позитивними змінами у показниках концентрації лептину. Отримані результати підтверджують потенційну роль структурованих комбінованих тренувань як дієвого підходу на основі фізичних вправ для покращення метаболічного та опорно-рухового профілів у межах даного дослідження.

Ключові слова: склад тіла, комбіновані тренування, лептин, м'язова маса, ожиріння.

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Effects of Individualised Nutrition on Performance and Athlete Triad Risk

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Abstract

Background. The Female Athlete Triad and Relative Energy Deficiency in Sport (RED-S) are multifactorial conditions primarily driven by low energy availability and associated with impaired physiological function and reduced athletic performance. Despite extensive theoretical and observational evidence, controlled experimental studies evaluating structured, personalised nutritional interventions remain limited.

Objectives. To evaluate the effectiveness of a structured, personalised, multidisciplinary nutritional intervention on sport-specific performance, energy availability, and risk indicators of the Female Athlete Triad in competitive female athletes.

Material and Methods. A multicentre controlled quasi-randomised study included 480 competitive female athletes (25.1 ± 4.3 years), assigned to an intervention group (IG, n = 240) or control group (CG, n = 240) for 24 weeks. The intervention combined individualised dietary planning, structured nutritional education, and continuous follow-up. Primary outcomes were sport-specific performance (normalised composite index) and estimated energy availability (kcal/kg FFM/day). Secondary outcomes included Triad risk (LEAF-Q ≥ 8), eating behaviour (EDE-Q), nutritional knowledge (NSKQ), and body composition (DXA). Mixed-effects and multivariate regression models were applied (p < 0.05).

Results. The intervention group demonstrated significantly greater improvements in sport-specific performance compared with the control group (−5.8% ± 3.1 vs −0.9% ± 2.8; β = −0.31; 95% CI −0.42 to −0.20; p < 0.001), with a large standardized effect size (Cohen's d = 1.66). Estimated energy availability increased significantly in the IG compared with the CG (+6.3 ± 5.9 vs +0.8 ± 4.7 kcal/kg FFM/day; β = 0.28; 95% CI 0.19–0.37; p < 0.001; Cohen's d = 1.03).

The prevalence of Triad risk (LEAF-Q ≥ 8) decreased from 30.4% to 18.0% in the IG compared with 29.2% to 27.9% in the CG (OR = 0.49; 95% CI 0.34–0.71; p < 0.001). Significant improvements were observed in eating behaviour (EDE-Q; β = −0.24; 95% CI −0.35 to −0.12; p = 0.002) and nutritional knowledge (NSKQ; β = 0.41; 95% CI 0.29–0.53; p < 0.001). No significant changes were observed in bone mineral density or body composition.

Conclusions. A structured, personalised nutritional intervention significantly improves sport-specific performance, increases energy availability, and reduces the risk of the Female Athlete Triad in competitive female athletes.

These findings provide experimental evidence supporting the implementation of multidisciplinary, individualised nutritional programmes as an effective strategy for improving both health and performance in women's sport.

Keywords: Female Athlete Triad, RED-S, energy availability, nutritional intervention, sports performance.

Introduction

The Female Athlete Triad is one of the main emerging health issues in competitive women's sport. It is a complex

clinical condition involving the interaction of nutritional, endocrine, metabolic and behavioural factors. First formally described by the American College of Sports Medicine (ACSM) in the 1990s, the Triad is characterised by the presence of three interconnected components: low energy availability (LEA), menstrual dysfunction, and reduced bone mineral density (BMD) (American College of Sports

Medicine, 1997; Nattiv et al., 2007). These components do not necessarily occur simultaneously or in a clinically overt form, and they can occur along a continuum of severity, which often makes early recognition of the condition difficult.

Understanding of the Female Athlete Triad has evolved significantly over the past two decades. In particular, the International Olympic Committee (IOC) proposed the concept of Relative Energy Deficiency in Sport (RED-S) in 2014, subsequently updating it to include the systemic effects of LEA on numerous physiological systems, regardless of biological sex (Mountjoy et al., 2014; Mountjoy et al., 2018). The RED-S model recognises that chronic energy deficiency relative to training-induced expenditure compromises reproductive function, bone health, basal metabolism, protein synthesis, immune function, cardiovascular health, glycaemic regulation, gastrointestinal function, and mental health (Mountjoy et al., 2018). Furthermore, the RED-S model places specific emphasis on the consequences of LEA for performance, such as reduced training capacity, an increased risk of injury, impaired recovery and decreased competitive performance (Mountjoy et al., 2018).

Low energy availability is now considered the primary aetiological factor in both the Athlete's Triad and Relative Energy Deficiency in Sport (RED-S) (Mountjoy et al., 2018). This is defined as the energy remaining for physiological functions after the energy cost of physical exercise is subtracted from total calorie intake and normalised for lean body mass (kcal/kg of fat-free mass per day). Studies indicate that values below 30 kcal/kg FFM/day are associated with the suppression of the hypothalamic–pituitary–gonadal axis, alterations in GnRH pulsatile secretion, and consequent functional hypoestrogenism (De Souza et al., 2014). However, suboptimal levels between 30 and 45 kcal/kg FFM/day can also lead to negative physiological adaptations, particularly if they are prolonged or associated with high training loads (De Souza et al., 2014).

The prevalence of the Athlete's Triad and RED-S-related conditions varies greatly in the literature, with estimates ranging from 20% to 60% for the presence of at least one component depending on the sport, competitive level, and diagnostic criteria used (Nattiv et al., 2007; Mountjoy et al., 2014). Endurance sports (e.g. long-distance running, cycling and triathlons), aesthetic disciplines (e.g. artistic gymnastics, dance and figure skating) and weight-class sports are particularly high-risk contexts due to high energy expenditure, aesthetic expectations and pressure to maintain a low body mass. Nevertheless, recent evidence indicates that LEA and dysfunctional eating behaviours are also prevalent in team and power sports, particularly during periods of intense competitive training (Mountjoy et al., 2018).

A critical aspect of managing the Athlete Triad is its subclinical and underdiagnosed nature. Many female athletes with chronic EAA do not report complete amenorrhoea, but experience less obvious menstrual changes such as oligomenorrhoea or anovulatory cycles, which may go unnoticed by both the athlete and technical/health staff. Similarly, BMD reduction can develop progressively over time, increasing the risk of stress fractures and reducing peak bone mass (Nattiv et al., 2007; De Souza et al., 2014). This can have long-term consequences for skeletal health and increase the risk of osteoporosis in adulthood.

Alongside the pathophysiological aspects, psychological and socio-cultural factors also play a decisive role. Numerous qualitative and quantitative studies have demonstrated that female athletes are frequently subjected to explicit or implicit pressures concerning body weight, body composition, and the aesthetics of sporting performance (Trakman et al., 2018; Heaney et al., 2011). Coaches, judges, the media and social networks often contribute to the construction of unrealistic body ideals, encouraging the normalisation of dietary restriction and the adoption of nutritional practices that are not based on scientific evidence (Trakman et al., 2018). In this context, carbohydrate restriction is one of the most frequently reported behaviours, despite extensive literature demonstrating the fundamental role of carbohydrates in supporting high-intensity training and preserving energy availability (Burke et al., 2019).

Poor nutritional knowledge is an additional risk factor. Studies of athletes at different competitive levels show that a significant proportion have incomplete or incorrect knowledge of energy requirements, nutritional timing, and the consequences of low energy availability (LEA) (Trakman et al., 2018; Alaunyte et al., 2015). This lack of information is often exacerbated by limited access to qualified sports nutrition professionals, particularly at amateur or university level (Heaney et al., 2011). Consequently, many athletes adopt self-taught dietary strategies influenced by non-scientific sources, which can have negative repercussions for their health and performance (Heaney et al., 2011).

From a performance perspective, LEA and the Athlete Triad are associated with a reduction in the ability to adapt to training, an increased perception of fatigue, longer recovery times, and an increased risk of musculoskeletal injuries (Mountjoy et al., 2014; Heikura et al., 2017). Stress fractures, tendinopathies and recurrent infections are common clinical manifestations of chronic EAA in female athletes, significantly impacting training continuity and sporting careers (Nattiv et al., 2007). These issues emphasise that nutrition is a central, rather than accessory, factor in performance and sporting longevity.

Available evidence suggests that an energy availability of at least 45 kcal/kg FFM/day is necessary to maintain menstrual function, bone health, and optimal physiological function in female athletes (De Souza et al., 2014). However, it is difficult to translate these theoretical recommendations into daily practice, particularly when faced with high training volumes, academic or work commitments, and logistical limitations. Furthermore, most of the studies that have contributed to defining these thresholds are observational or short-term experimental in nature and are often conducted in controlled laboratory settings.

A significant limitation of the existing literature is the lack of controlled experimental studies that evaluate the effectiveness of structured, personalised nutritional interventions within the context of competitive sport. While many studies focus on the association between LEA and clinical outcomes, few have systematically tested intervention programmes integrating dietary plans, nutritional education, and multidisciplinary support to assess their impact on health and sporting performance.

Despite the growing scientific interest in the Female Athlete Triad and RED-S, a critical gap persists in the translation of theoretical knowledge into effective preventive

strategies within real sporting environments. Current research has clearly established low energy availability as the central aetiological mechanism underlying these conditions; however, most prevention approaches continue to rely primarily on screening tools, general nutritional guidelines, or educational recommendations rather than structured intervention models (Mountjoy et al., 2018).

This creates an unresolved contradiction in the current literature: while RED-S is recognised as a multifactorial condition requiring behavioural, nutritional and organisational modifications, the majority of existing strategies focus mainly on risk identification rather than on experimentally tested, comprehensive prevention programmes.

As a result, athletes may be screened and informed about the risks of low energy availability without receiving practical, personalised strategies capable of modifying dietary behaviours within the context of demanding training schedules and sociocultural pressures.

Consequently, the effectiveness of current prevention approaches remains limited. Generic nutritional advice, short-term educational sessions, and non-individualised dietary recommendations often fail to produce sustainable behavioural changes or to adequately restore energy availability in athletes exposed to high training loads (Heaney et al., 2011; Trakman et al., 2018).

This limitation highlights the need for experimentally tested, multidisciplinary interventions capable of integrating personalised nutritional planning, structured education and continuous monitoring within real competitive settings.

In light of these considerations, large-scale experimental studies conducted in multicentre settings that are representative of real-world sporting practices are needed to evaluate the effectiveness of evidence-based nutritional interventions in preventing the female athlete triad and relative energy deficiency in sport (RED-S).

These studies should consider not only physiological and performance outcomes, but also educational, cultural, and organisational factors influencing adherence to proposed nutritional strategies.

This experimental study therefore aims to address this gap by evaluating the impact of a personalised, structured, multidisciplinary nutritional intervention on sports performance and risk indicators for the Female Athlete Triad in a large sample of competitive female athletes.

By experimentally testing a personalised, multidisciplinary nutritional intervention implemented in real-world competitive environments, the present study seeks to move beyond observational associations and provide practical evidence for effective prevention strategies.

Integrating quantitative and qualitative measures will provide an in-depth understanding of the mechanisms through which nutrition can support health and performance in women's sport.

This will contribute to the development of replicable, evidence-based intervention models.

Study hypotheses

Based on the existing literature on low energy availability and the Female Athlete Triad, this study tested a set of predefined primary and secondary hypotheses regarding the effects of a structured, personalised nutritional intervention in competitive female athletes.

Primary hypotheses

1. Athletes receiving the personalised nutritional intervention will show significantly greater improvements in sport-specific performance compared with athletes receiving generic nutritional guidance.
2. Athletes in the intervention group will demonstrate a significantly greater increase in estimated energy availability (kcal/kg FFM/day) compared with the control group.

Secondary hypotheses

In addition to the primary outcomes, the intervention is expected to produce favourable changes in several health and behavioural indicators associated with the Female Athlete Triad and RED-S:

3. The prevalence of Triad risk (LEAF-Q ≥ 8) will decrease significantly in the intervention group compared with the control group.
4. Eating disorder risk behaviours, assessed using the EDE-Q, will decrease in the intervention group.
5. Sports nutrition knowledge, measured through the NSKQ, will increase significantly in the intervention group.
6. The intervention will support the maintenance or improvement of body composition and bone health indicators, assessed using DXA.

These hypotheses guided the selection of outcome measures and the statistical analyses applied in the study.

Materials and methods

Study Design

A multicentre, controlled, quasi-randomised experimental study conducted between January 2022 and December 2025 at sports medicine centres, universities and competitive sports clubs.

Participants

480 competitive female athletes (average age 25.1 ± 4.3 years) were recruited.

Inclusion Criteria:

- Biological female.
- Aged 18–35.
- Participation in official competitions.
- Training ≥ 5 hours/week.

Exclusion Criteria:

- pregnancy or breastfeeding
- known endocrine disorders
- use of hormonal contraceptives in the previous 6 months
- injuries limiting performance

Grouping

The athletes were assigned to:

- Intervention Group (IG; $n=240$)
- Control Group (CG; $n=240$)

The assignment was stratified by sport type and competitive level.

Experimental Nutritional Intervention

The experimental nutritional intervention was designed based on the latest scientific evidence in the fields of sports nutrition, women's health, and the prevention of the Female Athlete Triad and Relative Energy Deficiency in Sport (RED-S). The rationale behind the intervention recognises low energy availability (LEA) as the primary cause of the endocrine, metabolic and bone changes observed in female athletes, and as a key factor in decreased athletic performance. Consequently, the programme adopted a personalised, progressive and multidimensional approach, integrating nutritional assessment, dietary planning, nutritional education and continuous follow-up.¹

Initial Individual Nutritional Assessment

The initial phase of the intervention involved a thorough, personalised nutritional assessment. This was considered essential for the early identification of LEA conditions and for establishing effective, sustainable dietary strategies. The literature highlights that standardised, non-personalised approaches are often ineffective at correcting LEA in female athletes, particularly in contexts involving a high training load.

The assessment included:

- Analysis of total energy expenditure, estimated by combining training data (duration, intensity and frequency), validated questionnaires and, where available, instrumental measurements (e.g. accelerometry). An accurate estimate of energy expenditure is essential, as underestimating the cost of exercise is one of the main causes of unintentional EER.
- Estimation of energy availability, calculated as the difference between energy intake and exercise cost, normalised for lean body mass (kcal/kg FFM/day). Numerous studies have shown that EAE is a more reliable predictor of menstrual dysfunction and bone health alterations than simple energy balance.
- Qualitative and quantitative analysis of eating habits using food diaries and structured interviews. This phase identified restrictive eating patterns, incorrect macronutrient distribution, inadequate nutritional timing, and dysfunctional eating beliefs, all of which are frequently reported in athletes.

Personalised nutrition plan:

Based on the initial assessment, a personalised nutrition plan was developed for each athlete in the intervention group. Personalisation is a central element of the intervention, as the literature shows that nutritional strategies tailored to individual needs improve adherence and long-term effectiveness.

The dietary plan was structured according to the following principles:

- Target energy availability ≥ 45 kcal/kg FFM/d, a value commonly recognised as the threshold for maintaining endocrine function and bone health

in female athletes. This target was progressively adjusted in cases of severe AED in order to reduce the risk of poor adaptation or psychological resistance to increased energy intake.

- Carbohydrates: 5–8 g/kg/d, modulated according to training load, stage of the season and sport discipline. An adequate carbohydrate intake is essential to support performance, preserve muscle glycogen and reduce the endocrine stress associated with intense training. Carbohydrate restriction, frequently observed in female athletes, has been associated with an increased risk of LEA and menstrual disturbances.
- Protein: 1.6–2.0 g/kg/day, in line with recommendations for athletes engaged in endurance and strength training. Adequate protein intake supports lean mass maintenance, muscle protein synthesis and recovery, which are particularly important in conditions of previous LEA.
- Fats ≥ 25 –30% of total energy, with attention to the quality of fatty acids. Insufficient lipid intake has been associated with reduced steroid hormone production and impaired reproductive function.
- Peri-workout nutritional timing, including pre- and post-exercise meals and snacks, with the aim of reducing prolonged periods of intra-diurnal energy deficit. Emerging evidence indicates that the timing of energy intake, in addition to the total amount, also influences hormonal regulation and the risk of LEA.

Structured nutritional education

A distinctive feature of the intervention was the structured nutrition education programme, divided into six sessions spread throughout the intervention, conducted both individually and in small groups. The literature emphasises that dietary prescriptions alone are often insufficient to bring about lasting changes in eating behaviours, especially in the presence of deep-rooted beliefs and socio-cultural pressures.

The educational sessions addressed the following topics in a progressive and interactive manner:

- physiopathology of the Athlete Triad and RED-S;
- role of energy availability in health and performance;
- importance of carbohydrates in women's sport;
- nutrition and bone health;
- nutritional strategies for recovery and injury prevention.

This educational approach aims to improve nutritional knowledge, which has been associated in several studies with better diet quality and a reduction in risky eating behaviours (Trakman et al., 2018; Alaunyte et al., 2015).

Follow-up and monitoring

Monthly follow-ups were a key component of the intervention, allowing for dynamic adaptation of the nutrition plan based on changes in training load, the competitive season, and individual responses. Previous studies indicate that continuous monitoring significantly increases adherence to and effectiveness of nutrition interventions in female athletes (Burke et al., 2019).

During the follow-ups, the following were assessed:

- adherence to the nutritional plan

- changes in energy availability
- any logistical or psychological difficulties
- subjective perception of energy, recovery and performance

Control group

The control group received only generic, non-personalised nutritional guidance, in line with standard practice in many sporting contexts. This approach reflects the reality of many competitive environments, where specialist nutritional support is limited or absent, and allows for a comparison of the effectiveness of the structured intervention with current practices (Heaney et al., 2011).

Assessments

The assessments were selected in order to capture the multidimensional effects of nutritional intervention on the health, eating behaviour and athletic performance of female athletes. In line with methodological recommendations for studies on RED-S and the Female Athlete Triad, an integrated approach combining physiological, performance, psychometric and qualitative measures was adopted. This strategy allows us to overcome the limitations of studies focused on individual outcomes and to explore the interactions between nutritional, endocrine and behavioural factors.

Primary outcome

Performance

Sports performance was defined as the primary outcome because it represents a relevant functional indicator for both athletes and technical staff, and is one of the key elements through which LEA and the Athlete Triad influence sporting careers. Discipline-specific tests were used, selected according to the type of sport practised (endurance, team sports, aesthetic disciplines or weight categories), in order to ensure ecological validity and applicability.

The use of specific tests, rather than generic fitness measures, is supported by literature highlighting how LEA differentially affects performance components depending on the metabolic and neuromuscular demands of the discipline (Heikura et al., 2017). Performance was assessed under standardised conditions and replicated over time to reduce intra-individual variability.

Estimated energy availability

Estimated energy availability (kcal/kg of lean body mass per day) represents the second primary outcome, as it is considered the central physiological determinant of the Athlete Triad and RED-S. The decision to include energy availability as a primary outcome is consistent with IOC recommendations and studies showing that even moderate changes in this parameter are associated with significant endocrine and metabolic changes.

Energy availability was estimated by combining:

- daily energy intake;
- energy cost of exercise;

- instrumentally measured lean mass.

Although the estimation of energy availability has inherent limitations, it remains one of the most widely used and informative tools for assessing the risk of EAD in application contexts.

Secondary outcome

Athlete's triad risk (LEAF-Q)

The risk of the Female Athlete Triad was assessed using the Low Energy Availability in Females Questionnaire (LEAF-Q), a validated tool widely used in scientific literature. The LEAF-Q allows athletes at risk to be identified on the basis of gastrointestinal symptoms, menstrual dysfunction and history of injury, providing a practical and clinically relevant measure of LEA risk.

The use of the LEAF-Q as a secondary outcome is justified by its sensitivity in detecting changes in the risk of the Triad following nutritional interventions or changes in training load.

Eating behaviour (EDE-Q)

Eating behaviour was assessed using the Eating Disorder Examination Questionnaire (EDE-Q), a validated tool for identifying dysfunctional eating behaviours and pathological attitudes towards food and body image (Fairburn & Beglin, 1994). The inclusion of this measure responds to the need to monitor possible side effects of nutritional interventions and to explore the link between LEA, cognitive restriction and the risk of eating disorders, which has been widely documented in female athletes.

The EDE-Q also allows us to distinguish between intentional and unintentional restriction, which is crucial to understanding the dynamics that lead to LEA.

Nutritional knowledge (NSKQ)

Nutritional knowledge was assessed using the Nutrition for Sport Knowledge Questionnaire (NSKQ), a tool specifically validated for athletic populations. The literature suggests that a higher level of nutritional knowledge is associated with better diet quality, greater energy availability and a reduction in risky eating behaviours.

The assessment of nutritional knowledge allowed us to explore the mediating role of nutritional education on physiological and performance outcomes, providing useful information for the implementation of future educational interventions.

Body composition and bone health (DXA)

Body composition and bone mineral density were assessed using dual-energy X-ray absorptiometry (DXA), considered the gold standard for assessing BMD and lean mass in female athletes (Nana et al., 2015). The decision to include DXA as a secondary outcome reflects the clinical importance of bone health in the Female Athlete Triad, as EAD and hypoestrogenism are associated with reduced BMD and an increased risk of stress fractures (Nattiv et al., 2007; De Souza et al., 2014).

Although changes in BMD require prolonged observation periods, the inclusion of this measure allows early changes to be detected and the potential impact of the intervention on skeletal health in the medium to long term to be assessed.

Qualitative Analysis

A sub-sample of 42 athletes (21 in the intervention group and 21 in the control group) participated in semi-structured interviews conducted before and after the intervention. Qualitative analysis was included to explore subjective perceptions, barriers and facilitators of behavioural change, aspects that cannot be fully captured by quantitative measures alone.

The interviews were analysed using thematic analysis according to Braun and Clarke (2006), following an inductive-deductive approach. Reporting was in accordance with the COREQ (Consolidated Criteria for Reporting Qualitative Research) guidelines, ensuring transparency and methodological rigour.

An a priori statistical power analysis was conducted to determine the minimum sample size required for the study. The calculation was performed using G*Power software (version 3.1) for repeated-measures comparisons between two groups.

Based on previous studies investigating nutritional interventions in female athletes, a moderate effect size (Cohen's $f = 0.25$) was assumed for the primary outcomes (sport performance and energy availability). The significance level (α) was set at 0.05, and the desired statistical power ($1-\beta$) was 0.80.

The power analysis indicated that a minimum sample of approximately 210 participants per group would be required to detect statistically significant between-group differences. To account for potential dropouts and missing data, the target sample size was increased, resulting in a final sample of 480 athletes (240 per group) included in the study.

Statistical Analysis

Statistical analysis was conducted according to the intention-to-treat principle in order to preserve the benefits of group assignment and reduce the risk of attrition bias.

The following were used:

- Mixed-effects linear regression models were used to analyse continuous outcomes related to the primary hypotheses (sport performance and estimated energy availability).
- Logistic regression models were applied to assess dichotomous outcomes related to Triad risk (LEAF-Q ≥ 8).
- Secondary continuous outcomes (EDE-Q scores, NSKQ scores, and DXA-derived body composition variables) were analysed using multivariate linear regression models.
- Mixed models accounted for the hierarchical structure of the data (athletes nested within sports centres).

The level of statistical significance was set at $p < 0.05$, in line with biomedical and sports research conventions.

Results

Sample characteristics

Baseline characteristics of the participants are presented in Table 1.

Table 1. Baseline characteristics of the sample

Variable	Intervention Group (n=240)	Control Group (n=240)	p
Age (years)	25.2 $\pm$ 4.4	25.0 $\pm$ 4.2	0.67
Training volume (h/week)	8.7 $\pm$ 3.0	8.5 $\pm$ 2.8	0.59
Endurance sports (%)	44.2	43.8	1.00
Team sports (%)	31.0	31.1	1.00
Aesthetic/weight-class sports (%)	24.8	25.1	1.00
Energy availability (kcal/kg FFM/d)	38.6 $\pm$ 6.4	38.9 $\pm$ 6.2	0.71
LEAF-Q ≥ 8 (%)	30.4	29.2	0.78
Lean mass (kg)	45.8 $\pm$ 4.6	46.0 $\pm$ 4.7	0.74
Fat mass (%)	21.4 $\pm$ 4.2	21.7 $\pm$ 4.3	0.69

The study included a total of 480 competitive athletes, of whom 240 were assigned to the intervention group (IG) and 240 to the control group (CG). The overall mean age was 25.1 $\pm$ 4.3 years, with no significant differences between the two groups at baseline ($p = 0.67$). Weekly training volume (mean 8.6 $\pm$ 2.9 hours/week) also did not differ significantly between IG and CG ($p = 0.59$).

In relation to the type of sport practised:

- 44% ($n = 211$) of the athletes practised endurance sports,
- 31% ($n = 149$) practised team sports,
- 25% ($n = 120$) practised aesthetic disciplines or weight category sports.

The distribution of disciplines was comparable between the groups ($\chi^2 = 1.12$; $p = 0.57$), indicating adequate comparability of the sample.

At baseline, 29.8% of athletes ($n = 143$) had a LEAF-Q ≥ 8 score, indicative of low energy availability risk and the Female Athlete Triad. The prevalence of LEAF-Q ≥ 8 did not differ significantly between GI (30.4%) and GC (29.2%) at enrolment ($p = 0.78$). Similarly, there were no significant differences between the groups in estimated energy availability, athletic performance, or body composition at baseline.

Effects of the intervention on primary outcomes

The effects of the intervention on the primary outcomes are summarised in Table 2.

The sports performance indicator reported in Table 2 represents a normalized composite performance index constructed from standardized sport-specific performance measures collected for each athlete. To facilitate comparison across different sport disciplines, baseline performance was set to a reference value of 100 for each participant. Subsequent measurements were expressed as percentage change relative to this baseline reference.

For performance variables where lower values indicate better performance (e.g., time-based measures such as

Table 2. Primary outcomes

Outcome	Group	Baseline	Post-intervention	Between-group difference	β (model estimate)	95% CI	p	Cohen's d	Interpretation
Sports performance (%)	IG	100	94.2 $\pm$ 3.1	-4.9	-0.31	-0.42 to -0.20	<0.001	1.66	Large
	CG	100	99.1 $\pm$ 2.8						
Energy availability (kcal/kg FFM/d)	IG	38.6 $\pm$ 6.4	44.9 $\pm$ 5.8	+5.5	0.28	0.19–0.37	<0.001	1.03	Large
	CG	38.9 $\pm$ 6.2	39.7 $\pm$ 6.0						

Note. Cohen's d was calculated for the between-group difference in change scores using pooled standard deviations and interpreted according to conventional thresholds (0.2 = small, 0.5 = medium, 0.8 = large). For sports performance, the negative sign reflects greater improvement in the intervention group because lower values of the normalised performance index indicate better performance

Table 3. Secondary outcomes

Outcome	Intervention Group	Control Group	Effect estimate	95% CI	p
LEAF-Q ≥ 8 prevalence (%)	30.4 $\rightarrow$ 18.0	29.2 $\rightarrow$ 27.9	OR 0.49	0.34–0.71	<0.001
EDE-Q total score	-0.62 $\pm$ 0.41	-0.05 $\pm$ 0.38	β -0.24	-0.35 – -0.12	0.002
NSKQ score (points)	+18.4 $\pm$ 9.6	+3.1 $\pm$ 7.8	β 0.41	0.29–0.53	<0.001
Lean mass (kg)	+0.4 $\pm$ 0.6	+0.1 $\pm$ 0.5	β 0.09	-0.01–0.19	0.07
Fat mass (%)	-0.8 $\pm$ 1.2	-0.2 $\pm$ 1.1	β -0.12	-0.24–0.01	0.06
Bone mineral density	no change	no change	–	–	0.41

sprint time or endurance completion time), the normalized index decreases when performance improves. Therefore, a reduction of the index from the baseline value of 100 to 94.2 in the intervention group reflects an improvement in performance relative to baseline.

The index was calculated by standardizing the raw performance outcome for each athlete relative to their baseline value and then averaging across the relevant performance indicators within each sport category. This normalization procedure allowed performance changes to be compared across heterogeneous sport disciplines while maintaining baseline comparability between the intervention and control groups.

The results for secondary outcomes are reported in Table 3.

To complement the p-values and regression coefficients, effect sizes were calculated for the primary outcomes to quantify the magnitude of the intervention effects. For continuous variables, Cohen's d was computed as the standardized mean difference between the intervention and control groups. Effect sizes were interpreted according to conventional thresholds (small = 0.2, medium = 0.5, large = 0.8).

In addition, 95% confidence intervals (95% CI) were calculated for all primary outcomes to provide an estimate of the precision of the observed effects. For regression analyses, standardized regression coefficients (β) together with their corresponding 95% confidence intervals were reported.

Reporting both p-values and effect size measures allows a more comprehensive interpretation of the statistical results by combining information on statistical significance with the magnitude and practical relevance of the observed effects.

Performance

At the end of the intervention, the intervention group demonstrated a significantly greater improvement in sport-specific performance than the control group ($-5.8\% \pm 3.1$ vs $-0.9\% \pm 2.8$; $\beta = -0.31$; 95% CI -0.42 to -0.20 ; $p < 0.001$), with a large standardized effect size (Cohen's d = 1.66).

Analysis using mixed models, adjusted for age, type of sport and sports centre, showed a significant main group

effect ($\beta = -0.31$; 95% CI -0.42 to -0.20 ; $p < 0.001$). The effect was consistent across different types of disciplines, with no significant interactions between group and type of sport (p for interaction = 0.21).

Estimated energy availability

Estimated energy availability increased significantly in the intervention group compared with the control group ($+6.3 \pm 5.9$ vs $+0.8 \pm 4.7$ kcal/kg FFM/day; $\beta = 0.28$; 95% CI 0.19 – 0.37 ; $p < 0.001$), corresponding to a large effect size (Cohen's d = 1.03).

The difference between the groups was statistically significant ($p < 0.001$). At the end of the intervention, 67.5% of athletes in the IG achieved an energy availability of ≥ 45 kcal/kg FFM/d, compared to 32.1% in the CG ($p < 0.001$).

Effects of the intervention on secondary outcomes

Athlete's triad risk (LEAF-Q)

At follow-up, the prevalence of athletes with LEAF-Q ≥ 8 was significantly reduced in the intervention group, from 30.4% to 18.0%, while in the control group it remained essentially unchanged (from 29.2% to 27.9%).

Multivariate logistic regression analysis showed that belonging to the IG was associated with a significant reduction in the risk of LEAF-Q ≥ 8 (OR = 0.49; 95% CI 0.34 – 0.71 ; $p < 0.001$), regardless of age, type of sport, and baseline energy availability.

Eating behaviour (EDE-Q)

The intervention group showed a significant reduction in total EDE-Q scores, particularly in the cognitive restriction and weight concern subscales ($p < 0.01$). In the control group, EDE-Q scores did not show significant changes from baseline. No clinically relevant increases in EDE-Q scores were observed in either group.

Table 4. Summary of regression models

Outcome	Model	Covariates	Effect estimate	95% CI	p
Sports performance	Mixed-effects linear regression	Age, sport type, centre	$\beta = -0.31$	-0.42 – -0.20	<0.001
Energy availability	Mixed-effects linear regression	Age, baseline EA, centre	$\beta = 0.28$	0.19 – 0.37	<0.001
LEAF-Q ≥ 8	Logistic regression	Age, sport type, baseline EA	OR = 0.49	0.34 – 0.71	<0.001
EDE-Q	Linear regression	Age, baseline score	$\beta = -0.24$	-0.35 – -0.12	0.002
NSKQ	Linear regression	Age, baseline score	$\beta = 0.41$	0.29 – 0.53	<0.001

Nutritional knowledge (NSKQ)

The total NSKQ score increased significantly in the IG ($+18.4 \pm 9.6$ points) compared to the CG ($+3.1 \pm 7.8$ points; $p < 0.001$). The greatest increase was observed in the sections relating to carbohydrates and nutritional timing.

Body composition and bone health (DXA)

No significant changes in bone mineral density were observed during the intervention period in either group. However, in the intervention group, lean mass was maintained and there was a slight reduction in the percentage of fat mass, while no significant changes were observed in the control group. No differences between groups were observed in terms of changes in total body weight.

A summary of the regression models is presented in Table 4.

Qualitative Results

The thematic analysis of the semi-structured interviews revealed five main themes, with marked differences between the intervention group and the control group in the post-intervention period.

7. Overcoming the fear of carbohydrates, with greater acceptance of their role in supporting training and recovery.
8. Greater awareness of the role of energy, understood as a functional resource for health and performance.
9. Reduction in the normalisation of dietary restriction, previously perceived as an integral part of sports culture.
10. Greater trust in the multidisciplinary staff, particularly in the sports nutritionist.
11. Improved subjective perception of performance and recovery, even in the absence of obvious changes in body composition.

In the control group, these themes emerged sporadically and unsystematically.

Discussion

This controlled experimental study provides robust evidence that a structured, personalised nutritional intervention improves both athletic performance and health indicators associated with the Athlete Triad and Relative Energy Deficiency in Sport (RED-S) in a large sample of competitive female athletes. The increase in energy availability, reduction in Triad risk and improvement in performance observed in the intervention group confirm nutrition's central role as a physiological and functional

determinant in competitive women's sport (Mountjoy et al., 2014; Mountjoy et al., 2018).

A significant increase in energy availability was observed in the intervention group, with a substantial proportion of athletes reaching or exceeding the threshold of 45 kcal/kg FFM/d. This finding is consistent with previous research identifying this threshold as necessary for maintaining endocrine function and bone health in athletes (De Souza et al., 2014; Nattiv et al., 2007). Previous experimental studies have demonstrated that even modest increases in energy availability can result in enhanced leptin, insulin-like growth factor 1 (IGF-1) and gonadotropin hormone secretion, facilitating the restoration of menstrual function and reducing the catabolic state.

The significant reduction in LEAF-Q scores observed in the intervention group suggests that increased energy availability translates into clinically relevant benefits by reducing the likelihood of functional manifestations of the Athlete Triad. This finding is consistent with observational studies showing a strong association between low energy availability and Triad-related outcomes (Mountjoy et al., 2018), but it also makes an experimental contribution by demonstrating that this risk can be reduced through targeted nutritional intervention.

The significant improvement in athletic performance observed in the intervention group is a particularly important practical outcome. The literature suggests that energy availability deficiency compromises the ability to adapt to training through multiple mechanisms, including reduced energy substrate availability, increased endocrine stress and altered metabolic responses (Heikura et al., 2017; Burke et al., 2019). The results of the present study support the hypothesis that optimising energy availability enables these adaptations to be maximised, resulting in measurable improvements in discipline-specific performance.

Notably, these performance improvements occurred without significant changes in total body weight or bone mineral density in the short term. This contradicts the common belief that increasing energy intake necessarily leads to an increase in body weight, which is frequently reported among athletes and identified as a barrier to adopting adequate nutritional strategies. Therefore, the results of this study help to dispel this myth by highlighting that a balanced diet can improve performance without having a negative effect on body composition (Nana et al., 2015).

Another important finding that emerged from the study is the improvement in eating behaviours and nutritional knowledge in the intervention group.

The reduction in EDE-Q scores, particularly in the cognitive restriction dimension, suggests that the intervention did not increase the risk of dysfunctional eating behaviours; in fact, it contributed to a healthier relationship with food. This finding is consistent with studies showing that nutrition interventions

based on education and ongoing support can reduce risky eating behaviours in athletes (Fairburn & Beglin, 1994).

The significant increase in nutritional knowledge, as measured by the NSKQ, further supports the importance of education as a key component of the intervention. Previous evidence indicates that greater nutritional knowledge is associated with a better-quality diet, greater energy availability and a reduction in the normalisation of dietary restriction among female athletes (Trakman et al., 2018; Alaunyte et al., 2015; Heaney et al., 2011). The qualitative results of the present study reinforce this, showing that athletes developed a greater awareness of the role of energy and carbohydrates in supporting training and recovery.

Integrating qualitative data is one of this study's strengths, as it allows the quantitative results to be contextualised and the mechanisms of behavioural change to be explored. The themes that emerged from the interviews, such as overcoming the fear of carbohydrates and reducing the normalisation of restriction, align with literature identifying cultural and organisational factors as critical determinants of athletes' eating behaviours (Trakman et al., 2018).

Participants in the intervention group reported greater trust in the multidisciplinary staff, which highlights the importance of an integrated approach involving nutritionists, sports physicians and coaches. Previous studies have shown that multidisciplinary interventions are more effective than isolated strategies in preventing and managing the Athlete Triad and Relative Energy Deficiency in Sport (RED-S) (Mountjoy et al., 2014; Mountjoy et al., 2018). The results of the present study provide further empirical support for these recommendations.

From a practical standpoint, the findings imply that systematically implementing personalised, evidence-based nutritional programmes could effectively enhance the health and performance of competitive female athletes. Using screening tools such as the LEAF-Q, combined with energy availability assessments and structured educational programmes, could help to identify at-risk athletes early on and prevent the long-term consequences of low energy availability (Nattiv et al., 2007; De Souza et al., 2014).

Despite its strengths, the present study has some limitations. The estimation of energy availability, although based on established methods, remains subject to measurement errors. Furthermore, the intervention may not have been long enough to observe significant changes in bone mineral density, as these require longer follow-up periods (Nana et al., 2015). Finally, the absence of complete randomisation is another limitation, although using multivariate statistical models and baseline-comparable groups reduces the risk of bias.

Overall, the results of this study reinforce the evidence that low energy availability is a modifiable determinant of health and performance in women's sport. A structured, personalised nutritional intervention supported by continuous education and a multidisciplinary approach is an effective and sustainable strategy for the prevention of the Female Athlete Triad and RED-S, with positive effects on both the well-being of athletes and their competitive performance (Mountjoy et al., 2018).

Conclusions

This controlled experimental study provides solid evidence that a structured, personalised nutritional

intervention based on scientific evidence improves energy availability, reduces the risk of the Female Athlete Triad, and optimises sports performance in competitive female athletes. The results confirm that low energy availability is a significant yet modifiable factor affecting the health and performance of female athletes, and that targeted interventions can deliver clinically and functionally significant benefits, even within the context of competitive activity.

Integrating individualised dietary planning, structured nutrition education and continuous follow-up has proven particularly effective in improving both physiological and performance indicators and in promoting positive changes in athletes' eating behaviours and nutritional beliefs. These results highlight the importance of a multidisciplinary approach in which sports nutritionists play a pivotal role within women's competitive teams, collaborating closely with sports physicians and coaches.

From an application perspective, the study supports the systematic adoption of screening and nutritional intervention programmes in competitive sports contexts. The aim is to prevent the consequences of essential amino acid (EAA) deficiency early on and promote a sports culture that is oriented towards health and sustainable performance. Furthermore, the results emphasise the necessity of moving beyond generic or non-personalised nutritional approaches, which frequently fail to address the unique requirements of female athletes.

Finally, this work helps to fill an important gap in the literature by providing experimental data on a nutritional intervention applied in a multicentre, real-world setting. Future studies should evaluate the long-term effects of such interventions on bone health and sporting longevity, and further explore the mechanisms through which nutritional education and multidisciplinary support influence adherence and clinical outcomes.

Ethics Approval

The study was conducted in accordance with the principles of the Declaration of Helsinki. The research protocol was reviewed and approved by the Ethics Committee of the University of Naples "Parthenope".

Informed Consent

All participants provided written informed consent prior to participation in the study. Participants were informed about the study procedures, potential risks, and their right to withdraw from the study at any time without consequences.

Data Availability Statement

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

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Conflicts of Interest

The authors declare no conflict of interest.

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The authors declare that artificial intelligence tools were used solely for language editing and text refinement. All scientific content, analysis, and interpretations were developed and verified by the authors.

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Ефективність індивідуалізованого нутріційного втручання у підвищенні результативності та зниженні ризику тріади спортсменок

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

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Обґрунтування. Тріада спортсменок та відносний дефіцит енергії у спорті (RED-S) є багатофакторними станами, зумовленими передусім низькою енергетичною доступністю та пов'язаними з порушенням фізіологічних функцій і зниженням спортивної результативності. Незважаючи на значну кількість теоретичних та обсерваційних досліджень, контрольовані експериментальні роботи, що оцінюють ефективність структурованих, персоналізованих нутріційних втручань, залишаються обмеженими.

Мета. Оцінити ефективність структурованого, персоналізованого, мультидисциплінарного нутріційного втручання щодо спортивної результативності, енергетичної доступності та показників ризику тріади спортсменок у кваліфікованих спортсменок.

Матеріали і методи. Багатоцентрове контрольоване квазірандомізоване дослідження включало 480 кваліфікованих спортсменок (25.1 ± 4.3 року), яких було розподілено на групу втручання (IG, $n = 240$) та контрольну групу (CG, $n = 240$) тривалістю 24 тижні. Втручання включало індивідуалізоване планування харчування, структуровану нутріційну освіту та постійний супровід. Основними показниками були спортивна результативність (нормалізований інтегральний індекс) та розрахована енергетична доступність (ккал/кг безжирової маси тіла/день). Додаткові показники включали ризик тріади (LEAF-Q ≥ 8), харчову поведінку (EDE-Q), нутріційні знання (NSKQ) та склад тіла (DXA). Застосовано змішані моделі та багатофакторний регресійний аналіз ($p < 0.05$).

Результати. У групі втручання спостерігалася статистично значуще покращення спортивної результативності порівняно з контрольною групою ($-5.8\% \pm 3.1$ проти $-0.9\% \pm 2.8$; $\beta = -0.31$; 95% ДІ -0.42 до -0.20 ; $p < 0.001$) з великим стандартизованим ефектом (Cohen's $d = 1.66$). Розрахована енергетична доступність достовірно зросла у групі втручання порівняно з контрольною групою ($+6.3 \pm 5.9$ проти $+0.8 \pm 4.7$ ккал/кг безжирової маси тіла/день; $\beta = 0.28$; 95% ДІ 0.19 – 0.37 ; $p < 0.001$; Cohen's $d = 1.03$). Поширеність ризику тріади (LEAF-Q ≥ 8) зменшилась з 30.4% до 18.0% у групі втручання порівняно з 29.2% до 27.9% у контрольній групі (OR = 0.49 ; 95% ДІ 0.34 – 0.71 ; $p < 0.001$). Виявлено достовірне покращення харчової поведінки (EDE-Q: $\beta = -0.24$; 95% ДІ -0.35 до -0.12 ; $p = 0.002$) та рівня нутріційних знань (NSKQ: $\beta = 0.41$; 95% ДІ 0.29 – 0.53 ; $p < 0.001$). Достовірних змін мінеральної щільності кісткової тканини та складу тіла не встановлено.

Висновки. Структуроване, персоналізоване нутріційне втручання достовірно покращує спортивну результативність, підвищує енергетичну доступність і знижує ризик тріади спортсменок у кваліфікованих спортсменок. Отримані результати надають експериментальні докази ефективності мультидисциплінарних індивідуалізованих нутріційних програм як інструменту підвищення здоров'я та результативності у жіночому спорті.

Ключові слова: тріада спортсменок, RED-S, енергетична доступність, нутріційне втручання, спортивна результативність.

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