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Review Article

Functional Evolution of Experimental Design in Sports Science: From Bibliometric Analysis to a Functional Concept

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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. Experimental design is the principal methodological framework for establishing causal relationships in sports science. Traditional classifications describe experimental designs according to structural characteristics, such as the number of factors, randomization procedures, measurement organization, or statistical methods. However, these approaches do not explain how the methodological functions of experimental design evolve from hypothesis testing to mathematical modelling, programming, and model-based decision making.

Objectives. To investigate the functional evolution of experimental design in sports science, determine the methodological role of full factorial experiments (2^k), and develop a functional concept of experimental design based on bibliometric and systematic methodological analyses.

Material and Methods. The study was conducted in two stages. First, a bibliometric analysis of publications indexed in the Scopus database (2000–2026) was performed to identify the structure of research on experimental designs and to construct an analytical corpus. After duplicate removal, the main bibliometric corpus comprised 1653 publications. Second, a systematic methodological analysis of a specialized corpus of 244 publications was carried out to evaluate the realization of the cognitive and constructive potential of experimental designs. Particular attention was paid to studies integrating full factorial experiments with mathematical modelling, regression analysis, and discriminant analysis.

Results. The bibliometric analysis demonstrated that contemporary sports science is dominated by subject-oriented terminology, whereas methodological concepts related to experimental design are rarely represented in author keywords or publication titles. The systematic methodological analysis showed that experimental designs with similar structural characteristics perform substantially different methodological functions. A functional concept of experimental design was developed, according to which its methodological significance is determined by the level of realization of its cognitive and constructive potential. Full factorial experiments were identified as the methodological link connecting experimental analysis with mathematical modelling. Three levels of realization of the constructive potential of experimental design were identified: local model-based control, programming of the pedagogical process, and system-level management.

Conclusions. The study proposes a functional concept of experimental design that complements traditional structural classifications. The methodological contribution of the study consists in introducing a new principle for classifying experimental designs according to the level of realization of their cognitive and constructive potential. Full factorial experiments occupy a central methodological position in this framework by enabling the transition from hypothesis testing to mathematical modelling, programming, and model-based management of pedagogical and training processes.

Keywords: experimental design, full factorial experiment, sports science, mathematical modelling, regression analysis, discriminant analysis, bibliometric analysis, systematic methodological analysis, pedagogical programming, model-based decision making.

Introduction

Experimentation is one of the principal methods for establishing causal relationships in the natural sciences,

medicine, education, and sports science. Experimental design determines the structure of a study, the way experimental factors are manipulated, data collection procedures, and the statistical approaches available for analyzing the obtained results (Goodwin, 2004; Creswell & Creswell, 2018). Consequently, the development of experimental methods is inseparably linked to the evolution of scientific methodology.

In contemporary sports science, experimental research serves as a fundamental tool for evaluating the effectiveness of educational programmes, training interventions, recovery strategies, physical therapy, and pedagogical approaches (Bishop, 2008). One- and multifactorial experimental designs, together with analysis of variance, regression techniques, and mixed-effects models, are widely applied, particularly in studies involving repeated measurements and longitudinal observations (Hopkins et al., 2009; Newans et al., 2022). At the same time, the evolution of experimental design has been accompanied not only by increasingly sophisticated research strategies but also by the expansion of mathematical modelling techniques and the integration of multivariate analytical methods.

Experimental designs are traditionally classified according to their structural characteristics, including the number and type of experimental factors, the structure of the experimental plan, randomization procedures, repeated-measures organization, and the corresponding statistical methods (Alferes, 2012; Kirk, 2012; Montgomery, 2020). Although this approach is essential for describing the organization of experimental research, it primarily characterizes the structure of the experiment rather than the methodological functions it performs in scientific inquiry. Studies based on similar experimental structures may differ substantially in the knowledge they generate, the interpretation of their findings, and the extent to which their results can be translated into practical applications. Consequently, structural classification alone is insufficient for evaluating the cognitive and constructive potential of experimental design.

In contemporary sports science, experimental studies are predominantly interpreted in terms of statistical hypothesis testing, estimation of main effects and interactions, and the application of analysis of variance, regression, and related statistical techniques (Montgomery, 2020). Considerably less attention has been devoted to the use of experimental results for constructing mathematical models, describing factor spaces, optimizing pedagogical or training interventions, and developing systems of model-based decision making (Box & Wilson, 1951; Myers et al., 2016).

Among multifactorial experimental designs, the full factorial experiment (FFE, 2^k design) occupies a distinctive methodological position. It has been widely employed to investigate main effects and factor interactions across numerous scientific disciplines (Box & Wilson, 1951; Montgomery, 2020). Beyond its traditional role in statistical hypothesis testing, the FFE provides the methodological foundation for constructing mathematical models of factor spaces, identifying local optima, and optimizing the processes under investigation (Myers et al., 2016). When combined with mathematical modelling techniques, the FFE enables the transition from analysing experimental effects to quantitatively describing relationships and supporting evidence-based practical decision making.

The practical implementation of this approach has been demonstrated in a series of studies devoted to modelling motor learning, the development of motor abilities, and pedagogical control in school physical education, where full factorial experiments were integrated with regression and discriminant analyses to construct mathematical models of the educational process (Ivashchenko, 2020; Khudolii et al., 2019). Subsequent studies further demonstrated the possibility of

integrating the results of a series of interrelated experiments into systems of mathematical models intended for predicting learning outcomes, programming pedagogical interventions, and supporting educational decision making. These findings indicate that the full factorial experiment performs not only an analytical function associated with hypothesis testing but also a constructive function through mathematical modelling, pedagogical programming, and model-based management of educational and training processes.

Despite the widespread application of experimental designs in sports science, recent methodological studies increasingly emphasize the need to move beyond the formal description of research designs toward understanding their role in generating and integrating scientific knowledge (Khudolii et al., 2026a; Khudolii et al., 2026b). However, it remains unclear how experimental design evolves from an instrument of statistical hypothesis testing into a methodological framework for mathematical modelling, programming, and model-based management. Likewise, the methodological position of the full factorial experiment within this transition and the relationship between the cognitive and constructive potential of experimental design have not yet been systematically established. Although the classical theory of factorial experimentation and response surface methodology provides the theoretical foundations for such a transition, it does not conceptualize it as an evolution of the methodological functions of experimental design (Box & Wilson, 1951).

Therefore, there is a need to move beyond the structural classification of experimental designs toward a functional framework that explains not only how experiments are organized but also how they contribute to knowledge generation, mathematical modelling, and evidence-based management of pedagogical and training processes. This perspective constitutes the conceptual foundation of the present study.

The purpose of this study was to develop and substantiate a functional concept of the evolution of experimental design in sports science based on bibliometric and systematic methodological analyses, to determine the methodological role of the full factorial experiment, and to construct a conceptual model describing the transition from statistical hypothesis testing to model-based design and management of pedagogical and training processes.

Матеріали і методи

Study design

The study was conducted in two interrelated stages combining bibliometric analysis and systematic methodological analysis. The first stage comprised a bibliometric analysis of scientific publications to characterize the structure of research on experimental designs in sports science, physical education, and related fields, identify temporal and methodological trends, and form analytical corpora for the subsequent methodological evaluation (Creswell, 2018; Page et al., 2021).

The second stage involved a systematic methodological analysis of the selected publications. Unlike conventional systematic reviews focused on evaluating the effectiveness of interventions, this stage was designed to investigate the methodological functions of experimental design in the

process of scientific inquiry. Each publication was examined with respect to the structure of the experimental design, the methodological role of the design in the study, the use of mathematical modelling, and the extent to which experimental results were employed for optimization, programming, or model-based decision making.

During the comparative analysis, an analytical framework was developed that enabled the classification of publications according to the level of realization of the cognitive and constructive potential of experimental design. The analytical categories were not predefined but were derived inductively through an iterative comparative analysis of the selected publications.

Thus, the bibliometric analysis provided a quantitative characterization of the scientific field of experimental design research, whereas the systematic methodological analysis enabled the reconstruction of the functional evolution of experimental design, identification of the methodological role of the full factorial experiment (2^k) in contemporary sports science, and development of a functional concept describing the transition from statistical hypothesis testing to mathematical modelling, programming, and model-based management (Lopatiev, Bartik, & Cieřlicka, 2026; Ivashchenko, Khudolii, & Khudolii, 2026).

Information source

The source of information for this study was the Scopus database (Elsevier), one of the world's largest multidisciplinary bibliographic and citation databases indexing peer-reviewed journals, conference proceedings, book series, and other scholarly publications. Scopus was selected because of its broad coverage of sports science, physical education, health sciences, and related disciplines, as well as its advanced search capabilities and the possibility of exporting complete bibliographic records for subsequent bibliometric analysis.

The search was performed using the Scopus Advanced Search interface on 30 July 2026 and covered publications published between 2000 and 2026. This time span enabled the analysis of the long-term development of experimental designs in sports science over the past quarter century.

The analysis included documents indexed by Scopus as Articles, Reviews, Conference Papers, and Book Chapters. Bibliographic records were exported in Plain Text format, which preserves the complete set of bibliographic metadata required for bibliometric analysis, including publication title, authors, affiliations, abstract, author keywords, source title, publication year, references, and citation information. Duplicate records were identified and removed before the bibliometric analysis. The resulting metadata constituted the basis for the bibliometric analysis, formation of analytical corpora, and the subsequent systematic methodological analysis (Aria & Cuccurullo, 2017).

The search strategy, publication selection criteria, and the procedures used to construct the analytical corpora are described in the following subsection.

Search Strategy

The literature search was conducted in a stepwise manner using the Advanced Search interface of the Scopus

database. The search strategy was based on the principle of progressively narrowing the subject area, thereby enabling the construction of analytical publication corpora corresponding to the objectives of each stage of the study.

At the first stage, a broad search query was employed to identify publications related to experimental designs, full factorial experiments, design of experiments, and statistical methods used in multifactorial research. The search included different terminological variants describing full factorial experiments (full factorial design, 2×2 factorial design, 2^k factorial design, and two-level factorial design), together with related methodological concepts such as design of experiments, response surface methodology, factorial ANOVA, mixed-design ANOVA, and group $\times$ time interaction. Search terms were combined using Boolean operators to maximize the sensitivity and completeness of the initial search.

At the second stage, the search was restricted to publications in sports science, physical education, exercise science, sports training, motor learning, motor development, kinesiology, and related disciplines. In addition, a publication-year filter (2000–2026) was applied to construct the main bibliometric corpus used to analyse publication trends, the structure of the research field, and methodological developments in experimental design.

At the third stage, a targeted search was performed to identify studies in which experimental results were used not only for statistical hypothesis testing but also for mathematical modelling, optimization, programming, or model-based management. Accordingly, the search strategy was expanded by incorporating the terms regression model, response surface methodology, optimization, programming, decision making, control, and discriminant analysis, combined with terms describing experimental designs.

The search strategy was refined iteratively through repeated evaluation of the search results and adjustment of keywords to ensure both comprehensive coverage and high relevance of the retrieved publications. Each successive stage involved not only thematic refinement but also increasing methodological specificity of the selection criteria, allowing a transition from a broad main bibliometric corpus to a specialized corpus suitable for systematic methodological analysis (Page et al., 2021; Creswell & Creswell, 2018).

Following methodological refinement, publications were included in the final corpus if they met all of the following criteria: (1) application of a multifactorial experimental design; (2) development of mathematical models based on experimental results; and (3) use of these models for optimization, programming, pedagogical control, or model-based decision making. Studies in which multifactorial experimental designs were used exclusively for statistical hypothesis testing, without subsequent mathematical modelling or constructive interpretation of the obtained results, were excluded from the final corpus.

Construction of the Analytical Publication Corpus

The analytical publication corpus was constructed sequentially in accordance with the study design and research objectives.

At the first stage, a broad main bibliometric corpus comprising 3,514 publications was established. This corpus

Table 1. Stages of constructing publication corpora for bibliometric and systematic methodological analyses

Stage	Objective	Main search terms	Output
1. Initial search	Identification of publications on experimental designs regardless of research field	factorial design, full factorial design, 2×2 factorial design, 2^k factorial design, design of experiments, response surface methodology, factorial ANOVA, mixed-design ANOVA	Initial publication corpus
2. Thematic refinement	Construction of the sports science corpus	sport, sports science, physical education, exercise, motor learning, motor development, physical training, kinesiology	Main main bibliometric corpus
3. Methodological refinement	Identification of studies demonstrating the constructive use of experimental results	regression model, response surface methodology, optimization, programming, decision making, control, discriminant analysis	Specialized methodological corpus
4. Final selection	Construction of the final corpus for systematic methodological analysis	Application of inclusion and exclusion criteria	Confirmed core of constructive implementation

included studies on experimental designs irrespective of their disciplinary field and was used to characterize the overall structure of the research domain, assess the extent of application of experimental approaches, and identify major methodological trends.

At the second stage, thematic filtering combined with a publication-year restriction (2000–2026) resulted in the construction of the main main bibliometric corpus, consisting of 1,653 publications in sports science, physical education, exercise science, sports training, motor learning, motor development, kinesiology, and related disciplines. This corpus served as the empirical basis for analysing publication trends, the structure of the research field, leading publication sources, thematic directions, and methodological developments in experimental design.

At the third stage, a specialized methodological corpus of 244 publications was established for in-depth methodological analysis. This corpus included studies in which experimental designs were potentially used not only for statistical hypothesis testing but also for mathematical modelling, optimization, programming, or the development of model-based management systems.

Subsequent systematic methodological analysis identified a confirmed core of constructive implementation, consisting of 11 publications. These studies demonstrated the complete realization of the constructive potential of experimental design, encompassing the planning of full factorial experiments, analysis of experimental data, development of mathematical models, and the application of these models to programming, prediction, and evidence-based management of educational and training processes.

Accordingly, the study was based on three interrelated analytical publication corpora, each serving a distinct methodological purpose. The broad main bibliometric corpus was used to characterize the overall structure of the research field, the main main bibliometric corpus to analyse the development of experimental designs in sports science, and the specialized methodological corpus to investigate the functional evolution of experimental design and evaluate the realization of its cognitive and constructive potential.

The sequential construction of the analytical publication corpora and their application at different stages of the study are presented in Table 1.

Bibliometric Analysis

Bibliometric analysis was performed using the metadata of publications exported from the Scopus database (Aria & Cuccurullo, 2017). Bibliographic data were processed and analysed using the bibliometrix package implemented in the R environment, which provides comprehensive bibliometric analysis, statistical summarization of bibliographic metadata, and visualization of bibliometric indicators.

The main main bibliometric corpus (1,653 publications) was analysed to examine annual publication trends, the distribution of publications across sources, thematic areas, author keywords, and other bibliometric characteristics. Particular attention was given to publications addressing multifactorial experimental designs, full factorial experiments (FFE, 2^k), and the statistical approaches used to analyse experimental data.

The results of the bibliometric analysis were used to characterize the structure of the research field, evaluate temporal trends in the development of experimental designs, and identify methodological trends in sports science. These bibliometric characteristics also provided the basis for constructing the specialized methodological corpus and for the subsequent systematic methodological analysis.

In the present study, bibliometric analysis was considered a tool for mapping the research field, whereas the evaluation of the cognitive and constructive potential of experimental designs was performed at the subsequent stage through systematic methodological analysis (Donthu et al., 2021).

Systematic Methodological Analysis

Following the construction of the analytical publication corpora, a systematic methodological analysis was conducted. Unlike conventional systematic reviews, which primarily evaluate the effectiveness of interventions, this stage aimed to investigate the functions of experimental design in scientific inquiry, identify patterns in their functional evolution, and determine the methodological role of the full factorial experiment within the development of contemporary experimental methodology. The analysis was grounded in the principles of systems research, inductive

Table 2. Protocol for the Systematic Methodological Analysis of the Functional Evolution of Experimental Designs

Stage	Object of evaluation	Main evaluation criteria	Evaluation outcome
1. Structural analysis	Characteristics of the experimental design	Number and type of experimental factors, structure of the experimental design, factor combination strategy, and statistical methods employed	Identification of the experimental design type and its methodological characteristics
2. Evaluation of cognitive potential	Functions of experimental design in scientific inquiry	Identification of main effects and factor interactions, construction of mathematical models, description of the factor space, and explanation of experimental relationships	Determination of the level of realization of the cognitive potential of the experimental design
3. Evaluation of constructive potential	Practical application of experimental results	Use of mathematical models for optimization, programming, prediction, pedagogical control, and model-based management	Determination of the level of realization of the constructive potential of the experimental design
4. Integrated methodological evaluation	Synthesis of analytical findings	Integrated assessment of the realization of experimental design functions	Classification of the study according to its functional category (local management, programming, or system-level management)

generalization, and conceptual modelling (Creswell & Creswell, 2018; Lopatiev et al., 2026).

The systematic methodological analysis was performed according to an author-developed evaluation protocol, which involved the sequential assessment of each publication across four interrelated analytical domains (Table 2).

According to the proposed protocol, the functional role of the experimental design was determined following the structural analysis of each study. Particular attention was paid to publications in which full factorial experiments were combined with mathematical modelling techniques, especially regression, discriminant, and logistic analyses. For each publication, the level of realization of the cognitive potential of the experimental design, the manner in which mathematical models were applied, and the degree to which these models were integrated into the programming, prediction, or model-based management of educational and training processes were evaluated. This approach is consistent with the contemporary understanding of mathematical modelling as the final stage of interpreting experimental findings and the transition from identifying empirical regularities to supporting evidence-based practical decision making (Lopatiev et al., 2026; Ivashchenko et al., 2026).

The analytical categories were not predefined but emerged inductively through a comparative analysis of the selected publications. For each study, the structure of the experimental design, statistical interpretation of the results, application of mathematical modelling, and the level of practical implementation of the developed models were systematically compared. The synthesis of shared methodological characteristics enabled the development of a functional classification of experimental designs, identification of the levels of realization of their cognitive and constructive potential, reconstruction of the transition from statistical hypothesis testing to mathematical modelling, programming, and model-based management, and the formulation of a conceptual model describing the functional evolution of experimental design (Lopatiev et al., 2026; Ivashchenko et al., 2026).

Results

Structure of the Research Field of Multifactorial Experimental Designs

The bibliometric analysis of the main bibliometric corpus (1,653 publications) revealed a steady increase in the number of studies addressing multifactorial experimental designs in sports science between 2000 and 2026 (Figure 1). The most pronounced growth in publication activity occurred after the mid-2010s, indicating increasing methodological interest in experimental approaches, multifactorial research designs, and contemporary statistical methods. These findings demonstrate that experimental design has become one of the principal methodological tools in contemporary sports science.

The search strategy enabled the sequential construction of analytical publication corpora, each serving a distinct methodological function within the study (Table 3).

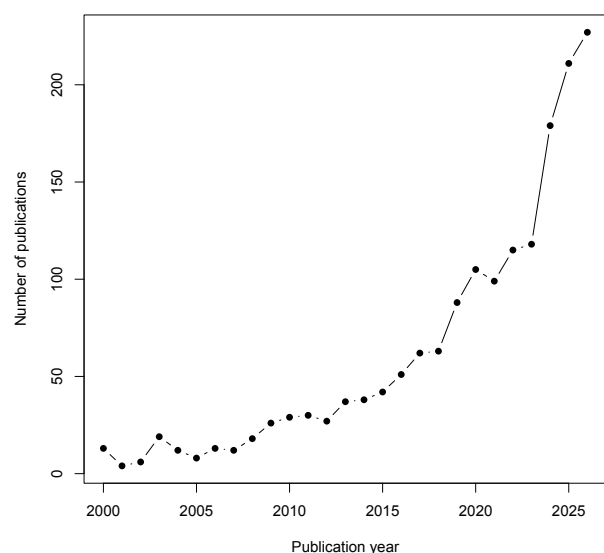


Fig. 1. Annual scientific production on multifactorial experimental designs in sports science (2000–2026)

Table 3. Construction of the Analytical Publication Corpora

Stage	Analytical corpus	Number of publications	Purpose
1	General search corpus	3,514	Identification of the overall research field of multifactorial experimental studies
2	Main sports science corpus (2000–2026)	1,653	Analysis of experimental design structures, publication sources, and temporal trends
3	Specialized corpus of model-based management studies	244	Identification of studies in which mathematical models were used to support practical decision making
4	Confirmed core of constructive implementation	11	Analysis of the transition from experiment → mathematical model → practical management

The general search corpus (3,514 publications) represented the contemporary research field of multifactorial experimental studies without disciplinary restrictions. Its analysis demonstrated that factorial experimental approaches are applied across a broad spectrum of scientific disciplines, confirming their universal methodological significance.

Following thematic refinement to sports science, physical education, sports training, exercise science, motor learning, and related disciplines, the main bibliometric corpus (1,653 publications) was established. This corpus served as the empirical basis for the bibliometric analysis of the research field, publication trends, leading publication sources, and methodological developments in experimental design.

Subsequent refinement to 244 publications identified studies in which experimental results were potentially used for mathematical modelling, optimization of pedagogical or training interventions, and evidence-based decision making. Consequently, the focus of the analysis shifted from the structural characteristics of experimental designs to their functional application.

The systematic methodological analysis of the specialized corpus demonstrated that only 11 publications represented the complete realization of the constructive potential of experimental design, encompassing the entire sequence from full factorial experimentation to the development of mathematical models and their application for programming or managing educational and training processes. These findings indicate that the transition from experimental verification of effects to model-based management remains relatively uncommon, even among studies explicitly concerned with mathematical modelling.

Overall, the results demonstrate that the sequential construction of analytical publication corpora not only ensured the representativeness of the bibliometric analysis but also provided the methodological foundation for the subsequent systematic methodological analysis. This approach made it possible to trace the transition from the broad research field of experimental studies to a confirmed core of publications in which experimental design performs a constructive methodological function. The logic of this progressive refinement constituted the methodological basis for the subsequent analysis of the functional evolution of experimental design.

Functional Evolution of Experimental Design

The systematic analysis of the main bibliometric corpus demonstrated that the evolution of experimental

design has been accompanied not only by increasing structural complexity of experimental designs but also by the progressive expansion of their cognitive capabilities. The identified patterns indicate a gradual transition from the use of experimentation as a means of establishing experimental effects to its application for mathematical modelling, programming, and model-based management of pedagogical processes.

At the first level, experimental design serves to establish the effect of an intervention through comparisons between experimental groups or analyses of changes over time. Such studies determine whether statistically significant changes have occurred; however, they do not explain the mechanisms underlying these changes or identify the conditions under which the intervention is most effective.

The second and third levels are characterized by the transition to the analysis of factor interactions. The inclusion of attributive and manipulated factors makes it possible to determine for whom, under which conditions, and through which combinations of pedagogical interventions the experimental effect changes. At this stage, experimental design performs not only the function of statistical hypothesis testing but also the function of explaining the underlying relationships.

The next stage of development is associated with the application of the full factorial experiment (2^k). When combined with regression analysis, the full factorial experiment enables the construction of mathematical models describing the factor space, whereas the use of discriminant analysis makes it possible to investigate the multivariate structure of experimental outcomes and classify the implemented experimental conditions. The integration of these approaches represents a new level of scientific inquiry, at which experimental design evolves from analysing individual relationships to constructing an interconnected system of mathematical models.

The highest level of realization is achieved when the results of a series of interconnected experiments are used for programming, pedagogical monitoring, and the management of educational and training processes. At this stage, experimental design ceases to function solely as an instrument for hypothesis testing and acquires a constructive function by supporting the transition from the generation of scientific evidence to model-based management of pedagogical systems.

The synthesis of these findings made it possible to develop a hierarchy of the cognitive capabilities of experimental designs, reflecting the progressive expansion

Table 4. Hierarchy of the Cognitive Capabilities of Experimental Designs

Level	Study structure	Object of inquiry	Central question	Potential outcome
I	Experimental group $\times$ time	Effect	Did a change occur?	Identification of the experimental effect and differences in temporal dynamics
II	Experimental $\times$ attributive factor; attributive factor $\times$ time	Effect differentiation	For whom, when, or under what conditions does the effect differ?	Identification of the dependence of the effect on age, sex, qualification, or other participant characteristics
III	Two manipulated factors; 2×2 factorial design	Interaction	How does the effect of one factor depend on the level of another?	Main effects, interactions, synergistic or antagonistic relationships between factors
IV-A	Full factorial experiment (2^k) with regression modelling	Relationships within the factor space	Which mathematical relationship best describes the process?	Regression model describing the local factor space
IV-B	Full factorial experiment (2^k) with discriminant analysis	Multivariate structure of outcomes	Which combination of variables best discriminates among experimental conditions?	Canonical functions, centroids, classification, and recognition of experimental conditions
V	Full factorial experiment (2^k) with regression and discriminant analyses	Integrated system	How can the factor space and outcome system be structured simultaneously?	Integration of factor–outcome models with multivariate classification
VI	Series of interconnected experiments and a research programme	Managed process	How can mathematical models be used for planning, monitoring, and modifying the process?	Selection of optimal conditions, programming, pedagogical monitoring, and system-level management

Table 5. Methodological Trajectories of Multifactorial Experimental Designs and Their Analytical Outcomes

Methodological trajectory	Object being structured	Primary analytical outcome	Boundary of cognitive capability
Group $\times$ time	Temporal dynamics of experimental groups	Differences in changes between groups	The internal structure of the intervention remains unexplored
Randomized factorial experiment	Combinations of two interventions	Individual and combined effects of intervention components	Primarily limited to comparisons of implemented conditions without modelling the factor space
Two manipulated factors	Factor interactions	Main effects and interactions	Mathematical modelling of the process is not essential
Full factorial experiment (2^k) with regression modelling	Controlled factor space	Mathematical models of individual outcome variables	Describes only a local region of the factor space; the multivariate structure of outcomes may remain unexplored
Full factorial experiment (2^k) with discriminant analysis	Outcome variable space	Recognition and classification of experimental conditions	Does not identify the coordinates of untested local optima
Full factorial experiment (2^k) with regression and discriminant analyses	Factor space and outcome system	Mathematical modelling combined with multivariate selection of optimal conditions	Full management requires integration into a broader programme of subsequent actions
Research programme	Integrated educational or training process	Programming, monitoring, and management based on an integrated system of models	Highest confirmed level of cognitive and constructive realization

of their functions—from identifying experimental effects to mathematical modelling, programming, and model-based management (Table 4).

The proposed hierarchy describes the general logic underlying the functional evolution of experimental design. At the same time, the analysis of the specialized methodological corpus demonstrated that these capabilities are realized through different methodological trajectories, which differ in the object being structured, the nature of

the analytical outcomes, and the limits of their cognitive capabilities.

Analysis of the specialized methodological corpus demonstrated that these methodological trajectories represent different ways of realizing the cognitive potential of experimental design. The simplest trajectory is the group $\times$ time design, which enables the evaluation of changes between experimental conditions but does not reveal the internal structure of pedagogical or training interventions.

Randomized factorial experiments and studies involving two manipulated factors expand analytical possibilities by examining main effects and interactions; however, their conclusions remain limited to the experimental conditions that have actually been implemented.

A qualitatively new stage is achieved through the application of the full factorial experiment (2^k). The combination of full factorial experiments with regression modelling provides a mathematical description of the factor space, whereas discriminant analysis enables the investigation of the multivariate structure of outcomes and the classification of experimental conditions. The integration of these approaches substantially expands the cognitive capabilities of experimental design, although the complete realization of its constructive potential requires the subsequent application of mathematical models within a unified research programme.

The highest level of methodological realization is achieved when the results of interconnected experiments are integrated into a system of mathematical models used for programming pedagogical processes, organizing pedagogical monitoring, and supporting management decisions. Under these conditions, experimental design acquires a constructive function and becomes an instrument of model-based management of educational and training processes.

Overall, the identified methodological trajectories should not be regarded as alternative classifications of experimental designs but rather as successive stages in the expansion of their methodological functions—from identifying experimental effects to constructing integrated systems of mathematical models that support model-based programming and management of educational and training processes. This pattern provided the conceptual foundation for the model of the functional evolution of experimental design presented in the following section.

Functional Evolution of Experimental Design

The comparative analysis of the main bibliometric corpus and the specialized methodological corpus demonstrated that the traditional classification of experimental designs according to the number of factors, the structure of the experimental design, or the statistical methods employed does not adequately reflect the evolution of their methodological functions. The integration of the findings from the bibliometric and systematic methodological analyses made it possible to formulate a functional interpretation of the evolution of experimental design.

The results indicate that the development of experimental design is determined not so much by the increasing structural complexity of experimental designs as by the progressive expansion of the functions they perform in scientific inquiry. At the initial stage, experimental design serves primarily to test statistical hypotheses and establish causal relationships between the investigated factors. The subsequent stage is characterized by the use of experimental data to develop mathematical models that describe the factor space, quantify factor interactions, and predict outcomes within the investigated domain.

A further stage in the evolution of experimental design is marked by the transition from explaining empirical

relationships to their practical application. At this level, mathematical models become instruments for selecting optimal educational or training conditions, programming pedagogical processes, organizing pedagogical monitoring, and supporting management decision-making. Consequently, the functional evolution of experimental design is characterized by a gradual transition from experimental analysis to model-based programming and management of pedagogical systems.

Within this evolutionary framework, the full factorial experiment (2^k) occupies a pivotal methodological position. The analysis demonstrated that it provides the methodological foundation for the transition from statistical analysis to mathematical modelling by enabling the construction of an orthogonal factor space, quantitative estimation of main effects and factor interactions, and the development of regression models. However, the realization of its constructive potential is determined not by the factorial design itself but by the integration of experimental data with mathematical modelling techniques and by the subsequent use of these models for programming and managing educational and training processes.

Accordingly, the evolution of experimental design should be interpreted as a functional rather than a purely structural process, in which its methodological role progressively expands from statistical hypothesis testing to mathematical modelling, programming, and model-based management of pedagogical processes. This functional perspective complements the traditional structural classification of experimental designs by emphasizing not only how experiments are organized but also what methodological functions they perform in the generation, modelling, and application of scientific knowledge.

The Full Factorial Experiment as a Methodological Hub in the Evolution of Experimental Design

The detailed analysis of the specialized methodological corpus demonstrated that the methodological application of the full factorial experiment (2^k) is heterogeneous. Even among studies in which the use of a full factorial experiment was explicitly confirmed, substantial differences were observed in the subsequent analytical approaches and in the extent to which experimental findings were translated into practical applications (Table 6).

The largest group of publications (40.0%) employed full factorial experiments to develop regression models describing individual outcome variables. In these studies, mathematical modelling was primarily used to quantify the relationships between manipulated factors and outcome variables, thereby enabling the identification of local optima and prediction of responses within the experimental factor space.

A separate group of studies (20.0%) combined full factorial experiments with discriminant analysis. Rather than modelling individual outcome variables, these investigations focused on discriminating and classifying experimental conditions on the basis of multiple outcome characteristics, thereby extending the analysis from univariate relationships to multivariate evaluation of pedagogical or training interventions.

The most methodologically advanced approach was identified in studies integrating regression and

Table 6. Structure of the Sports Pedagogy Cluster of Full Factorial Experiment Studies

Analytical branch	Application of the full factorial experiment	Publications (n)	%
Full factorial experiment with regression or mathematical modelling	Development of mathematical models describing the relationships between manipulated factors and individual outcome variables	6	40.0
Full factorial experiment with discriminant analysis	Multivariate discrimination and classification of experimental conditions	3	20.0
Full factorial experiment with regression and discriminant analyses	Simultaneous modelling of the factor space and the outcome structure	4	26.7
Full factorial experiment with insufficiently described analytical branch	The full factorial design was confirmed, but the subsequent analytical model could not be identified from the title, abstract, or keywords	2	13.3
Total		15	100.0

Note. This classification represents a conservative distribution based exclusively on information reported in publication titles, abstracts, and author keywords. The absence of explicit reference to regression or discriminant modelling in the abstract does not necessarily indicate that these methods were not applied in the full text.

discriminant analyses within a single experimental design (26.7%). The combination of these analytical methods enabled simultaneous modelling of the factor space and the multivariate outcome structure, thereby providing the methodological basis for multicriteria selection of optimal educational or training conditions. This group of studies most fully realized the constructive potential of the full factorial experiment.

In two publications (13.3%), the application of a full factorial experiment was confirmed; however, the information presented in the titles, abstracts, and author keywords was insufficient to determine the subsequent analytical approach. These findings indicate that the mere use of a full factorial experiment does not, by itself, characterize the level of realization of its methodological capabilities and that evaluation of its methodological role requires consideration of the complete analytical workflow.

Overall, these findings indicate that the methodological significance of the full factorial experiment is determined not by the factorial design itself but by the extent to which experimental evidence is integrated with mathematical modelling and subsequently translated into model-based programming and management of educational and training processes. Accordingly, the full factorial experiment should be regarded not simply as a statistical design but as the methodological hub linking experimental research with mathematical modelling, pedagogical programming, and evidence-based management.

Realization of the Constructive Potential of the Full Factorial Experiment

Analysis of the confirmed core of publications demonstrated that the constructive potential of the full factorial experiment (2^k) is realized not through the factorial design itself but through the mathematical processing of experimental data. The integration of full factorial experiments with regression and discriminant analyses provides a sequential transition from experimental planning to mathematical modelling, multicriteria evaluation of experimental conditions, and evidence-based decision-making (Khudolii et al., 2019; Ivashchenko, 2020).

The analytical process begins with the construction of an orthogonal factorial matrix, which ensures systematic variation of manipulated factors and provides the basis for quantitative analysis of their effects. At this stage, the full factorial experiment determines the structure of experimental conditions but does not yet produce a mathematical model of the investigated process (Box & Wilson, 1951; Montgomery, 2020).

Regression analysis subsequently generates mathematical models describing the relationships between manipulated factors and individual outcome variables. These models quantify main effects and factor interactions and enable prediction within the investigated region of the factor space (Myers et al., 2016; Khudolii et al., 2019).

Discriminant analysis complements regression modelling by focusing on the multivariate structure of experimental outcomes. It generates canonical functions, identifies centroids of experimental conditions, and classifies multivariate outcome patterns, thereby enabling multicriteria comparison of alternative pedagogical or training interventions (Khudolii et al., 2019; Ivashchenko, 2020).

The integration of regression and discriminant analyses completes the analytical workflow. Regression models describe quantitative relationships within the factor space, whereas discriminant functions support multicriteria selection among experimentally implemented conditions. This methodological sequence is clearly illustrated by the study of Ivashchenko et al. (2018), in which a full factorial experiment was combined with regression modelling to identify optimal experimental conditions and subsequently with discriminant analysis to determine the most appropriate pedagogical regime. Consequently, experimental design evolves from explaining empirical relationships to supporting programming, pedagogical monitoring, and model-based management of educational and training processes.

The methodological framework presented in Table 7 demonstrates that the realization of the constructive potential of the full factorial experiment requires the integration of complementary analytical approaches. The factorial design provides the experimental structure, regression analysis models quantitative relationships within the factor space, and discriminant analysis supports multicriteria evaluation

Table 7. Methodological Framework for Realizing the Constructive Potential of the Full Factorial Experiment (2^k)

Analytical component	Analytical space	Principal question	Analytical outcome
Full factorial experiment	Space of manipulated factors	Which combinations of factor levels should be implemented?	Orthogonally organized system of experimental conditions
Regression modelling	Relationships between factors and an individual outcome variable	How do manipulated factors and their interactions influence a specific outcome?	Mathematical model describing the local factor space
Discriminant analysis	Multivariate outcome space	Which variables best discriminate among experimental conditions?	Canonical functions, centroids, and classification of experimental conditions
Integration of regression and discriminant analyses	Factor space and outcome system	Which experimental condition is optimal when multiple outcomes are considered simultaneously?	Multicriteria selection among implemented experimental conditions
Research programme	Integrated educational or training process	How can the system of mathematical models be applied to planning and monitoring?	Programming, pedagogical monitoring, and management

Table 8. Levels of Realization of the Constructive Potential of Experimental Design

Level	Mode of realization	Publications	Typical outcomes	Representative publications
I. Local model-based management	Optimization of individual pedagogical or training parameters	7	Selection of repetitions, rest intervals, exercise sequences, local optimization	Ivashchenko et al. (2018); Ivashchenko et al. (2019); Kapkan et al. (2019a,b); Ivashchenko et al. (2020); Khudolii et al. (2020); Zima & Ivashchenko (2022)
II. Programming of educational and training processes	Design of pedagogical processes	1	Allocation of training means, time distribution, pedagogical programming	Ivashchenko (2020)
III. System-level model-based management	Integration of interconnected experiments into systems of mathematical models	3	Programming, pedagogical monitoring, and management of pedagogical systems	Khudolii et al. (2019); Ivashchenko (2020); Khudolii et al. (2026)

of experimental conditions. Together, these components establish the methodological basis for programming and managing educational and training processes.

The final stage of the systematic methodological analysis evaluated the extent to which mathematical models developed from full factorial experiments were applied to practical problems. Analysis of the confirmed core of 11 publications demonstrated that the constructive potential of experimental design is realized at three interconnected levels, differing in the scale of the managed object and the practical application of mathematical models (Table 8).

The first and most common level, represented by seven studies, involved local model-based management, in which mathematical models were used to optimize individual pedagogical or training parameters, such as repetitions, rest intervals, exercise sequences, and other manipulated variables.

The second level, identified in a single study, extended mathematical modelling from optimizing individual interventions to programming educational and training processes, including the allocation of instructional time, selection of training means, and organization of pedagogical structures.

The highest level comprised three studies in which interconnected factorial experiments were integrated into comprehensive systems of mathematical models supporting programming, pedagogical monitoring,

prediction, and management of educational and training processes. At this level, individual experiments became components of coordinated research programmes rather than isolated investigations.

Overall, these findings demonstrate that the complete realization of the constructive potential of experimental design remains relatively uncommon. Even within the specialized methodological corpus, most studies employed mathematical modelling primarily for local optimization, whereas the integration of mathematical models into comprehensive systems for programming and management represented the exception rather than the rule. Accordingly, model-based management may be regarded as the highest contemporary level of realization of the constructive potential of experimental design in sports science.

Discussion

Functional Reinterpretation of Experimental Design

Experimental designs are traditionally classified according to their structural characteristics, including the number of factors, randomization procedures, measurement organization, and statistical methods. Such classifications are essential for describing the organization of research but do not fully explain the methodological functions

that experimental design performs in scientific inquiry (Goodwin, 2004; Creswell & Creswell, 2018). Contemporary reviews of research designs in sports science likewise classify studies as experimental, quasi-experimental, observational, longitudinal, mixed-methods, and related designs, while paying relatively little attention to the functional use of experimental results (Nicholas et al., 2025).

The bibliometric analysis demonstrated that the contemporary scientific discourse describes experimental studies primarily through their substantive research topics rather than through the methodological characteristics of their designs. The most frequent author keywords referred to research objects, interventions, and outcomes (e.g., exercise, resistance training, physical activity, rehabilitation, athletic performance, and physical education), whereas terminology directly related to experimental design rarely appeared among the dominant descriptors. Likewise, publication titles predominantly referred to experimental studies or quasi-experimental studies, while terms such as full factorial experiment or factorial experimental design were encountered only occasionally. These findings indicate that experimental design is widely applied as a methodological tool but is rarely considered an independent object of methodological investigation.

The systematic methodological analysis complements these observations. Studies with similar structural characteristics frequently performed fundamentally different methodological functions. In most publications, experimentation concluded with statistical hypothesis testing or the evaluation of factor interactions. Only a limited number of studies extended experimental findings to mathematical modelling, optimization, pedagogical programming, or model-based management of educational and training processes (Khudolii, 2019; Ivashchenko, 2020). These observations are consistent with recent meta-research in sports science highlighting persistent challenges related to experimental design, statistical methodology, reporting quality, and the translation of research findings into practical decision-making (Warmenhoven et al., 2025).

Taken together, these findings support a functional reinterpretation of experimental design. Rather than viewing experimental design solely as the organizational structure of an experiment, it may be regarded as a methodological system whose functions progressively expand according to the objectives of scientific inquiry. Within this framework, experimental design serves not only to establish causal relationships but also to support mathematical modelling, integration of empirical knowledge, pedagogical programming, and model-based decision-making. This interpretation is consistent with contemporary views of scientific methodology emphasizing the transition from isolated empirical findings to integrated systems of knowledge (Khudolii et al., 2026a; Khudolii et al., 2026b).

Accordingly, the proposed functional concept does not replace traditional structural classifications of experimental design but complements them by introducing the methodological functions of experimental design as an additional principle of classification.

From Hypothesis Testing to Model-Based Decision Making

One of the principal findings of the present study is that the evolution of experimental design in sports science is

characterized by a gradual transition from statistical hypothesis testing to the use of mathematical models as instruments for practical decision-making. Within the traditional experimental paradigm, the primary objective is to establish statistically significant differences between experimental conditions and estimate effect sizes. Although this approach provides evidence regarding intervention effectiveness, it offers limited guidance for optimizing educational or training processes (Goodwin, 2004; Creswell & Creswell, 2018).

The present findings demonstrate that integration of full factorial experiments with regression and discriminant analyses fundamentally changes the function of experimental design. Experimental data become the basis for constructing mathematical models describing factor interactions, predicting outcomes, and selecting optimal pedagogical or training conditions (Montgomery, 2020).

Importantly, this transition is not simply the result of employing more sophisticated statistical procedures. Rather, it reflects a change in the methodological function of experimental design itself. At the initial level, experimentation primarily provides empirical evidence. At subsequent levels, experimental data are transformed into mathematical models that support pedagogical programming, monitoring, and management. This progression was consistently observed within the confirmed methodological core identified in the present study (Khudolii, 2019; Ivashchenko, 2020).

These findings are also consistent with the epistemological interpretation of modelling as the mechanism linking empirical observations with organized scientific knowledge (Lopatiev et al., 2026). Within this perspective, mathematical models perform not only descriptive and predictive functions but also provide the conceptual basis for evidence-based decision-making.

The Methodological Role of the Full Factorial Experiment

The present findings refine the methodological interpretation of the full factorial experiment (2^k). While traditionally regarded as one of several multifactorial experimental designs (Montgomery, 2020), the present analysis demonstrates that its principal methodological significance lies in establishing the link between experimentation and mathematical modelling.

The constructive potential of the full factorial experiment is determined not by the factorial design itself but by the subsequent mathematical processing of experimental data. Orthogonal factorial matrices provide the structural basis for systematic variation of manipulated factors; however, only the integration of regression and discriminant analyses enables the transition from statistical evaluation of experimental effects to modelling the factor space, multicriteria evaluation of outcomes, and evidence-based selection of optimal pedagogical or training conditions (Khudolii, 2019; Ivashchenko, 2020).

The findings further demonstrate that complete realization of the constructive potential of the full factorial experiment remains relatively uncommon. Even among studies specifically selected for methodological analysis, only a limited number integrated mathematical models into systems supporting pedagogical programming and management, whereas most studies remained focused on statistical significance testing.

Accordingly, the methodological significance of the full factorial experiment is determined not by the factorial

design itself but by the extent to which experimental evidence is integrated with mathematical modelling and subsequently translated into model-based programming and management of educational and training processes. In this sense, the full factorial experiment may be regarded as the methodological hub linking experimental research with mathematical modelling, pedagogical programming, and evidence-based management.

Implications for Sports Science and Experimental Research

The proposed functional concept has important methodological implications for the planning of future research in sports science. It encourages researchers to consider not only the structural characteristics of experimental designs but also the methodological function that experimental design is intended to perform within a particular study. Under this perspective, experimentation becomes part of a broader research programme directed toward the accumulation of knowledge, development of mathematical models, and support of practical decision-making.

The findings further indicate that full realization of the constructive potential of experimental design requires systematic integration of experimental data with mathematical modelling and pedagogical monitoring. Such integration provides the methodological basis for moving from isolated experiments toward coordinated research programmes in which successive investigations contribute to programming, prediction, and management of educational and training processes. This interpretation is consistent with the conception of physical education as a managed learning process in which pedagogical monitoring becomes regulatory only when integrated into a comprehensive instructional model (Ivashchenko et al., 2026).

More broadly, the proposed functional perspective is consistent with contemporary methodological trends emphasizing the transition from isolated empirical findings toward integrated conceptual frameworks and research programmes (Khudolii et al., 2026a; Khudolii et al., 2026b). The bibliometric findings indicate that although experimental research is widely conducted in sports science, methodological aspects of experimental design remain underrepresented in the scientific discourse. This observation further supports the relevance of the functional approach proposed in the present study.

Accordingly, experimental design should no longer be regarded solely as a framework for organizing experiments but as a methodological system supporting the generation, modelling, programming, and practical application of scientific knowledge. This functional perspective constitutes the principal methodological contribution of the present study and provides a conceptual framework for future methodological research in sports science.

Conclusions

The bibliometric analysis of 1,653 publications and the systematic methodological analysis of a specialized corpus of 244 publications demonstrated that experimental studies in sports science are predominantly classified according to the structural characteristics of experimental designs, whereas the methodological functions of experimental design have received little systematic attention. The bibliometric findings further

revealed that contemporary scientific discourse is dominated by subject-oriented terminology, while concepts directly related to experimental design are largely absent from author keywords and publication titles, indicating that experimental design is generally employed as an implicit methodological instrument rather than an explicit object of methodological investigation.

The present study proposes a functional concept of experimental design, according to which its methodological significance is determined not only by the structure of the experimental design but primarily by the level of realization of its cognitive and constructive potential. Unlike traditional structural classifications, the proposed functional perspective interprets experimental design as a methodological system whose functions progressively expand from statistical hypothesis testing to mathematical modelling, pedagogical programming, and model-based management of educational and training processes.

The findings demonstrate that the full factorial experiment (2^k) occupies a central methodological position in this functional evolution by providing the foundation for the transition from experimental analysis to mathematical modelling. Its constructive potential is realized not through the factorial design itself but through its integration with regression and discriminant analyses, enabling mathematical modelling of the factor space, optimization of pedagogical interventions, and evidence-based decision-making.

The systematic methodological analysis identified three hierarchical levels of realization of the constructive potential of experimental design: local model-based management, programming of educational and training processes, and system-level model-based management. Complete realization of this potential was found to be relatively uncommon and occurred only when experimental findings were integrated into interconnected systems of mathematical models supporting pedagogical programming, monitoring, and management.

Overall, the findings extend the current methodological understanding of experimental design in sports science by introducing its functional classification as a complementary methodological framework. This perspective provides a conceptual basis for the transition from isolated experimental studies toward coordinated research programmes integrating experimentation, mathematical modelling, pedagogical programming, and evidence-based management of educational and training processes.

Ethics Approval

Ethical approval was not required for this study because it was based exclusively on the analysis of bibliographic metadata and previously published scientific literature. The study did not involve human participants, animals, or the collection or use of personal data.

Informed Consent

Informed consent was not required because the study did not involve human participants or the collection or use of personal data.

Data Availability Statement

The bibliographic data used in this study were obtained from the Scopus database. The search strategy, eligibility

criteria, and the analytical publication corpus developed for this study are available from the corresponding author upon reasonable request.

AI Transparency Statement

The authors used AI-assisted tools to improve the organization of the manuscript, enhance language quality, and improve the readability of the text. All scientific decisions, including the conceptualization of the study, development of the methodology, construction of the analytical publication corpus, analysis and interpretation of the findings, and preparation of the final manuscript, were made exclusively by the authors. The authors reviewed, verified, and approved all AI-assisted outputs and accept full responsibility for the accuracy, integrity, and originality of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Функціональна еволюція експериментального дизайну у спортивній науці: від бібліометричного аналізу до формування функціональної концепції

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

Реферат. Стаття: 15 с., 8 табл., 1 рис., 28 джерел.

Передумови. Експериментальний дизайн є основною методологічною основою встановлення причинно-наслідкових зв'язків у спортивній науці. Традиційні класифікації описують експериментальні дизайни за їх структурними характеристиками, такими як кількість факторів, процедури рандомізації, організація вимірювань або застосовані статистичні методи. Водночас такі підходи не пояснюють, яким чином методологічні функції експериментального дизайну еволюціонують від статистичної перевірки гіпотез до математичного моделювання, програмування та модельно обґрунтованого прийняття рішень.

Мета. Дослідити функціональну еволюцію експериментального дизайну у спортивній науці, визначити методологічну роль повного факторного експерименту (ПФЕ 2^k) та розробити функціональну концепцію експериментального дизайну на основі бібліометричного та систематичного методологічного аналізів.

Матеріал і методи. Дослідження виконано у два етапи. На першому етапі проведено бібліометричний аналіз публікацій, індексованих у базі даних Scopus (2000–2026 рр.), з метою визначення структури досліджень експериментальних дизайнів та формування аналітичного корпусу документів. Після видалення дублікатів бібліометричний корпус складався з 1653 публікацій. На другому етапі проведено систематичний методологічний аналіз спеціалізованого корпусу з 244 публікацій для оцінювання рівня реалізації пізнавального та конструктивного потенціалу експериментальних дизайнів. Особливу увагу приділено дослідженням, у яких повний факторний експеримент поєднувався з методами математичного моделювання, регресійного та дискримінантного аналізу.

Результати. Бібліометричний аналіз показав, що сучасна спортивна наука характеризується домінуванням предметно орієнтованої термінології, тоді як методологічні поняття, пов'язані з експериментальним дизайном, рідко представлені серед авторських ключових слів або в назвах публікацій. Систематичний методологічний аналіз засвідчив, що експериментальні дизайни з подібними структурними характеристиками можуть виконувати принципово різні методологічні функції. На цій основі розроблено функціональну концепцію експериментального дизайну, відповідно до якої його методологічне значення визначається рівнем реалізації пізнавального та конструктивного потенціалу. Встановлено, що повний факторний експеримент є методологічною ланкою, яка поєднує експериментальний аналіз із математичним моделюванням. Виділено три рівні реалізації конструктивного потенціалу експериментального дизайну: локальне модельно обґрунтоване керування, програмування педагогічного процесу та системне керування.

Висновки. Запропоновано функціональну концепцію експериментального дизайну, яка доповнює традиційні структурні класифікації. Методологічний внесок дослідження полягає у запровадженні нового принципу класифікації експе-

риментальних дизайнів за рівнем реалізації їх пізнавального та конструктивного потенціалу. Повний факторний експеримент займає центральне методологічне місце в цій концепції, забезпечуючи перехід від статистичної перевірки гіпотез до математичного моделювання, програмування та модельно обґрунтованого керування педагогічними й тренувальними процесами.

Ключові слова: експериментальний дизайн, повний факторний експеримент, спортивна наука, математичне моделювання, регресійний аналіз, дискримінантний аналіз, бібліометричний аналіз, систематичний методологічний аналіз, педагогічне програмування, модельно обґрунтоване прийняття рішень.

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Artificial Intelligence in Physical Education Pedagogy: A Bibliometric and Thematic Review of Pedagogical Applications and Emerging Concerns (2015–2025)

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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. As artificial intelligence increasingly enters educational practice, PE pedagogy faces a distinct question that extends beyond online, blended, or technology-enhanced delivery. This study mapped research on artificial intelligence in PE pedagogy from 2015 to 2025, focusing on publication growth, conceptual structure, interdisciplinary foundations, pedagogical applications, and emerging concerns.

Materials and Methods. Using a bibliometric and thematic review design, bibliographic data were retrieved from Scopus and analyzed through Bibliometrix/Biblioshiny and VOSviewer. After filtering and data cleaning, the final corpus comprised 1,000 documents published across 389 sources.

Results. The results revealed a marked post-2020 expansion, indicating growing scholarly attention to AI-related pedagogical applications in PE. The field was strongly interdisciplinary, spanning PE, educational technology, computer science, engineering, and health-related domains. Conceptual and thematic analyses showed that the literature is anchored in PE, artificial intelligence, machine learning, deep learning, data mining, physical education teaching, virtual reality, and movement-related analytics. Bibliographic coupling and co-citation analyses further indicated that the field is developing through the convergence of computational innovation and pedagogical application rather than within a single disciplinary tradition.

Conclusions. The study positions AI in PE pedagogy as an emerging computational-pedagogical research domain. The evidence should be interpreted as structural and thematic mapping, not as proof of instructional effectiveness. As a conceptual contribution, the review advances a Pedagogically Accountable AI in PE Framework centered on computational function, pedagogical translation, embodied movement learning, human agency, and ethical accountability.

Keywords: artificial intelligence, bibliometric analysis, emerging concerns, pedagogical applications, physical education.

Introduction

Artificial intelligence (AI) is no longer a peripheral issue in education because it is increasingly shaping how teaching is planned, enacted, assessed, and reflected upon across subject areas. In physical education (PE), this transition is becoming more visible as researchers and practitioners examine how AI may support lesson preparation, instructional decision-making, learner monitoring, performance analysis, feedback generation,

and teacher development (Jastrow et al., 2022; Konukman et al., 2025; Y. Wang & Wang, 2024). Scholarship on digital technology in PE has already established that the subject is not insulated from wider educational transformation, but is instead negotiating how emerging technologies intersect with its curricular aims, pedagogical traditions, and embodied modes of learning (Casey et al., 2017; Jastrow et al., 2022; Lupton, 2022; Østerlie et al., 2025). Yet AI raises a more specific pedagogical problem than broader forms of digitally mediated PE. Online learning, blended delivery, virtual instruction, and technology-enhanced access mainly concern how PE is mediated, delivered, or extended through digital environments. AI, by contrast, can participate in the

pedagogical process itself through classification, prediction, recommendation, adaptation, automation, feedback generation, and decision-support. This makes AI in PE more than a passing technological trend or a general extension of digital learning. It represents a computational-pedagogical frontier where questions of teaching quality, subject integrity, teacher judgment, learner representation, and educational purpose become increasingly entangled with data-driven systems and technological decision-making.

Within this emerging frontier, the literature suggests that AI is beginning to influence core pedagogical work in PE rather than merely serving as an external add-on. Recent studies have shown how AI-supported systems can facilitate reflective practice, generate automated movement-related feedback, strengthen self-assessment, and support more individualized learning processes in PE settings (Hsia et al., 2024, 2025; Huang et al., 2026). At the same time, work on PETE and teacher digital competency indicates that the pedagogical value of new technologies in PE is not determined only by the tools themselves, but also by teachers' professional judgment, digital confidence, curricular interpretation, and assessment literacy (Fletcher et al., 2024; Østerlie et al., 2025; Wallace et al., 2023). Earlier PE pedagogy research likewise showed that mobile applications, video feedback, and digital video can enhance feedback processes, self-assessment, motivation, and learning experiences when technologies are pedagogically integrated rather than simply appended to instruction (J. E. Lee & Gao, 2020; O'Loughlin et al., 2013; Potdevin et al., 2018). These studies suggest that AI-supported PE should not be understood only through the language of technological adoption. Its pedagogical significance lies in how it may reorganize lesson planning, assessment, feedback, learner monitoring, adaptive instruction, and teacher decision-making. However, such possibilities also require caution because AI can intensify long-standing questions about who interprets movement, how student performance is represented, and how teachers balance professional judgment with automated or semi-automated forms of instructional support.

As this literature expands, its development should not be understood solely in terms of technical efficiency or instructional novelty. Broader scholarship on AI in education has shown that AI-supported teaching raises important concerns about data use, teacher agency, transparency, learner representation, and the educational consequences

of automated decision-support (Fu & Weng, 2024; Gouseti et al., 2025; Holmes et al., 2022; Nguyen et al., 2023). These concerns are especially salient in PE because teaching often involves visible, embodied, and interpretive forms of learning in which movement, participation, effort, and competence are observed, assessed, and pedagogically acted upon. Even when such concerns are not consistently foregrounded in the PE literature itself, the growing use of AI in teaching, evaluation, and learning support invites critical attention to how instructional systems are designed, implemented, and justified within educational practice (Baek et al., 2018; Murtagh et al., 2023; Sargent & Calderón, 2021). This critical stance aligns with work urging PE scholars to think carefully about digitality, values, and human flourishing in technologically mediated settings, particularly the argument that PE must remain concerned with learning to be human in a digital world rather than simply adopting technologies for their own sake (Chambers & Sandford, 2019; Fletcher et al., 2024; Murtagh et al., 2023; Standal, 2026; Wallace et al., 2023). In this regard, the present study examines AI in PE pedagogy through a bibliometric and thematic review. Specifically, it maps the growth and intellectual structure of scholarship addressing AI in PE-related teaching and teacher-education contexts. Furthermore, it identifies dominant pedagogical applications and use cases, and synthesizes major thematic directions and emerging concerns associated with AI-supported teaching, assessment, feedback, movement analytics, adaptive instruction, and teacher decision-support (Fu & Weng, 2024; Gouseti et al., 2025; Holmes et al., 2022; Østerlie et al., 2025; Standal, 2026; Y. Wang & Wang, 2024).

Materials and Methods

Research Design

This study employed a bibliometric research design to map the development, collaboration patterns, conceptual structure, and intellectual foundations of research on AI in PE pedagogy. Bibliometric analysis was appropriate because it allows large bodies of scientific literature to be examined through publication, citation, and network-based indicators. Following established bibliometric guidance, the study combined performance analysis and science mapping to examine the field's productivity profile and relational structure (Donthu et

Table 1. Search strategy and inclusion parameters

Parameter	Description
Database & indexes	Scopus
Search field	TITLE-ABS-KEY
Search string	TITLE-ABS-KEY (("physical education" OR "health and physical education" OR "school physical education" OR "physical education teacher education" OR PETE) AND ("artificial intelligence" OR "generative artificial intelligence" OR "machine learning" OR "deep learning" OR ChatGPT OR "large language model*" OR algorithm* OR "learning analytic*") AND (pedagog* OR teach* OR learn* OR instruct* OR assess* OR feedback OR curricul* OR "teacher education" OR "teacher training" OR "reflective practice"))
Language	English
Document types	Article, review, conference paper
Final timespan of corpus	2015–2025
Date of extraction	April 24, 2026

al., 2021; Jiang et al., 2025). This approach was suitable because AI in PE pedagogy spans pedagogical, ethical, assessment-related, teacher education, and technological conversations.

Data Source and Search Strategy

Table 1 presents the search strategy and inclusion parameters. Bibliographic data were retrieved from Scopus, which provides curated multidisciplinary metadata suitable for bibliometric analysis (Baas et al., 2020). The search was conducted in TITLE-ABS-KEY by combining PE terms with AI-related and pedagogy-related terms. This independently constructed search logic delimited AI in PE pedagogy rather than broader digital, online, blended, or technology-enhanced PE. The search was limited to English-language articles, reviews, and conference papers published from 2015 to 2025. Of the 1,383 records retrieved, 1,000 remained after filtering and cleaning.

Corpus Comparison with the Related Digitally Mediated PE Review

To further clarify the independence of the present corpus, a record-level comparison was conducted between the present AI in PE pedagogy dataset and the author's related bibliometric review on digitally mediated PE (Lobo, 2026). The comparison used Scopus EID as the primary matching identifier, with DOI and normalized title used as supporting checks. The present AI in PE pedagogy corpus contained 1,000 records, while the digitally mediated PE corpus contained 1,358 records. A total of 355 records were shared across the two datasets, representing 35.50% of the present AI in PE pedagogy corpus and 26.14% of the digitally mediated PE corpus. Conversely, 645 records, or 64.50% of the present corpus, were unique to this study, while 1,003 records, or 73.86% of the digitally mediated PE corpus, were unique to the related review. This partial overlap was expected because some AI-related work appears within the broader landscape of digitally mediated PE scholarship. However, the majority of records in both corpora were distinct. The digitally mediated PE review was broader in scope and included studies on online learning, blended learning, open distance learning, mobile learning, virtual learning, and technology-enhanced delivery. In contrast, the present corpus was constructed through a separate search strategy centered on AI-related terms and retained only records with substantive links to PE pedagogy, teaching, learning, assessment, feedback, PETE, movement learning, adaptive instruction, or instructional decision-making.

Eligibility Criteria and Corpus Delimitation

Records were included when they matched the finalized search strategy and were indexed in Scopus as English-language articles, reviews, or conference papers. They were retained only when the title, abstract, keywords, or source information showed a substantive link between AI-related approaches and PE pedagogy, teaching, learning, assessment, feedback, PETE, movement learning, or instructional decision-making. Records were excluded when they addressed general educational technology, online or blended learning, distance education, generic AI in education, public health, biomechanics, sport analytics, or computational modeling without an explicit

PE-pedagogy connection. After corpus delimitation, the final dataset comprised 1,000 documents published across 389 sources and authored by 1,748 authors, including 665 articles, 323 conference papers, and 12 reviews.

Data Cleaning and Preprocessing

Before analysis, the records were cleaned to improve metadata consistency and reduce noise, since bibliometric results depend heavily on source metadata quality (Passas, 2024). Cleaning involved checking author names, source titles, and keyword expressions for formatting inconsistencies. Author's Keywords were standardized for spelling, capitalization, hyphenation, pluralization, abbreviations, and closely related variants. When needed, a VOSviewer thesaurus was used to merge semantically equivalent terms. Author's Keywords were prioritized for thematic interpretation because they more directly reflected the authors' stated conceptual emphases, while indexed terms were treated cautiously due to their broader and sometimes less field-specific character.

Bibliometric Analysis

The cleaned dataset was analyzed using Bibliometrix/Biblioshiny and VOSviewer, which supported descriptive profiling, science mapping, and thematic analysis of the field (Aria & Cuccurullo, 2017, 2026; Van Eck & Waltman, 2010). Descriptive analysis summarized annual production, source productivity, citation characteristics, document types, and collaboration indicators. Network analyses examined country-level co-authorship, Author's Keyword co-occurrence, trend topics, source-level bibliographic coupling, and source co-citation. Thematic evolution analysis was also conducted to trace how dominant topics shifted across the study period. Author-level co-authorship was explored but not emphasized because the resulting network was sparse and weakly connected. These procedures were used to assess the productivity, conceptual structure, collaboration patterns, research fronts, intellectual foundations, and thematic development of AI in PE pedagogy.

Network Thresholds and Visualization Parameters

Thresholds were set to balance inclusiveness and interpretive clarity. Author's Keyword co-occurrence used a minimum threshold of 5 occurrences. Author-level co-authorship used a minimum threshold of 3 documents. Source-level bibliographic coupling used a minimum threshold of 4 documents. Lastly, source co-citation used a minimum threshold of 20 citations. Meanwhile, thematic evolution analysis was organized across three periods. In the VOSviewer maps, node size indicated item prominence, link thickness represented relationship strength, and colors identified clusters.

Results

Descriptive Profile and Publication Growth

The final dataset included 1,000 Scopus-indexed documents published from 2015 to 2025, consisting of

665 articles, 323 conference papers, and 12 reviews across 389 sources. The corpus showed an annual growth rate of 46.77%, with an average of 5.72 citations per document and 12.4% international co-authorship. As shown in Figure 1, publication output increased from 5 documents in 2015 to 50 in 2020, then rose sharply to 147 in 2022. Although output declined to 111 documents in 2023, it surged to 294 in 2024 and remained high at 232 in 2025. This pattern indicates the rapid post-2020 expansion of research on AI in PE pedagogy, particularly around teaching, assessment, feedback, movement analytics, and teacher-support applications. Citation averages were higher among earlier publications, especially in 2015 (50.00), 2016 (24.89), and 2018 (12.67), while recent outputs showed lower citation averages, particularly in 2024 (3.36) and 2025 (1.56), because of shorter citation windows.

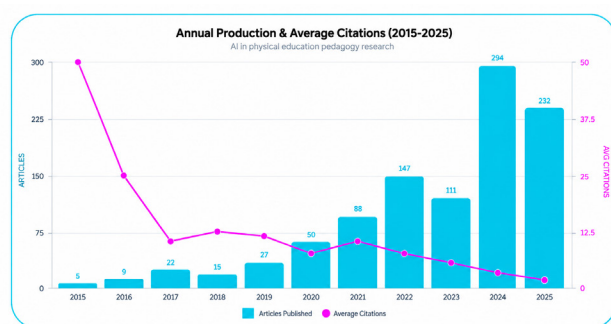


Fig. 1. Annual scientific production in AI in physical education pedagogy research (2015–2025)

Leading Sources, Authors, Affiliations and Influential Documents

The most relevant sources were concentrated in technical, computational, interdisciplinary, and applied publication outlets. Applied Mathematics and Nonlinear Sciences led the corpus with 107 documents, followed by Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering (32), Scientific Reports (24), and MCB Molecular and Cellular Biomechanics (23). Other leading sources included ACM International Conference Proceeding Series and Computational Intelligence and Neuroscience (22), followed by Advances in Intelligent Systems and Computing and Mobile Information Systems (20). Scientific Programming and Journal of Physics: Conference Series also appeared among the most productive outlets. This pattern suggests that research on AI in PE pedagogy is being shaped mainly through computational, engineering, data-driven, and interdisciplinary venues rather than traditional PE pedagogy journals, reflecting the field's development at the intersection of PE, educational technology, AI, analytics, and instructional systems.

The most cited authors were led by Wang, Y. with 104 citations, followed by Lee, H. S. and Lee, J. (47). Other influential authors included Wang, C. (28), Wu, X. (26), Zhang, S. (26), Wang, H. (25), Zhou, T. (24), YanRu, L. (23), and Cao, F. (22). This pattern indicates that author-level

Table 2. Most relevant sources within the corpus (2015–2025)

Sources	Number of articles
Applied Mathematics and Nonlinear Sciences	107
Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering LNICST	32
Scientific Reports	24
MCB Molecular and Cellular Biomechanics	23
ACM International Conference Proceeding Series	22
Computational Intelligence and Neuroscience	22
Advances in Intelligent Systems and Computing	20
Mobile Information Systems	20
Scientific Programming	16
Journal of Physics: Conference Series	14

influence in the corpus is shaped mainly by scholars working on AI-supported PE teaching, instructional evaluation, curriculum innovation, machine vision, and system-based approaches to physical education.

Table 3. Most cited authors within the corpus (2015–2025)

Author	Citations
Wang, Y.	104
Lee, H. S.	47
Lee, J.	47
Wang, C.	28
Wu, X.	26
Zhang, S.	26
Wang, H.	25
Zhou, T.	24
YanRu, L.	23
Cao, F.	22

The most influential documents within the corpus centered on AI-supported PE teaching, intelligent evaluation, machine vision, curriculum design, teaching-resource allocation, and mobile or multimedia-assisted assessment systems. Lee and Lee (2021) led the corpus with 47 local citations and 149 global citations, followed by Zhou et al. (2024) and YanRu (2021) with 23 local citations each. Other influential works included Yang et al. (2020), Z. Li and Wang (2021), Xi Liang and Xi Liang (2022), De-kun and Memon (2022), Zhang (2021), Cao et al. (2022), and S. Li et al. (2024). These documents show that the corpus is intellectually anchored in applied AI work on PE teaching, instructional evaluation, curriculum innovation, movement-related analysis, and system-supported educational practice rather than purely technical or philosophical discussions of artificial intelligence.

At the institutional level, the most productive affiliations were led by Gdansk University of Physical Education and Sport (9), followed by Capital University of Physical Education and Sports, Lviv Polytechnic National University,

Table 4. Most cited documents within the corpus (2015–2025)

Document	Local citations	Global citations
Lee, H. S., & Lee, J. (2021). Applying Artificial Intelligence in Physical Education and Future Perspectives. <i>Sustainability</i> , 13(1), 351. https://doi.org/10.3390/su13010351	47	149
Zhou, T., Wu, X., Wang, Y., Wang, Y., & Zhang, S. (2024). Application of artificial intelligence in physical education: A systematic review. <i>Education and Information Technologies</i> , 29(7), 8203–8220. https://doi.org/10.1007/s10639-023-12128-2	23	47
YanRu, L. (2021). An artificial intelligence and machine vision based evaluation of physical education teaching. <i>Journal of Intelligent & Fuzzy Systems</i> , 40(2), 3559–3569. https://doi.org/10.3233/JIFS-189392	23	39
Yang, D., Oh, E.-S., & Wang, Y. (2020). Hybrid Physical Education Teaching and Curriculum Design Based on a Voice Interactive Artificial Intelligence Educational Robot. <i>Sustainability</i> , 12(19), 8000. https://doi.org/10.3390/su12198000	22	76
Li, Z., & Wang, H. (2021). The effectiveness of physical education teaching in college based on Artificial intelligence methods. <i>Journal of Intelligent & Fuzzy Systems</i> , 40(2), 3301–3311. https://doi.org/10.3233/JIFS-189370	18	38
Xi Liang, X. L., & Xi Liang, J. Y. (2022). Recommendation Algorithm for Equilibrium of Teaching Resources in Physical Education Network Based on Trust Relationship. <i>Journal of Internet Technology</i> , 23(1), 135–143. https://doi.org/10.53106/160792642022012301014	15	55
De-kun, J., & Memon, F. H. (2022). Design of Mobile Intelligent Evaluation Algorithm in Physical Education Teaching. <i>Mobile Networks and Applications</i> , 27(2), 527–534. https://doi.org/10.1007/s11036-021-01818-1	14	43
Zhang, J. (2021). Reform and innovation of artificial intelligence technology for information service in university physical education. <i>Journal of Intelligent & Fuzzy Systems</i> , 40(2), 3325–3335. https://doi.org/10.3233/JIFS-189372	14	50
Cao, F., Xiang, M., Chen, K., & Lei, M. (2022). Intelligent Physical Education Teaching Tracking System Based on Multimedia Data Analysis and Artificial Intelligence. <i>Mobile Information Systems</i> , 2022, 1–11. https://doi.org/10.1155/2022/7666615	14	42
Li, S., Wang, C., & Wang, Y. (2024). Fuzzy evaluation model for physical education teaching methods in colleges and universities using artificial intelligence. <i>Scientific Reports</i> , 14(1), 4788. https://doi.org/10.1038/s41598-024-53177-y	13	15

Table 5. Most relevant affiliations within the corpus (2015–2025)

Affiliation	Articles
Gdansk University of Physical Education and Sport	9
Capital University of Physical Education and Sports	8
Lviv Polytechnic National University	8
South China Normal University	8
Wuhan Sports University	8
Shandong University	7
Xinjiang University	7
Zhengzhou University	7
Beijing Sport University	6
Chengdu Sport University	6

South China Normal University, and Wuhan Sports University (8). Other relevant affiliations included Shandong University, Xinjiang University, and Zhengzhou University (7), followed by Beijing Sport University and Chengdu Sport University (6). This distribution suggests that research on AI in PE pedagogy is supported by sport-focused universities, teacher education settings, and multidisciplinary institutions, indicating that the field is developing across pedagogical, sport, and technological knowledge environments.

Collaborative Structure of the Field

As shown in Figure 2, the country-level co-authorship map indicates that research on AI in PE pedagogy is internationally connected but unevenly integrated. China occupied the most central and visually prominent position, suggesting a strong role in both publication activity and collaborative reach. The United States and the United Kingdom also appeared as well-connected nodes, while South Korea, Japan, Thailand, Malaysia, the Philippines, Portugal, Italy, and Spain contributed to the wider collaboration

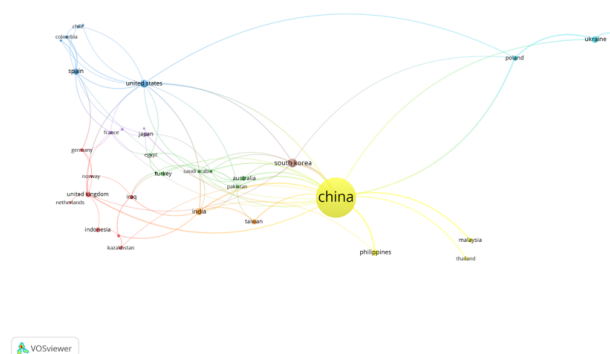


Fig. 2. Country-level co-authorship network in AI in physical education pedagogy research (2015–2025)

structure. The field shows a growing transnational network, although collaboration remains concentrated around a limited number of active country hubs.

The global collaboration map in Figure 3 shows that cross-national collaboration was geographically broad but still concentrated around a few strong country links. The strongest collaborations were between China and Korea (21), China and the Philippines (11), China and Malaysia (7), China and India (5), and China and Poland (5). Other visible collaborations included China with Japan, Thailand, the United Kingdom, Pakistan, Ukraine, and the United States, as well as Spain with Colombia and Mexico, Ukraine with Poland and Slovakia, and the United States with India. Collaboration in AI in PE pedagogy extends across Asia, Europe, North America, and Latin America, although China remains the dominant collaboration hub.

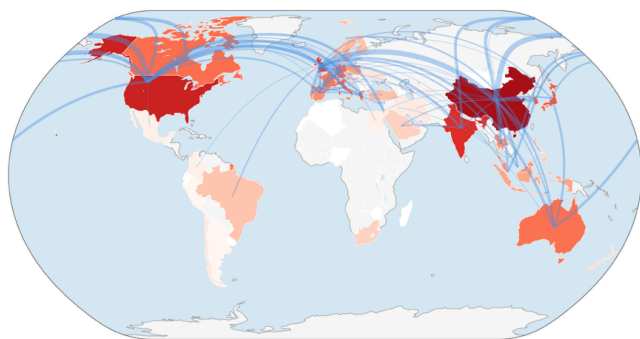


Fig. 3. Global collaboration map in AI in physical education pedagogy research (2015–2025)

Conceptual Structure of the Field

The Author Keywords co-occurrence network in Figure 4 revealed a densely connected conceptual structure anchored by “physical education” and “artificial intelligence.” The yellow cluster centered on “physical education” and included “virtual reality,” “augmented reality,” “student engagement,” and “online physical education,” indicating a strand on immersive and digitally enriched PE learning. The red cluster grouped “data mining,” “big data,” and teaching reform, reflecting data-driven pedagogical improvement. The orange cluster connected “sports,” “college and universities,” “teaching,” and “action recognition,” suggesting applied institutional and instructional use. The blue and cyan clusters contained technical terms such as “deep learning,” “neural network,” “convolutional neural network,” and “internet of things,” representing the computational infrastructure of the field. The purple and pink clusters linked “artificial intelligence,” “machine learning,” and related AI terms, bridging pedagogical and technical strands. The field is structured around immersive PE environments, data-driven teaching improvement, applied instructional deployment, and computational intelligence methods.

Table 6 confirms the centrality of PE and AI-related computational terms in the corpus. “Physical education” was the most frequent Author Keyword with 237 occurrences and the highest total link strength (TLS = 241), followed by “artificial intelligence” (124; TLS = 142), “deep learning” (64), and “machine learning” (56). Other frequent keywords included “physical education teaching,” “data mining,”

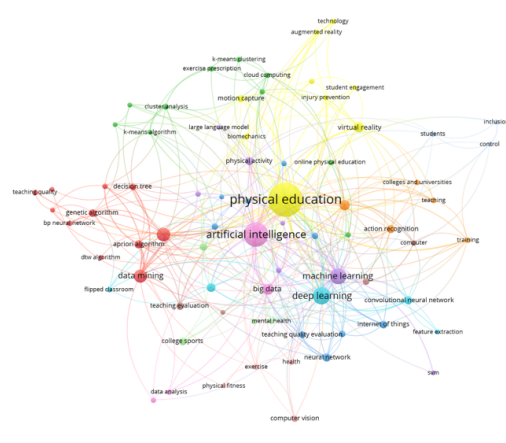


Fig. 4. Co-occurrence network of Author's Keywords in AI in physical education pedagogy research (2015–2025)

“big data,” “sports,” “virtual reality,” and “college physical education.” The keyword profile shows that the corpus is organized around PE as the main educational domain, with major conceptual emphasis on AI, machine learning, deep learning, data mining, teaching, virtual environments, and system-level applications in PE pedagogy.

Table 6. Most frequent Author's Keywords in AI in physical education pedagogy research

Rank	Author's Keyword	Occurrences	Total link strength
1	Physical education	237	241
2	Artificial intelligence	124	142
3	Deep learning	64	74
4	Machine learning	56	63
5	Physical education teaching	38	24
6	Data mining	37	42
7	Big data	26	36
8	Sports	23	38
9	Virtual reality	22	31
10	College physical education	17	18

The trend-topic analysis in Figure 5 shows a temporal shift from earlier performance, biomechanics, and system-processing terms toward more recent AI-enabled and education-facing themes. Earlier topics included “normal human,” “biomechanical phenomena,” and “task performance,” reflecting an initial focus on bodily function, movement performance, and system-level processing. Transitional terms such as “education,” “outcome assessment,” “robotics,” “physiology,” “health,” and “advanced analytics” suggest a widening concern with evaluation and technology-supported educational inquiry. More recent topics, including “physical education,” “students,” “sports,” “teaching,” and “artificial intelligence,” indicate that the field is now more strongly organized around pedagogical practice, learner populations, and AI-supported PE applications. The emergence of “motion capture” and “feature extraction” further suggests growing attention to data-rich movement analysis and computationally supported instruction.

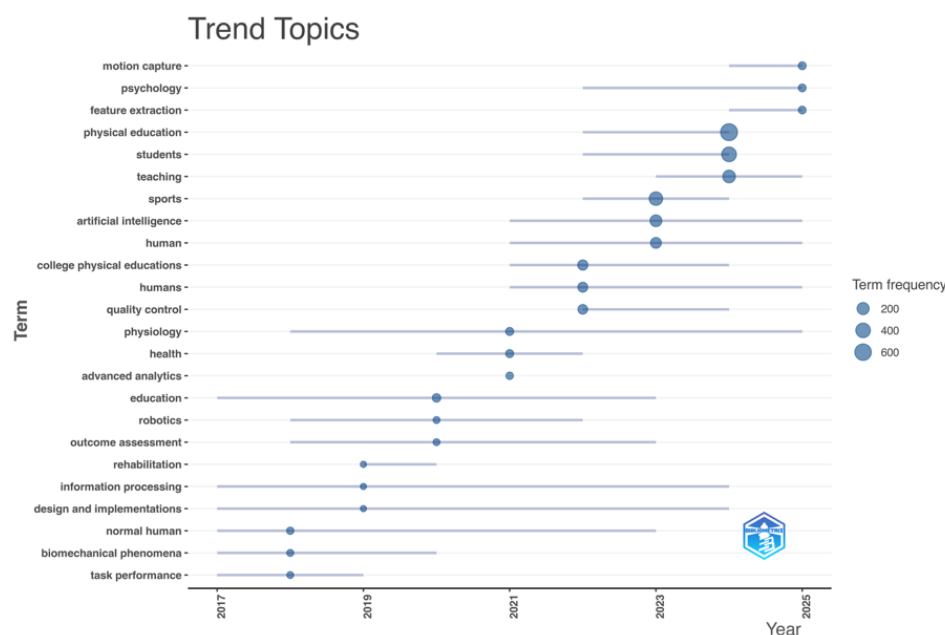


Fig. 5. Trend topics based on Author's Keywords in AI in physical education pedagogy research (2015–2025)

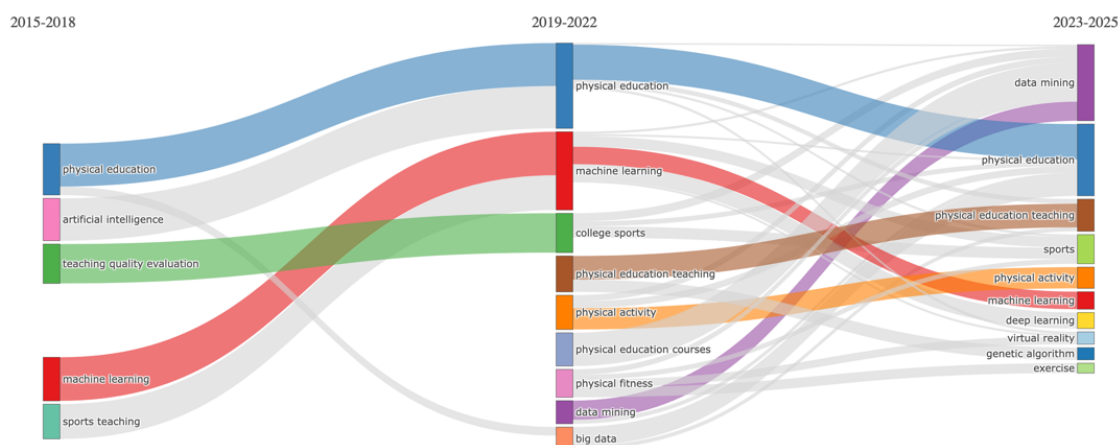


Fig. 6. Thematic evolution of AI in physical education pedagogy research (2015–2025)

The thematic evolution map in Figure 6 shows both continuity and diversification across the field. From 2015–2018, the main themes were “artificial intelligence,” “machine learning,” “physical education,” “sports teaching,” and “teaching quality evaluation,” reflecting early attention to AI concepts, PE instruction, and evaluation-related applications. During 2019–2022, these themes expanded into “physical education,” “machine learning,” “big data,” “data mining,” “college sports,” “physical activity,” “physical education teaching,” and “physical fitness,” indicating a broader connection between computational tools and PE teaching, learning, and movement-related contexts. By 2023–2025, the field consolidated around “physical education,” “physical education teaching,” “data mining,” “machine learning,” “deep learning,” “virtual reality,” “sports,” “genetic algorithm,” and “exercise.” The map suggests a shift from early AI and evaluation-oriented themes toward more specialized work on AI-supported PE teaching, data-driven

analysis, computational movement learning, and immersive instructional applications.

Intellectual Structure of the Field

The source-level bibliographic coupling network in Figure 7 shows a largely integrated but interdisciplinary publication front. Leading connected outlets included “Applied Mathematics and Nonlinear Sciences,” “ACM International Conference Proceeding Series,” “Mobile Information Systems,” “Scientific Reports,” and “Journal of Physical Education, Recreation and Dance.” This pattern indicates that AI in PE pedagogy is being developed across computational, engineering, interdisciplinary science, health-related, educational technology, and PE-oriented publication spaces. Rather than forming a single disciplinary tradition, the field is organized through overlapping computational and pedagogical publication fronts.

Discussion

Artificial Intelligence as Computational Pedagogical Agency in PE

AI should not be treated as a neutral extension of digital PE. Its deeper implication is that it introduces computational agency into pedagogical work. Once a system begins to classify learners, predict needs, recommend tasks, generate feedback, or organize instructional pathways, it is no longer only supporting delivery. It is participating in the production of pedagogical judgment. That shift deserves careful scrutiny because PE has always depended on situated interpretation. Teachers read bodies, emotions, hesitation, effort, confidence, space, risk, and social dynamics in ways that cannot be reduced to data traces. Broader reviews of AI in education show rapid growth around adaptive learning, prediction, assessment, and feedback, but they also show that technological application often develops faster than pedagogical theory (Matos et al., 2025; S. Wang et al., 2024). In PE, that imbalance may be even more consequential because movement learning is not only a technical process. It is relational, affective, embodied, and culturally situated. The danger is not simply that AI will enter PE. The danger is that PE problems may be reframed too quickly as optimization problems. Lesson planning may become sequencing by recommendation. Differentiation may become grouping by predicted ability. Support may become automated intervention. In practical lesson planning, this means that AI may influence how teachers select learning tasks, sequence movement activities, group students, anticipate difficulty, and adapt instruction based on predicted learner needs. Such support may make planning more responsive, but it may also narrow pedagogical imagination when teachers begin to design lessons around algorithmic recommendations rather than curricular purpose, embodied readiness, and student experience. These are not inherently wrong, but they change the center of pedagogical authority. Therefore, AI in PE requires more than adoption studies or tool evaluations. It requires a theory of how computational systems should remain answerable to the educational meaning of movement, rather than allowing movement to be reorganized around what machines can detect and process.

Algorithmic Assessment and Feedback in Embodied Movement Learning

Assessment and feedback are among the most tempting uses of AI in PE because they promise immediacy, precision, and scalability. A system that can detect movement patterns, identify errors, and generate feedback appears to solve a practical problem that PE teachers regularly face. Recent work on AI-based real-time feedback has shown how such systems may support movement quality, fluency, learning interest, and self-directed learning (Ma et al., 2025). Yet, the critical issue is not whether AI can assess movement. The issue is what kind of movement becomes assessable when AI becomes part of the assessment ecology. PE does not deal with movement as pure mechanics. A jump, throw, step, kick, or dance phrase carries intention, fear, rhythm, fatigue, confidence, memory, and social exposure. Algorithmic feedback may capture angles, speed, timing, posture, or error patterns, but these indicators do not exhaust the educational

meaning of movement. At the level of assessment, AI may shift PE from episodic teacher observation toward continuous movement capture, automated error detection, and performance profiling. This changes feedback from a relational exchange between teacher and learner into a mediated process shaped by what the system can detect, classify, and report. The pedagogical concern is not only accuracy, but whether AI-generated feedback helps students understand movement in ways that are meaningful, safe, and confidence-building. Datafication scholars have long argued that digital systems do not merely represent reality; they shape what institutions learn to value and act upon (Jarke & Breiter, 2019; Williamson et al., 2020). In PE, this means that AI feedback may quietly privilege measurable correctness over felt learning, experimentation, expression, and bodily confidence. Wearable and monitoring technologies already show how PE can slide into uncritical bodily surveillance when data are treated as naturally useful (Cereda, 2025). Thus, a critical AI pedagogy in PE should ask whether assessment expands students' movement possibilities or disciplines them into algorithmically preferred forms of performance. Feedback should help students understand movement, not make them feel permanently watched by a system that knows their body only through metrics.

Teacher Agency and Professional Judgment in AI Supported PE

The teacher's role becomes more complicated, not less, when AI enters PE. The common language of AI support can make the technology sound harmless, as though the teacher remains fully in control while the system quietly assists in the background. In practice, AI-generated classifications, recommendations, alerts, and feedback can carry strong pedagogical authority. Teachers may begin to trust them, adjust instruction around them, or feel pressured to justify decisions against them. This affects teacher decision-making at several levels. AI may suggest which students need remediation, which skills require further practice, which activities should be modified, or which learners are ready to progress. These suggestions can support teacher reflection, but they can also subtly redistribute authority from professional judgment to system-generated interpretation. Therefore, the teacher's pedagogical task, is not simply to use AI output, but to decide when it is educationally relevant, when it is incomplete, and when it must be resisted. This creates a new professional demand. PE teachers must not only know how to use AI tools; they must know how to disagree, reinterpret, and sometimes ignore them. Research on digital competency in PE and PETE already shows that technology integration depends on teachers' assessment literacy, curricular judgment, and professional confidence (Fletcher et al., 2024; Østerlie et al., 2025; Wallace et al., 2023). AI intensifies that requirement because the tool does not only display content or record performance. It interprets. Wider studies on teachers and AI have warned that application-focused research often outpaces professional development and pedagogical preparation (K. Li et al., 2025; Tan et al., 2025). For PE, this gap cannot be treated as a minor implementation issue. A teacher who cannot critically interpret AI output may become dependent on systems that flatten students into profiles, scores, risk categories,

or movement errors. Recent discussions of generative AI also stress that agency and decision-making must remain with educators rather than being transferred to automated systems (Alfarwan, 2025; Landa-Blanco, 2026). Hence, PE teachers should be positioned not as end-users of AI, but as critical pedagogical mediators. Their work is to translate, question, contextualize, and humanize AI outputs within the lived realities of movement learning.

Student Autonomy Datafication and the Ethics of AI Mediated PE

Student autonomy is often used to justify AI in education. Personalized goals, adaptive feedback, progress dashboards, and self-monitoring tools can appear to give students more control over learning. In PE, this promise is attractive because students differ widely in confidence, ability, body history, prior exposure, injury, motivation, and comfort with public performance. Yet, autonomy becomes thin when it is defined only as the ability to follow personalized data. A student may receive more feedback, tracking, and individualized recommendations while having less power to question how their body is being interpreted. For students, AI-supported autonomy may become a form of guided compliance if individualized recommendations are treated as instructions to follow rather than information to interpret. In movement learning, this is especially important because progress is not only demonstrated through technical correction or measurable improvement. It may also appear through confidence, rhythm, willingness to participate, creative exploration, bodily comfort, and the ability to make sense of one's own movement. Broader AI-in-education scholarship has raised continuing concerns about privacy, transparency, bias, learner representation, and the balance between automation and human control (Holmes et al., 2022; Nguyen et al., 2023). Human-centered work on learning analytics similarly emphasizes trust, safety, end-user involvement, and meaningful oversight rather than technical performance alone (Alfredo et al., 2024). These concerns become sharper in PE because the student body is already an object of observation. AI can make that observation more continuous, more granular, and more difficult to refuse. The ethical problem is not only data privacy. It is also bodily dignity. Students should not experience AI-mediated PE as a condition where every movement becomes evidence, every performance becomes a record, and every body becomes a dataset. Chambers and Sanford's (2019) reminder that PE should remain concerned with learning to be human in a digital world is especially relevant. A humane AI agenda in PE must protect the student's right to move imperfectly, privately, playfully, and experimentally. Autonomy should mean more than being guided by AI. It should include understanding, consent, contestation, and the freedom to remain more than what the system measures.

Toward a Pedagogically Accountable AI in PE Framework

This review proposes a Pedagogically Accountable AI in PE Framework as a conceptual contribution for future research and practice. AI integration in PE should not be evaluated only through technical accuracy, automation, prediction, or efficiency. It should also be judged according

to how it protects pedagogical judgment, embodied learning, student agency, and ethical responsibility. Human-centered AI scholarship has emphasized the need for human control, stakeholder involvement, trustworthiness, and safety in learning analytics and AI-supported education (Alfredo et al., 2024; Holmes et al., 2022). In PE, these concerns become more urgent because learning is bodily, visible, social, and emotionally charged. The proposed framework positions AI not as an independent pedagogical authority, but as a system that must be translated, questioned, and ethically governed before it becomes part of movement learning.

Figure 9 presents the proposed Pedagogically Accountable AI in PE Framework as a conceptual model for interpreting AI-supported PE practice. The model begins with computational function, which refers to what AI systems can technically perform, such as classification, prediction, recommendation, automation, movement recognition, assessment support, and feedback generation. These functions do not move directly into PE practice. They must pass through pedagogical translation, embodied movement learning, human agency, and ethical accountability before becoming educationally meaningful. Therefore, the proposed model frames AI-supported PE practice as a mediated outcome rather than a direct result of technological capability. In this proposed framework, lesson planning, assessment, feedback, movement analytics, teacher-supported decision-making, and inclusive participation remain accountable to teacher judgment, student agency, embodied experience, and ethical safeguards.

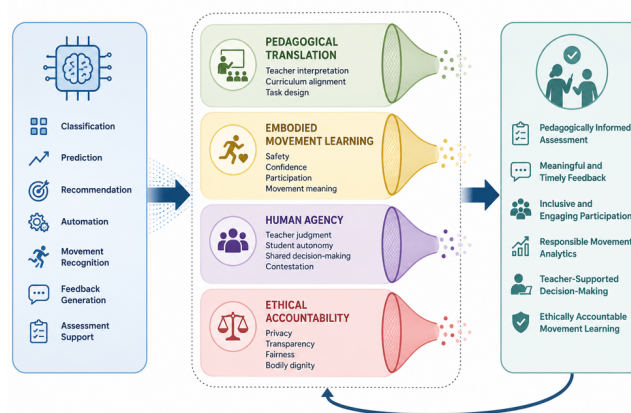


Fig. 9. Pedagogically Accountable AI in PE Framework.

Note: The framework illustrates how AI-supported PE should move from computational functions toward educational practice through pedagogical translation, embodied movement learning, human agency, and ethical accountability. The curved arrow indicates that AI-supported PE practice requires continuous review, interpretation, and adjustment rather than direct application of system-generated outputs

Computational Function

This refers to what AI systems are designed to do in PE. These functions may include classifying movement, detecting errors, predicting learner needs, recommending tasks, automating assessment, generating feedback, or supporting instructional decisions. Recent reviews of AI-based learning tools show that assessment, personalized

feedback, recommendations, and intelligent tutoring are now among the most common roles of AI in education (Luo et al., 2025). These functions may be useful in PE because teachers often handle large classes, varied skill levels, limited time, and complex movement tasks. Yet computational function should not be confused with pedagogical value. A system may accurately detect movement patterns without understanding why a student moves cautiously, avoids participation, or struggles with a task. This dimension describes what AI can process, but not what PE should value.

Pedagogical Translation

This concerns the work of turning AI outputs into meaningful instruction. Data, alerts, scores, and recommendations do not automatically become pedagogical knowledge. Teachers still need to interpret them, connect them to lesson objectives, adjust tasks, and decide whether automated feedback fits the learner, activity, and class context. This is especially important because AI in education has often developed faster in classroom application than in teacher professional development. Tan et al. (2025) found that research on AI in teaching remains more focused on application than on the professional learning teachers need to integrate AI responsibly. In PE, that gap is risky. A movement score, posture alert, or performance prediction may look objective, but it still requires professional interpretation. PE teachers need to decide whether AI feedback supports learning, reinforces narrow performance standards, or misreads the learner's embodied situation. This dimension keeps AI under the authority of curriculum, context, and teacher judgment.

Embodied Movement Learning

This keeps attention on what makes PE educationally distinctive. Movement is not only a biomechanical event or a performance output. It carries confidence, fear, rhythm, hesitation, fatigue, safety, enjoyment, social exposure, and cultural meaning. Chambers and Sandford (2019) argued that PE should remain concerned with learning to be human in a digital world, a point that becomes sharper when AI begins to evaluate bodies and movement. AI may support skill correction or performance feedback, but it may also push PE toward a narrow culture of monitoring and optimization. Datafication scholars have warned that digital systems shape what schools learn to see, value, and act upon (Jarke & Breiter, 2019; Williamson et al., 2020). In PE, movement can become too quickly translated into indicators, scores, alerts, and risk profiles. Therefore, AI-supported PE must remain accountable to embodied learning. The goal is not simply better measurement. The goal is richer, safer, more meaningful, and more inclusive movement participation.

Human Agency

This positions teachers and students as active interpreters of AI-supported PE. They should not become passive recipients of system-generated recommendations. Alfarwan (2025) emphasized that GenAI may support teaching and learning, but agency and decision-making must remain with teachers. This principle is crucial because teachers work

with situated, relational, and affective forms of learning. They notice embarrassment, overconfidence, discomfort, resistance, peer dynamics, and fear of failure. AI cannot fully read these conditions. Students also need agency in how AI feedback is received, questioned, and used. A learner should not be positioned as a body waiting to be corrected by a system. This dimension means that teachers can challenge AI outputs, students can understand and contest feedback, and both remain central to the learning process. Without this dimension, AI-supported PE may become efficient but disempowering. It may produce more information while reducing the human capacity to interpret, negotiate, and make meaning from movement.

Ethical Accountability

Ethical accountability is the dimension that prevents the framework from becoming a purely technical model of AI integration. It requires transparency, privacy, fairness, consent, anti-surveillance, and bodily dignity because AI use in PE often involves data about bodies, movement, performance, effort, fitness, participation, and learning behavior. These are not neutral data points. They can shape how students see themselves, how teachers interpret ability, and how institutions define improvement, risk, or readiness. Human-centered learning analytics research has shown that students and teachers are not always sufficiently involved in the design of AI-supported educational systems, even when these systems directly affect their learning and agency (Alfredo et al., 2024). Broader AI ethics scholarship in education also warns about bias, opacity, privacy, and the difficulty of balancing automation with human judgment (Holmes et al., 2022; Nguyen et al., 2023). For this reason, this dimension functions as the framework's critical safeguard. It asks whether AI-supported PE expands dignity, participation, and meaningful movement learning, or whether it intensifies surveillance, ranking, correction, and data-driven control. A system that tracks students efficiently but makes them feel watched, exposed, ranked, or reduced to bodily metrics is not pedagogically accountable, regardless of its technical sophistication.

Framework Contribution

The proposed Pedagogically Accountable AI in PE Framework rejects a linear model in which AI produces data and teachers simply apply it. AI outputs must pass through pedagogical translation, embodied context, human agency, and ethical scrutiny before becoming educational action. The framework is not presented as an empirically validated model. Rather, it is a conceptual contribution derived from the bibliometric and thematic synthesis. It offers a way to organize future research around a stronger question. AI-supported PE should not only ask whether systems work, but what kind of PE they help create. If AI strengthens teacher judgment, expands student participation, supports meaningful feedback, and protects bodily dignity, it may enrich PE pedagogy. If it narrows movement into monitoring, correction, prediction, and optimization, it risks weakening the educational purpose of the subject. This framework positions AI in PE as a pedagogical and ethical problem before it is a technical solution.

Conclusions

This review positions AI in PE pedagogy as more than a technical innovation. It is an emerging computational-pedagogical field that may reshape how movement is taught, assessed, interpreted, and experienced. Its central contribution is the Pedagogically Accountable AI in PE Framework, which argues that AI-supported PE must be judged not only by what systems can detect, automate, or optimize, but by how they protect pedagogical judgment, embodied learning, human agency, and ethical responsibility. The review does not establish the effectiveness of AI in PE. It shows instead that the field is entering a critical stage where future scholarship must decide whether AI will deepen the educational meaning of movement or reduce PE to monitoring, correction, and data-driven performance management.

Conceptual and practical implications

The review positions AI in PE pedagogy as a cross-cutting concern that requires stronger integration across PE pedagogy, PETE, educational technology, learning analytics, computer science, movement science, assessment studies, ethics, and teacher professional development. Conceptually, this means moving beyond tool-centered or innovation-centered accounts of AI toward a deeper understanding of how computational systems may reorganize lesson planning, assessment, feedback, teacher agency, student autonomy, and embodied movement learning. In practical terms, PE teachers, teacher educators, curriculum designers, school leaders, researchers, and AI developers should treat AI as a pedagogical system that requires interpretation, adaptation, and ethical scrutiny. AI-supported PE should be designed around teacher judgment, learner dignity, transparent feedback, meaningful assessment, inclusive participation, and responsible data use. The proposed framework encourages stakeholders to treat AI not as a substitute for PE teachers or as a neutral technical upgrade, but as a mediated pedagogical resource that must remain accountable to the educational purpose of movement.

Future research directions

Future research should move beyond mapping the growth of AI in PE pedagogy and examine how AI-supported systems actually function in teaching and learning contexts. Empirical studies are needed to test how AI affects lesson planning, assessment quality, feedback processes, student autonomy, teacher agency, and embodied movement learning. More work is also needed on PE teacher preparation, AI literacy, ethical decision-making, and professional development, particularly because AI outputs require pedagogical interpretation rather than direct application. Future studies should also examine students' lived experiences of AI-mediated PE, including issues of privacy, surveillance, confidence, inclusion, and bodily dignity. Finally, the proposed Pedagogically Accountable AI in PE Framework should be tested, refined, or challenged across different PE settings, learner groups, technologies, and cultural contexts.

Ethics Approval

This study relied exclusively on bibliographic records indexed in Scopus and did not involve human participants,

personal data, or direct intervention. This study has been exempted for ethical review by the Bulacan State University-Research Ethics Committee (BulSU-ERC) BulSUERC-2026-0124-EX.

Data Availability Statement

The bibliometric data that support the findings of this study were retrieved from the Scopus database. The dataset generated and analyzed during the current study, including the cleaned bibliographic records and thesaurus files used for mapping and visualization, is available from the author upon reasonable request, subject to database access and licensing restrictions.

AI Transparency Statement

During the preparation of this manuscript, the author used ChatGPT 5.4+ by OpenAI in a limited and supportive capacity for language refinement, organizational assistance, and drafting support. The author retained full control over the intellectual content of the manuscript and was solely responsible for the study design, search strategy, data analysis, interpretation, and final revision of the text. All AI-assisted outputs were carefully reviewed, edited, and validated by the author, who accepts full responsibility for the final submitted version.

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Conflicts of Interest

The author declares no conflict of interest.

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Штучний інтелект у педагогіці фізичного виховання: бібліометричний і тематичний огляд педагогічних застосувань та нових проблем (2015–2025)

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

Реферат. Стаття: 15 с., 7 табл., 9 рис., 53 джерело.

Мета. Оскільки штучний інтелект дедалі активніше впроваджується в освітню практику, педагогіка фізичного виховання стикається з окремим колом питань, що виходять за межі онлайн-, змішаного або технологічно підтримуваного навчання. Метою цього дослідження було здійснити картування наукових публікацій щодо штучного інтелекту в педагогіці фізичного виховання за 2015–2025 роки з акцентом на динаміці публікаційної активності, концептуальній структурі, міждисциплінарних засадах, педагогічних застосуваннях і нових проблемних аспектах.

Матеріали та методи. Дослідження виконано у форматі бібліометричного та тематичного огляду. Бібліографічні дані було отримано з бази Scopus та проаналізовано за допомогою Bibliometrix/Biblioshiny і VOSviewer. Після фільтрації та очищення даних остаточний корпус становив 1000 документів, опублікованих у 389 джерелах.

Результати. Результати засвідчили суттєве зростання кількості публікацій після 2020 року, що вказує на посилення наукового інтересу до педагогічних застосувань штучного інтелекту у фізичному вихованні. Дослідницьке поле має різно міждисциплінарний характер і охоплює фізичне виховання, освітні технології, комп'ютерні науки, інженерію та науки про здоров'я. Концептуальний і тематичний аналіз показав, що література зосереджена навколо таких напрямів, як фізичне виховання, штучний інтелект, машинне навчання, глибоке навчання, інтелектуальний аналіз даних, викладання фізичного виховання, віртуальна реальність та аналітика рухової діяльності. Аналіз бібліографічного зв'язку та співцитування також засвідчив, що це дослідницьке поле формується внаслідок конвергенції обчислювальних інновацій і педагогічного застосування, а не в межах однієї дисциплінарної традиції.

Висновки. Штучний інтелект у педагогіці фізичного виховання позиціонується як новий обчислювально-педагогічний напрям досліджень. Отримані результати слід розглядати як структурне й тематичне картування наукового поля, а не як доказ ефективності застосування штучного інтелекту в навчальному процесі. Як концептуальний внесок у розвиток напрямку в огляді запропоновано Рамкову модель педагогічно відповідального штучного інтелекту у фізичному вихованні, зосереджену на обчислювальній функції, педагогічній трансляції, навчанні через рухову діяльність, людській суб'єктності та етичній відповідальності.

Ключові слова: штучний інтелект, бібліометричний аналіз, нові проблемні аспекти, педагогічні застосування, фізичне виховання.

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Review Article

Mapping Trends and Gaps in Karate Research: A Bibliometric Analysis Based on the Scopus Database from 2000 to 2025

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Abstract

Background. Karate is rapidly growing as a global sport discipline, necessitating scientific data to effectively optimize future research. However, mapping of karate research trends has yet to yield adequate data. This has an impact on the understanding and development of sports science.

Objectives. This study aimed to map karate research using bibliometric analysis from 2000 to 2025 using the Scopus database.

Materials and Methods. Data were collected using specific keywords. The final data set consisted of 518 documents in RIS format. PRISMA, Mendeley, and Biblioshiny visualization were employed for screening and analysis.

Results. (1) Annual scientific production: stagnation occurred in 2000-2009, with the highest increase of 15% in 2024; (2) Most relevant authors: expertise was concentrated in only two researchers (11-12 documents); (3) Thematic mapping: karate became the main focus of research (motor themes), while comparative studies between martial arts began to decline (declining themes), and research began to shift toward themes with greater potential; (4) Co-occurrence network: the dominant research network involves biological and biomechanical approaches, with human participants as the primary focus; (5) Topic trends: a shift from a fundamental physiological focus to peak athlete performance and more specific aspects; (6) Thematic evolution: the use of technologies such as electromyography, echography, and algorithms in research design; (7) Factor analysis: methodological advances from observational studies to randomized controlled trials.

Conclusion. Karate research focuses on elite athletes and empirical studies, but researchers must collaborate and integrate across disciplines to increase the quantity and quality of future studies.

Keywords: karate martial arts, bibliometric analysis, trends and gaps, combat sport, research trend mapping.

Introduction

Karate is a Japanese martial art. It is currently developing into an attractive sport (Yudhistira & Tomoliyus, 2020). This potential is evident in the increasing number of competitive events (Yudhistira et al., 2025). According to Tijo and Marheni (2018), karate can be defined through both traditional values and research developments (Tijo & Marheni, 2018). Karate research is evolving in tandem with advances in sports science (Hadi & Yudhistira, 2023; Yudhistira et al., 2023). The study focuses on the psychological, physiological, and pedagogical aspects of karate (Doria et al., 2009; Nengsi, Wahyu & Ishak, 2021; Pekel et al., 2023). According to these studies, karate can be classified into two elements: how to improve performance and the development of research publications. However, no comprehensive discussion of the development, productivity, and trends in karate research has been incorporated into one. This is critical for promoting development and meeting the needs of karate practitioners. The publications of karate research remain scattered; thus, evaluating and analyzing publication development patterns frequently necessitates searching through academic databases, making it challenging to map prior research.

This dynamic limits the opportunities for establishing theoretical guidelines to improve future research, as past studies have only concentrated on original research. However, studies that discover research to provide insight into secondary data analysis, such as scoping reviews, systematic reviews, and bibliometric analysis, have not proven particularly successful. This undoubtedly has a theoretical basis, as current research is limited to assessing a single training method (Putriana et al., 2023; Widyastuti et al., 2025; Yudhistira et al., 2025), implying that study generalizations have yet to be adequately synthesized. The differences in study approaches, such as experimental, descriptive, and associative, make it difficult to synthesize patterns and trends in karate research. There is an urgent need to discuss the dynamics of cooperative patterns in karate research. Failure to undertake a specific study of trends, productivity, constraints, and research innovation would result in a lack of pragmatics when constructing problem analyses based on authentic evidence. Bibliometric analysis is a method for determining development trends and future research needs (Akhiruyanto & Yudhistira, 2024; Hafidz et al., 2024).

Because bibliometrics is based on prior research data, its impact extends beyond research analysis to the exploration of new research discourse. An example is the analysis of collaboration patterns, institutions, and productive authors (Leydesdorff et al., 2016). Researchers consider that the bibliometric analysis of karate has not received sufficient attention. Theoretical evidence has been found in studies conducted by Kek et al., Tropin et al., and Gabriela et al. (Gabriela et al., 2023; Gonçalves et al., 2025; Kek et al., 2023; Mazzei et al., 2022; Tropin et al., 2023).

However, these studies concentrated on general martial arts. The three bibliometric analyses on karate concentrated on techniques, injury analysis, and the development of karate in general. As a result, there has been no particular focus on identifying prospective future research utilizing a highly credible database such as Scopus. Choosing the Scopus database for data retrieval is a practical solution since it is

simple to filter and retrieve articles in a variety of document types. Furthermore, the literature coverage is constantly updated and verified, ensuring that publications submitted to Scopus are rigorously peer reviewed. Furthermore, adhering to academic standards increases the trustworthiness of articles and promotes best academic practices (T. Fischer et al., 2022). Based on prevailing concerns, this study aims to map trends and gaps in karate research using bibliometric analysis of the Scopus database from 2000 to 2025. This study focuses on the following aspects: (1) annual scientific output, (2) the most relevant author sources, (3) thematic mapping, (4) co-occurrence network, (5) research subject trends, (6) thematic evolution, and (7) factorial analysis. It is intended that this research will improve future karate research by addressing theoretical and practical demands and determining their urgency.

Materials and Methods

Study Participants

Participants in the research were published article documents. This study employed bibliometric analysis (Akhiruyanto & Yudhistira, 2024). Bibliometric analysis was used to map research trends, gaps, and productivity (Hossen & Pauzi, 2025). Bibliometric analysis helps with the identification of research gaps, which serves as the foundation for gap research (Chen et al., 2025). The bibliometric data screening procedure was carried out by three independent reviewers with doctorates in karate. Independent reviewers were involved to ensure scientific objectivity and transparency and to minimize data bias (Medrano-Ureña et al., 2020).

Data Collection and Filtering Procedures

The Scopus database was chosen for its broad coverage of sports science journals, high credibility, and thorough peer review (Plakias, 2025). Thus, Scopus is an ideal resource for charting bibliometric trends in karate. The data search was undertaken on June 29-30, 2026, with a focus on the years 2000 to 2025. The data gathering process followed a systematic procedure to ensure transparency and reproducibility, which included the following:

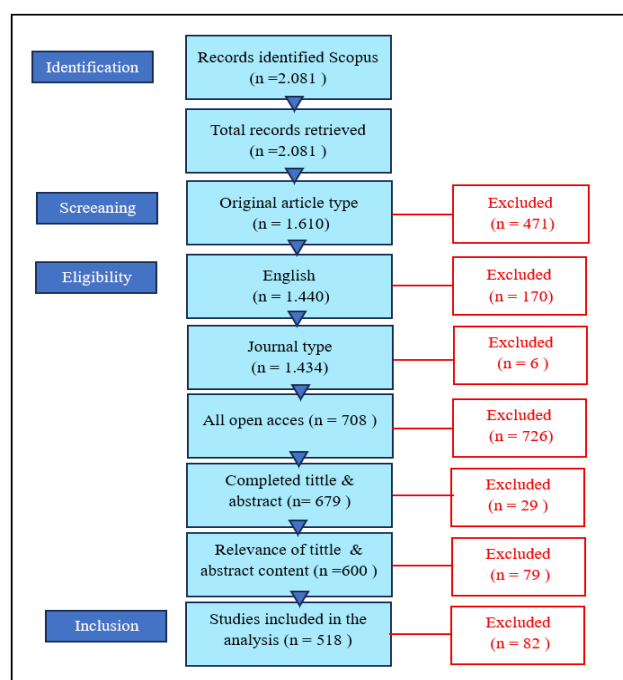
1. Identification in the Scopus database: The initial search was conducted using the specific keyword TITLE-ABS-KEY (("karate" AND ("kata" OR "kumite" OR "martial art*" OR "combat sport*"))), resulting in 2,081 records. This data was collected before screening.
2. Screening in the Scopus database: Screening was still conducted in the Scopus database. The stages included (1) determining the data type to be original research only, resulting in 1,610 records; (2) determining only English language records, resulting in 1,440 records; (3) determining only journal types, resulting in 1,434 records; and (4) determining only all open access records, resulting in 708 records.
3. Screening was performed using the Mendeley program and manually. The data were filtered using Scopus in the form of RIS and obtained 708. The

Table 1. Data collection strategy

No	Item	Description	Rationalization
1	Database source	Scopus	High credibility and a thorough review procedure
2	Query	TITLE-ABS-KEY (("karate" AND ("kata" OR "kumite" OR "martial art*" OR "combat sport*"))	Ensure that the documents selected specifically discuss karate, thereby minimizing ambiguity and irrelevant literature.
3	Language	Inggris	Discussing internationally to cover all topics
4	Publication year	2000-2025	Longer periods for more comprehensive data
5	Document type	Original article	To be more specific in looking for research patterns and trends in the original
6	Export data	RIS	To facilitate data visualization

data was then entered into Mendeley. At this stage, screening was used to ensure that the title and abstract data were complete, and 679 data points were obtained. The next stage was to assess the relevancy of the entire title and abstract material, which acquired 600 data.

4. Eligibility and Inclusion: During the final screening stage, the three experts had differing opinions. This was resolved by discussion and justification of the data assessment, yielding a final dataset of 518 documents. This data was then entered into the Biblioshny app. Figure 1 of the bibliometric PRISMA diagram illustrates this clearly (Song et al., 2025).

**Fig. 1.** Adaptation of PRISMA for Bibliometric studies

Data Validity

Three experts with doctoral degrees in karate examined the data's validity through discussion until consensus was obtained. The inter-rater reliability was calculated using Fleiss' Kappa. This statistical measure evaluates the consistency of expert agreement between more than two

raters. The analysis yielded a nearly perfect level of agreement, with a Fleiss Kappa value of 0.876. This is described in the following table.

Table 2. Inter-rater agreement analysis

	Value	Asymptotic Std. Error	Approximate T	Approximate Significance
Fleiss' Kappa	0.876	0.012	14.231	<0.001
N of Valid Cases	5.18			

Data Extraction and Visualization

Bibliography, author name, title, year, country affiliation, keywords, abstract, and number of citations are all included in the data from Scopus. Duplicate records were identified using Mendeley applications, and to improve metadata analysis, quantitative analysis and network patterns were compiled using Biblioshny applications (Akhiruyanto & Yudhistira, 2024).

Results

RQ1: Annual Scientific Production

Table 2 demonstrates that from 2000 to 2009, there is 0% stagnation, with 0 to 3 documents out of a total of 518. Between 2010 and 2025, there is a growth, albeit with fluctuations in some years. The biggest peak of 15% occurs in 2024. In that year, there was a significant rise in comparison

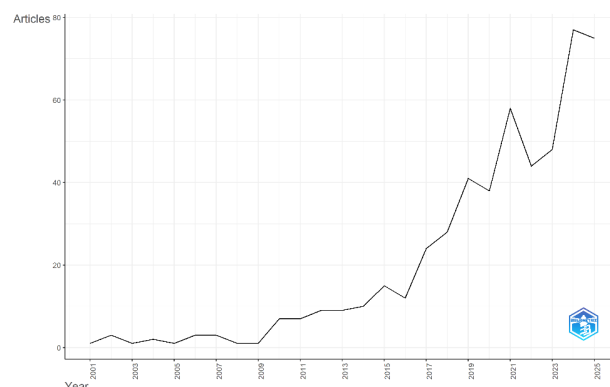
**Fig. 2.** Annual Scientific Production

Table 2. Annual Scientific Production

Year	Article	Total	Percentage
2000	0	518	0%
2001	1	518	0%
2002	3	518	1%
2003	1	518	0%
2004	2	518	0%
2005	1	518	0%
2006	3	518	1%
2007	3	518	1%
2008	1	518	0%
2009	1	518	0%
2010	7	518	1%
2011	7	518	1%
2012	9	518	2%
2013	9	518	2%
2014	10	518	2%
2015	15	518	3%
2016	12	518	2%
2017	24	518	5%
2018	28	518	5%
2019	41	518	8%
2020	38	518	7%
2021	58	518	11%
2022	44	518	8%
2023	48	518	9%
2024	77	518	15%
2025	75	518	14%

to prior and later years. Nonetheless, productivity growth is improving, although it has not yet reached its full potential. The figure below shows the illustration.

RQ2: Most Relevant Authors' Sources

Table 3. Most Relevant Authors Sources

Author	Articles	Articles Fractionalized
Cynarski W J	12	4.820634921
Franchini E	11	2.478968254
Tabben M	7	0.958333333
Augustovicova	6	1.333333333
Chaabène	6	0.847222222
Dopsaj M	6	1.25
Hachaj T	6	2.833333333
Koropanovski N	6	1.25
Marchenko S	6	2.416666667
Padulo J	6	0.971825397

Table 3 lists ten worldwide authors who have productively produced studies relating to research, such as Augustovicova (Augustovićová et al., 2021; D. Augustovicova et al., 2020, 2025; D. C. Augustovicova et al., 2025; Hadza et al., 2025; Horníková et al., 2025), Chaabène (Bouguezzi et al., 2024; Chaabène et al., 2012; El Ashker et al., 2022; Padulo et al., 2014; Tabben et al., 2013, 2014), Dopsaj (Jeknić et al., 2022,

2025; Marković et al., 2021; Mosler et al., 2025; Vuković et al., 2021, 2022), Hachaj (Hachaj, 2019; Hachaj et al., 2015, 2017; Hachaj, Koptyra, et al., 2018; Hachaj, Ogiela, et al., 2018; Hachaj & Ogiela, 2018), Koropanovski (Jeknić et al., 2025; Koropanovski et al., 2011; Vesković et al., 2019; Vuković et al., 2021, 2022, 2023), Marchenko (Marchenko, 2025; Marchenko et al., 2024; Marchenko, Ivashchenko, & Khudolii, 2023; Marchenko, Ivashchenko, & Kupreichenko, 2023; Marchenko, Khudolii, Ivashchenko, et al., 2023; Marchenko & Satdyiev, 2021), and Padulo (Alesi et al., 2014; Čular et al., 2018; Padulo et al., 2014; Vando et al., 2013, 2014, 2021) with a total of 6 original article documents. Tabben produced 7 original article documents (Padulo et al., 2014; Rezaei et al., 2019; Seyedi et al., 2024; Tabben et al., 2013, 2014, 2023), while Franchini had 11 original article documents (Herrera-Valenzuela et al., 2020; Julio & Franchini, 2021; Lassalvia et al., 2021; Loturco et al., 2014; Robalino et al., 2024; Robalino, e Silva Cabral, et al., 2025; Robalino, Vilas-Boas, et al., 2025; Schwartz et al., 2015, 2021; Tabben et al., 2013), and the highest peak was produced by Cynarski, namely 12 original article documents (Ambroży et al., 2021; Bajkowski & Cynarski, 2023, 2024; Branco et al., 2019; W J Cynarski, 2019; Wojciech J Cynarski & Johnson, 2023; Kistorz et al., 2022; Mercè et al., 2021; P. Piepiora et al., 2022; P. A. Piepiora et al., 2024; Radochoński et al., 2011). However, there is a significant difference between the top two authors and those listed behind them, and adjustments in collaboration patterns are needed to ensure equitable production. The image below shows the illustration.



Fig. 3. Most Relevant Authors Sources

RQ3: Thematic Mapping

Table 4. Thematic Mapping

Cluster	Callon Centrality	Callon Density	Rank Centrality	Rank Density	Cluster Frequency
Karate	19.59542	41.49307	4	3	1206
Martial Arts	20.73746	40.35369	5	2	995
Female	16.55227	53.5993	3	5	631
Exercise	10.82405	49.89444	2	4	316
Judo	9.957841	35.75218	1	1	176

According to Table 4, the mapping theme with the declining themes quadrant is judo. The niche theme is exercise, while the basic theme is martial arts, and the motor theme is karate. These themes are critically relevant and commonly used in karate research. The illustration is presented in the image below:



Fig. 4. Thematic mapping

RQ4: Co-occurrence Network

Table 5 highlights that the keyword network is divided into three clusters: Cluster 1, the most dominant core keyword network; Cluster 2, the most common supporting network in karate research; and Cluster 3, the least searched keyword network. This suggests that the research is dominated by biological and mechanical approaches that involve human participation. The figure below shows the illustration:

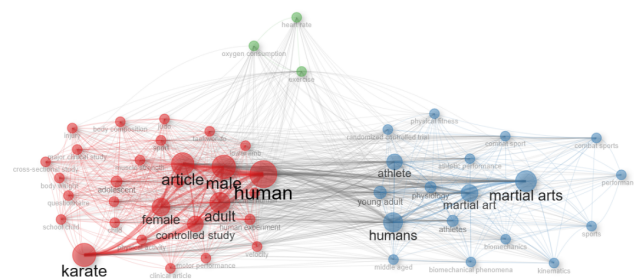


Fig. 5. Co-occurrence Network

RQ5: Research Topic Trends

Table 6 reveals that between 2014 and 2016, research trends focused on physiological aspects such as motor control, heart rate, lactic acid, muscle, and skeletal. In 2017, trends related to test algorithms. The trend in 2018-2020 is consistent with the previous year, with physiological factors

Table 5. Co-occurrence Network

Node	Cluster	Betweenness	Closeness	Page Rank
Karate	1	28.08918	0.020408	0.050172
Human	1	39.22787	0.020408	0.064668
Male	1	24.00946	0.020408	0.055326
Article	1	23.66789	0.020408	0.05274
Adult	1	16.92403	0.020408	0.046686
Female	1	13.17829	0.020408	0.040853
Controlled Study	1	10.53605	0.020408	0.035718
Adolescent	1	2.813236	0.019231	0.02242
Human Experiment	1	2.422064	0.019231	0.021016
Sport	1	2.17775	0.018519	0.019991
Training	1	1.833047	0.018868	0.016201
Physical Activity	1	0.81246	0.016949	0.014004
Child	1	1.171055	0.017544	0.015033
Major Clinical Study	1	0.400587	0.015873	0.0146
Body Mass	1	1.337988	0.018519	0.014655
Muscle Strength	1	0.779874	0.017544	0.01236
Questionnaire	1	0.250277	0.015385	0.013049
Judo	1	0.198654	0.015873	0.011702
Normal Human	1	0.93589	0.017857	0.013551
Clinical Article	1	0.261864	0.015385	0.011
Cross-Sectional Study	1	0.216158	0.015625	0.011109
Taekwondo	1	0.351505	0.016129	0.011195
Body Composition	1	0.123155	0.015625	0.009229
Motor Performance	1	0.120178	0.014493	0.009518
School Child	1	0.176243	0.015625	0.009854
Injury	1	0.040669	0.014706	0.007875
Velocity	1	0.153526	0.015152	0.008591

Table 5. Continued

Node	Cluster	Betweenness	Closeness	Page Rank
Body Weight	1	0.151948	0.015873	0.008046
Lower Limb	1	0.264284	0.016129	0.009037
Martial Arts	2	22.9387	0.020408	0.04601
Humans	2	18.51257	0.020408	0.04454
Martial Art	2	14.73395	0.020408	0.038027
Athlete	2	9.620737	0.020408	0.035416
Athletes	2	3.473289	0.02	0.022539
Young Adult	2	3.650371	0.019231	0.026324
Physiology	2	3.555143	0.019608	0.023147
Combat Sports	2	0.630953	0.015873	0.010217
Athletic Performance	2	1.91021	0.018182	0.01607
Combat Sport	2	0.797901	0.016949	0.009896
Sports	2	0.138165	0.013514	0.006489
Biomechanics	2	0.630083	0.015385	0.010694
Biomechanical Phenomena	2	0.297162	0.014706	0.009953
Kinematics	2	0.106279	0.013889	0.007281
Performance	2	0.014459	0.012658	0.005505
Physical Fitness	2	0.198396	0.015152	0.0079
Middle Aged	2	0.125044	0.014085	0.008731
Randomized Controlled Trial	2	0.06409	0.014706	0.009404
Exercise	3	1.817418	0.018182	0.016409
Heart Rate	3	0.008574	0.013514	0.006816
Oxygen Consumption	3	0.151331	0.014493	0.008431

Table 6. Research Topic Trends

Term	Frequency	Year (Q1)	Year (Median)	Year (Q3)
Heart Rate	14	2012	2014	2022
Motor Control	5	2013	2014	2019
Lactic Acid	6	2008	2015	2023
Priority Journal	5	2013	2015	2017
Muscle	11	2015	2016	2022
Skeletal	8	2013	2016	2023
Physiological	5	2009	2016	2020
Algorithms	7	2012	2017	2025
Oxygen Consumption	14	2010	2018	2020
Community Detection	10	2015	2018	2024
Adaptation	8	2014	2018	2022
Human Experiment	37	2018	2019	2023
Middle Aged	14	2014	2019	2023
Sport Injury	12	2009	2019	2021
Adolescent	44	2019	2020	2022
Physiology	43	2017	2020	2024
Sport	37	2010	2020	2022
Human	152	2018	2021	2024
Martial Arts	151	2018	2021	2024
Male	122	2019	2021	2024

Table 6. Continued

Term	Frequency	Year (Q1)	Year (Median)	Year (Q3)
Karate	192	2019	2022	2024
Young Adult	47	2019	2022	2024
Training	34	2020	2022	2024
Performance	16	2022	2023	2025
Wrestling	12	2021	2023	2025
Kata	11	2021	2023	2025
Athletic Performance	30	2020	2024	2025
Combat Sport	24	2020	2024	2025
Cross-Sectional Study	19	2021	2024	2025
Elite Athlete	6	2025	2025	2025
Elite Athletes	5	2022	2025	2025

such as oxygen consumption and physiological adaptability leading the way, followed by aspects of test algorithms such as community detection, with study participants focusing on adolescent males. The trend for 2021-2022 remains consistent with the previous year, with a concentration on experiments involving young athletes. In 2023-2025, the trend shifted toward cross-sectional studies and experimental performance improvement for elite athletes. In this context, research topic trends began to shift toward elite athlete participants looking to improve their physical and technical performance. The illustration is presented in the image below as follows. *RQ6: Thematic Evolution*

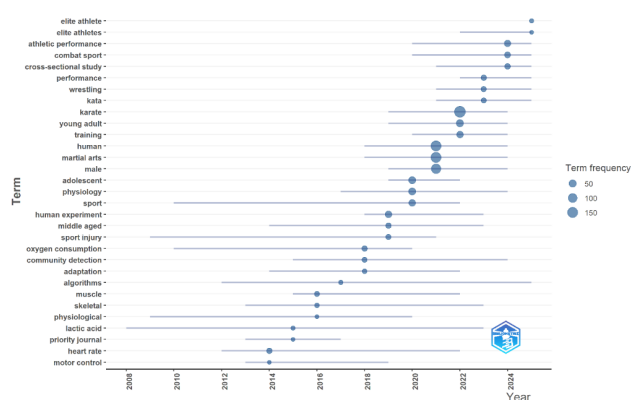


Fig. 6. Research Topic Trends

Table 7 demonstrates that many classic themes are shifting toward body mass and human experimentation, using advanced tests such as echography and electromyography, as well as algorithms. Biomechanical evolution, such as kinematics, acceleration, and dynamic time wrapping, demonstrates the integration of sport with science and technology. Karate study has evolved to include psychological aspects such as gender, stress, and aggression, in addition to muscle strength, balance, and agility. Diagnostic imaging, major clinical research, and randomized controlled trials are some examples of evolution in sports medicine. Physiological aspects, such as oxygen consumption, heart rate, and lactic acid, are evolving. Participants are no longer just adolescents, but also middle-aged, indicating not only competitive sports but also fitness. The figure below shows the illustration:

Table 7. Thematic Evolution

From	To	Words
Adolescent — 2001-2021	Adolescent — 2022-2025	Adolescent; Body Composition; Body Weight; Questionnaire; Athletic Injuries; Cross-Sectional Study; Injury; Body Fat; Body Height; Risk Factor; Incidence; Cross-Sectional Studies; Follow Up; Body Fat Percentage; Contusion
Adolescent — 2001-2021	Body Mass — 2022-2025	Judo; Body Mass; Taekwondo; Boxing; Social Network
Adolescent — 2001-2021	Human Experiment — 2022-2025	Sport; Echography; Diagnostic Imaging; Bone Density; Correlation Analysis
Adolescent — 2001-2021	Karate — 2022-2025	Training; Major Clinical Study; Child; School Child; Prospective Study; Basketball; Gymnastics; Linear Regression Analysis; Soccer
Adolescent — 2001-2021	Martial Arts — 2022-2025	Combat Sport
Athlete — 2001-2021	Body Mass — 2022-2025	Knee Function
Athlete — 2001-2021	Karate — 2022-2025	Clinical Article; Physical Activity; Case Report; Knee; Lower Limb; Cohort Analysis; Flexibility; Wellbeing
Athlete — 2001-2021	Martial Arts — 2022-2025	Athlete; Athletes; Biomechanical Phenomena; Biomechanics; Kinematics; Sports; Range Of Motion; Acceleration; Algorithms; Lower Extremity; Dynamic Time Warping
Community Detection — 2001-2021	Body Mass — 2022-2025	Community Detection; Complex Networks
Karate — 2001-2021	Adolescent — 2022-2025	Aggression
Karate — 2001-2021	Body Mass — 2022-2025	Normal Human; Wrestling
Karate — 2001-2021	Human Experiment — 2022-2025	Human Experiment; Gender; Stress
Karate — 2001-2021	Karate — 2022-2025	Karate; Human; Male; Article; Adult; Female; Controlled Study; Motor Performance; Muscle Strength; Velocity; Aged; Body Equilibrium; Coordination; Kata; Competition; Agility; Balance; Children
Karate — 2001-2021	Martial Arts — 2022-2025	Combat Sports; Randomized Controlled Trial; Muscle; Skeletal; Electromyography; Reaction Time; Kumite; Reliability
Martial Arts — 2001-2021	Adolescent — 2022-2025	Middle Aged; Fitness; Anthropometry; Endurance; Karate Athletes; Surveys And Questionnaires
Martial Arts — 2001-2021	Body Mass — 2022-2025	Exercise; Oxygen Consumption; Heart Rate; Exercise Test; Blood; Comparative Study; Lactic Acid
Martial Arts — 2001-2021	Human Experiment — 2022-2025	Psychology; Age
Martial Arts — 2001-2021	Karate — 2022-2025	Analysis of Variance; Adaptation; Perception; Strength
Martial arts — 2001-2021	Martial arts — 2022-2025	Martial arts; Humans; Martial art; Physiology; Young adult ; Athletic performance; Procedures; Physical fitness; Performance; Skeletal muscle; Choice reaction time

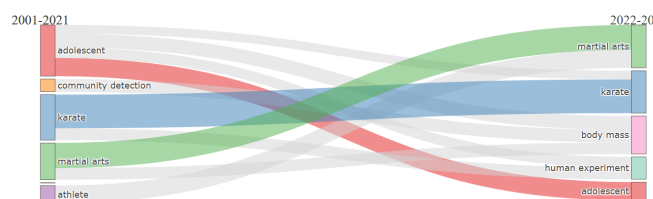


Fig. 7. Thematic Evolution

RQ7: Factorial Analysis

Table 8 shows that subject-centeredness, such as human, young adult, and middle-aged, has the greatest score, showing that karate research is always conducted with humans. Experimental rigor is defined by phrases such as randomized controlled trial, significant clinical study, controlled study, and cross-sectional study, which emphasize methodologically structured empirical research. Biomechanical studies are the subject of precise analysis, utilizing terms such as biomechanical phenomena, procedures, and kinematics. On the other hand, terms such as child, large clinical study, injury, and questionnaire imply that karate research involves children and employs observational methods rather than complex biomechanical analysis. Furthermore, the term “karate” refers to basic research that must be investigated in clinical and performance studies, whereas “martial arts” refers to a broader range of subjects, including physiological and performance research. The figure below shows the illustration:

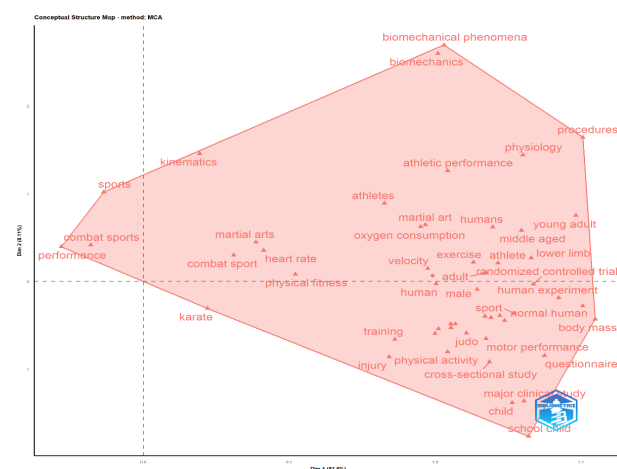


Fig. 8. Factorial Analysis

Discussion

The rapidly growing number of karate articles is now dispersed and not integrated into a single analysis, making it difficult to predict the direction of future research developments. This bibliometric analysis gives a summary of the global karate research trends and gaps. These findings are expected to provide strategic guidance for developing more innovative future research that addresses practical demands in the field.

RQ1: Annual Scientific Production

- Stagnation: The period from 2000 to 2009 was one of stagnation. Karate research had a low production, with only 0-3 publications published each year, accounting for

Table 8. Factorial Analysis

Word	Dim1	Dim2	Cluster
Karate	0.22	-0.31	1
Human	1	-0.03	1
Martial Arts	0.39	0.45	1
Male	1.14	-0.09	1
Article	1.05	-0.48	1
Adult	1.17	0.1	1
Humans	1.2	0.62	1
Martial Art	0.97	0.65	1
Female	1.24	-0.45	1
Controlled Study	1.19	-0.41	1
Athlete	1.22	0.21	1
Athletes	0.83	0.89	1
Young Adult	1.48	0.75	1
Adolescent	1.22	-0.39	1
Physiology	1.3	1.44	1
Combat Sports	-0.18	0.42	1
Human Experiment	1.42	-0.19	1
Sport	1.27	-0.36	1
Training	0.86	-0.66	1
Exercise	1.13	0.22	1
Athletic Performance	1.04	1.26	1
Physical Activity	1.04	-0.8	1
Child	1.26	-1.38	1
Major Clinical Study	1.3	-1.36	1
Combat Sport	0.31	0.3	1
Body Mass	1.55	-0.43	1
Muscle Strength	1.05	-0.53	1
Questionnaire	1.37	-0.84	1
Judo	1.11	-0.59	1
Normal Human	1.51	-0.28	1
Clinical Article	1.07	-0.48	1
Cross-Sectional Study	1.19	-0.92	1
Taekwondo	1.17	-0.4	1
Sports	-0.14	1.02	1
Biomechanics	1.01	2.6	1
Biomechanical Phenomena	1.03	2.69	1
Body Composition	1	-0.59	1
Kinematics	0.19	1.46	1
Motor Performance	1.17	-0.65	1
Performance	-0.28	0.4	1
Physical Fitness	0.52	0.08	1
School Child	1.32	-1.76	1
Heart Rate	0.41	0.35	1
Injury	0.84	-0.86	1
Middle Aged	1.3	0.58	1
Oxygen Consumption	0.95	0.62	1
Randomized Controlled Trial	1.34	-0.03	1
Velocity	0.97	0.15	1
Body Weight	1.01	-0.54	1
Lower Limb	1.33	0.27	1
Procedures	1.51	1.64	1

0% of the total. This suggests that karate has not yet gained prominence on the global sports science research agenda.

- Initial growth: The period 2010-2018 was an early stage, with stable but varying productivity gains. This

increase was most likely driven by the growing academic presence and professionalization of karate as a competitive sport, which necessitated the development of a scientific database to support training methods.

- **Acceleration:** The acceleration phase experienced the greatest expansion of 15% in 2024. This increase illustrates that karate is a dynamic and intriguing subject for global academics, as sports science advances in technology.

- **Critical analysis:** Although the curve shows a large improvement in publication production, there are still issues, such as stability. Given that karate is a driving (very significant) theme in thematic mapping, the 15% growth rate should be boosted even further through increased research collaboration.

- **Academic implications:** This growing pattern suggests that karate research is transitioning away from an emphasis on understanding traditional values. This illustrates the importance of conducting robust, empirically supported research to meet the challenges associated with modern performance and training methods.

RQ2: Most Relevant Authors' Sources

- **Expertise Dominance:** The most productive researchers are Cynarski WJ (12 articles) and Franchini E (11 articles). These two researchers are the mainstays of karate research. This dominance demonstrates that karate research globally continues to rely on a small group of academics who are dedicated to research over the long term. However, the largest number of publications (11-12) is still quite small during 25 years (2000-2025), indicating that the publishing rate per individual remains relatively slow for a motor theme study.

- **Quantity and Impact Gap:** Researchers including Tabben, Augustovicova, Chaabene, Dopsaj, Hachaj, Koropanovski, Marchenko, and Padulo each contributed 6-7 publications. This suggests a fragmentation of expertise, implying that karate research is conducted sporadically by a large number of academics around the world, but there is no central publication hub. This low productivity shows that karate research is frequently integrated within a broader study of martial arts or combat sports, rather than being the author's academic career.

- **The Need for Academic Regeneration:** According to research, there is a greater need for inclusive collaboration. Without a new generation of researchers capable of outperforming existing authors' publications, the field of karate research risks becoming stagnant in terms of productivity and methodological depth. Furthermore, the gap in the number of publications by prominent authors vs other authors emphasizes the need for improved mentorship to accelerate the development of scientific findings in karate research. One aspect of increasing the productivity of quality research is international collaboration (Wahid et al., 2021). Research productivity is an important indicator for evaluating a researcher's performance (J. Fischer et al., 2012).

RQ3: Thematic Mapping

- **Upper Right Quadrant (karate as a driving theme):** Karate's position as a driving theme is both mature and relevant in sports science studies. Karate research has attained rigorous criteria that serve as a fundamental

impetus for future research in the context of academic and applied scientific development.

- **Lower Right Quadrant (martial arts as a basic theme):** Martial arts as a basic theme indicates that while this issue has a large base, it has not been completely explored in the context of modern karate.

- **Upper Left Quadrant (exercise as a niche theme):** Exercise is a niche theme, which means that research on training, specifically in terms of enhancing physical performance and body composition, is developing and focusing on certain issues. This theme has a high level of specialized demand, but its relevance is less than that of the quadrant's motor themes.

- **Lower Left Quadrant (Judo as a declining theme):** The keyword "judo" is on the decline, indicating that research comparing karate and judo is becoming less common. This is a strong indication for researchers to abandon the comparative approach to martial arts and instead investigate variables more relevant to current research trends.

RQ4: Co-occurrence Network

- **Research Fragmentation:** The keyword network is organized into three main clusters, which highlight the importance of mechanical and biological approaches in karate research. Cluster 1 of this network contains basic factors such as human, male, and adult, confirming that karate research focuses on adult human participants who are primarily male. Cluster 2 is a common supporting network that includes athletic performance, biomechanics, kinematics, and physiology. Cluster 3 contains previously unexplored keywords such as heart rate and oxygen consumption, indicating a new direction in karate-related fitness research.

- **Centralization and Interrelationships of Variables:** In cluster 1, the keyword "human" has the highest betweenness value of 39.22 and a page rank of 0.064, making it the principal information bridge in karate research. Cluster 2, "martial arts," has the highest betweenness value (22.93), indicating a causal association between martial arts disciplines and athletic and biomechanical performance analysis.

- **Methodological Implications:** The dominance of mechanics and biology suggests that the research focus is on physical performance. The presence of variables such as randomized controlled trials in cluster 2 and controlled studies in cluster 1 supports the finding that karate research focuses on improving tougher standards. Furthermore, networks such as injury topics in cluster 1 have a weaker relationship than physical performance variables, indicating that more research into injury prevention is needed.

RQ5: Research Topic Trends

- **Initial Phase:** Between 2009 and 2016, research trends focused on basic physiology, such as heart rate, muscle, skeletal, and lactic acid. This research aimed to further analyze karate athletes' profiles using standard physiology.

- **Transition Phase:** Between 2017 and 2020, algorithmic research and community detection emerged, indicating the introduction of computational technology into karate research. This study began to extensively involve adolescent and young adult participants to focus on early talent development.

- **Current Phase:** Between 2021 and 2025, the focus switched toward elite athletes and athletic performance. Cross-sectional methodologies became increasingly common, providing for more robust and reliable empirical evidence. Combat and performance-related topics gained prominence in 2025, emphasizing the need to generate data that can be applied in actual, international competitive contexts.

- **Trend Analysis:** The focus shifts from basic physiological analysis to elite athlete athletic performance, which reflects the final competitive outcome. However, there is a discrepancy between general topics (192 frequency) and specialized topics connected to elite athletes (6 frequency), implying that karate research with elite athlete participants remains limited.

RQ6: Thematic Evolution

- **Transformation from tradition to technocracy:** From 2000 to 2010, karate research focused on descriptive and traditional concepts. This focus exemplified the academic community's early efforts to establish karate as a viable discipline. From 2011 to 2025, there is a shift toward technical issues, with the introduction of themes such as kinematics, diagnostic imaging, and electromyography, proving that karate research adhered to sports medicine standards and advanced biomechanics.

- **Population Diversity:** The evolution of research participants has expanded. While competitive athletes were once dominant, themes that focus on mental health, such as stress and aggression, have recently developed. This suggests that karate research is not only concerned with fitness and physical performance but also with mental health, indicating that karate research is becoming more socially relevant.

- **Methodological Evolution:** Research is no longer conducted separately on topics such as physiology and digital technology, but rather within a research framework. This evolutionary pattern is based on methodological convergence, which involves merging physical and empirical sensory data with in-depth psychological analyses.

RQ7: Factorial Analysis

- **Participant Centrality:** Humans are crucial to research participants since all studies rely on human participants for identification, which includes both soft sciences such as social and psychological aspects as well as hard sciences such as biomechanics and physical components. Categories such as young adult and middle age imply that research is not confined to elite athletes but also includes broader health and fitness aspects.

- **Methodological Quality:** The emergence of methodologies such as randomized controlled trials and controlled studies demonstrates that research data is very reliable. The adoption of these methodologies represents a move from observational to rigorous experimental research.

- **Thematic Cluster Segmentation:** The analysis suggests a sharp fragmentation, with research with children frequently isolated from complex biomechanical studies. This issue highlights the necessity for research that combines age-related developmental approaches with biomechanical factors to better understand the efficiency and efficacy of technical movements in karate.

- **Academic Implications:** Physically oriented and study design aspects demonstrate the importance of balancing methodologies with applicable research aims. Furthermore, the intricacy of research necessitates greater caution in selecting proper instruments and statistics to ensure scientific integrity.

Conclusions

The conclusions of this bibliometric investigation are described as follows. First, karate research has progressed from a stagnant period between 2000 and 2009 to a peak in 2024, suggesting that karate is a dynamic sports science discipline. There has been a methodical shift from basic physiological profiling research toward biomechanical and computational technology, as well as the adoption of rigorous procedures like randomized controlled trials. Second, the organization of research expertise is still controlled by two researchers, resulting in a productivity gap with collaborative demands and requiring academic regeneration to increase productivity and impact globally. Third, the keyword "karate" as a driving motif symbolizes stability, not in isolation from physical characteristics, but in the process of integrating sensory data and mental health into psychological aspects. Fourth, consider the challenges and future research. Publication productivity must be increased by multi-collaboration to avoid topic saturation and relevance to current needs. To understand the efficacy of karate techniques, age development (e.g., children and adolescents) must be integrated using biomechanical parameters. Although a recent study has focused on elite athletes, the proportion at the elite level remains low (6 articles) compared to general karate research (192 articles), indicating the need to expand elite athlete participation.

Ethical Considerations

This research uses secondary data, so it does not require ethical clearance.

Data Availability Statement

The research data are available to the corresponding author upon reasonable request. The research data were obtained from Scopus in RIS format, selected from 29-30 June 2026.

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AI Transparency Statement

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Conflicts of Interest

All authors declare no conflict of interest.

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Картування тенденцій і прогалин у дослідженнях карате: бібліометричний аналіз на основі бази даних Scopus за 2000–2025 роки

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

Реферат. Стаття: 16 с., 8 табл., 8 рис., 87 джерел.

Передумови. Карате стрімко розвивається як глобальна спортивна дисципліна, що зумовлює потребу в наукових даних для ефективної оптимізації майбутніх досліджень. Однак картування тенденцій досліджень карате досі не забезпечило достатнього обсягу даних. Це впливає на розуміння та розвиток спортивної науки.

Мета. Метою цього дослідження було картування досліджень карате за допомогою бібліометричного аналізу публікацій за 2000–2025 роки, індексованих у базі даних Scopus.

Матеріали та методи. Дані збирали за допомогою визначених ключових слів. Остаточний набір даних складався з 518 документів у форматі RIS. Для відбору та аналізу використовували PRISMA, Mendeley і візуалізацію Biblioshiny.

Результати. (1) Річна наукова продуктивність: у 2000–2009 роках спостерігалася стагнація, а найбільше зростання — 15% — зафіксовано у 2024 році; (2) Найбільш релевантні автори: дослідницька активність була зосереджена лише у двох авторів (11–12 документів); (3) Тематичне картування: карате стало основним напрямом досліджень (motor themes), тоді як порівняльні дослідження різних бойових мистецтв почали втрачати актуальність (declining themes), а дослідження почали зміщуватися до перспективніших тем; (4) Мережа спільної зустрічальності: у дослідницькій мережі домінують біологічний і біомеханічний підходи, а основним об'єктом дослідження є люди; (5) Тренди тематики: відбувся перехід від фундаментальної фізіологічної спрямованості до вивчення максимальної спортивної результативності та більш специфічних аспектів; (6) Тематична еволюція: використання в дизайні досліджень таких технологій, як електроміографія, ехографія та алгоритми; (7) Факторний аналіз: методологічний розвиток від спостережних досліджень до рандомізованих контрольованих випробувань.

Висновок. Дослідження карате зосереджені на спортсменах високої кваліфікації та емпіричних дослідженнях, однак для підвищення кількості та якості майбутніх досліджень необхідні ширша співпраця дослідників та інтеграція різних наукових дисциплін.

Ключові слова: карате, бойові мистецтва, бібліометричний аналіз, тенденції та прогалини, спортивні єдиноборства, картування дослідницьких тенденцій.

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Review Article

Movement-Based Interventions and Motor Competence in Physical Education and Paediatric Exercise Contexts: A Narrative Synthesis of Experimental Evidence

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Abstract

Objectives. Movement competence is fundamental to physical education, physical literacy, and sustained participation in physical activity. This critical narrative synthesis examined contemporary experimental and intervention-based evidence on movement-based interventions in children and adolescents, focusing on the direction, consistency, specificity, transferability, and methodological limitations of reported effects.

Materials and Methods. A structured narrative review was used to identify and critically integrate literature published from 2018 onward. Study selection considered population, design, intervention or experimental focus, comparator, outcome domain, context, language, and relevance to the review question. Eighteen studies formed the core evidence base: 16 intervention or comparative studies and two structured experimental assessment studies addressing strength-effort regulation as a component of motor control. Evidence was synthesized thematically, with attention to methodological strengths, limitations, inconsistencies, and transfer effects.

Results. Structured physical education and motor-competence programmes generally improved directly targeted gross motor and fundamental movement skills. Structured play, balance-bike training, physical activity programmes, and sport-based activities improved selected motor and fitness outcomes, but these gains did not consistently transfer to broader motor competence. Coordinative interventions improved several balance, jumping, and coordination outcomes, whereas effects on inhibitory control and other cognitive outcomes were inconsistent. Resistance training improved selected muscular fitness and performance outcomes, therapeutic exercise improved specific fundamental movement skills in a paediatric clinical population, and the FIFA 11+ Kids programme reduced overall injury incidence by 57% (IRR = 0.43, 95% CI: 0.29–0.61). Strength-effort studies also suggested that force-regulation accuracy may vary with the relative effort reproduced.

Conclusions. Contemporary evidence supports structured and developmentally appropriate movement experiences for improving motor competence and selected related outcomes in children and adolescents. However, benefits are often domain-specific, and improvements in directly practised abilities should not automatically be interpreted as transfer to generalised motor competence, physical activity, or cognitive functioning. Intervention structure, task specificity, progression, participant characteristics, and assessment methods appear to influence observed effects. Future studies should distinguish direct training effects from broader developmental transfer.

Keywords: motor competence, physical education, movement-based intervention, paediatric exercise, fundamental movement skills, physical literacy, narrative review, motor development.

Introduction

Movement competence is increasingly recognized as a central foundation of physical education, paediatric exercise, and lifelong physical activity participation. It includes fundamental movement and motor skills such as locomotor skills, object-control skills, balance, coordination, body management, effort regulation, and the capacity to adapt movement to changing task and environmental demands. Developmental models of motor competence suggest that children progress through increasingly complex movement stages, shaped by growth, maturation, instruction, practice opportunities, and environmental exposure (Goodway et al., 2019; Malina et al., 2004). From this perspective, motor competence is not merely a physical outcome but an essential developmental capacity linked with physical literacy, self-confidence, participation, and long-term engagement in health-enhancing physical activity (Lubans et al., 2010; Piotrowski et al., 2025; Stodden et al., 2008).

The preschool and school years represent sensitive periods for developing movement competence because neuromuscular, perceptual, cognitive, and psychosocial systems undergo rapid development during this phase. Earlier evidence has shown that fundamental movement skills are associated with habitual physical activity in young children and may influence later activity behaviour and weight-related outcomes (Fisher et al., 2005; Williams et al., 2008). Motor-skill intervention evidence further suggests that children's movement competence can improve when programmes are structured, developmentally appropriate, and task-focused (Logan et al., 2012). Recent experimental studies support this position, showing that brief physical education interventions, specialist-led motor competence programmes, and structured early-childhood activities can improve gross motor skills, balance, manual dexterity, aiming and catching, object movement, and broader fundamental movement skills (Mulvey et al., 2018; Navarro-Patón et al., 2024; Palmer et al., 2019; Strotmeyer et al., 2021).

Movement-based interventions have also expanded beyond traditional physical education lessons into structured play, playground design, family-based activity, technology-supported activity, balance-bike training, and comparative physical activity curricula. Evidence from partly structured playground activity, painted playgrounds, mHealth-supported motor skill programmes, family-based physical activity, and balance-bike or structured physical activity courses suggests that children may benefit most when movement experiences combine enjoyment, repetition, progression, feedback, and varied motor challenges (Kojić et al., 2024; Navarro-Patón et al., 2024; Ren et al., 2025; Staiano et al., 2022; Tortella et al., 2022). Such findings indicate that free play alone may not always be sufficient; rather, guided and contextually meaningful activity may be needed to support transferable motor development.

Recent evidence also highlights the cognitive-motor value of coordinative and cognitively enriched physical activity. Programmes involving coordination, balance, decision-making, inhibition, perceptual discrimination, and attention may contribute not only to physical fitness and motor competence but also to selected executive and attentional outcomes (Başarır et al., 2025; Şendil et al., 2024). This is important because movement learning requires

the integration of perception, action, attention, and self-regulation. Similarly, strength-effort assessment studies among school-aged children and pre-adolescent girls show that effort reproduction and force regulation are meaningful components of motor control, particularly when children are required to grade muscular effort across different thresholds (Choudhary et al., 2024; Ivashchenko et al., 2019).

Movement competence is also highly relevant for children with developmental coordination disorder, low motor competence, overweight or obesity, and clinical paediatric conditions. Developmental coordination disorder is associated with impaired functional performance, reduced participation, mental health difficulties, physical inactivity, and possible weight-related concerns (Wilson et al., 2013; J. Yu et al., 2016). Accordingly, therapeutic exercise, injury-prevention programmes, resistance training, Zumba, and collaborative or game-based pedagogies provide broader evidence that structured movement can support fitness, rehabilitation, physiological response, injury reduction, and movement learning across paediatric, adolescent, and educational exercise contexts (Al Attar et al., 2023; P. K. Choudhary & Dubey, 2024; S. Choudhary & Choudhary, 2025; Joschtel et al., 2022; Kumar et al., 2025; Saha et al., 2026).

Therefore, the purpose of this critical narrative synthesis was to examine contemporary experimental and intervention-based evidence concerning movement-based approaches and motor competence in physical education and paediatric exercise contexts. Rather than determining a pooled intervention effect, the review sought to critically compare how structured physical education, guided play, coordinative exercise, resistance training, injury-prevention programmes, therapeutic exercise, sport-based activity, and complementary experimental motor-control evidence contribute to understanding motor development in children and adolescents. Particular attention was given to the consistency of findings across studies, the extent to which improvements were specific to directly trained outcomes or transferred to broader domains, the methodological limitations of the available evidence, and the implications of these patterns for physical education and future research.

Materials and Methods

The present study was designed as a structured critical narrative review rather than a systematic review or meta-analysis. The purpose of the review was to identify, organize, compare, and interpret contemporary experimental evidence relevant to movement-based interventions and motor competence across physical education and paediatric exercise contexts. A structured search and explicit selection framework were used to improve transparency; however, these procedures were intended to support the rigor of the narrative synthesis rather than to claim exhaustive identification of all eligible literature. Accordingly, the review was not conducted according to PRISMA reporting requirements, did not seek to generate a pooled treatment estimate, and should not be interpreted as a systematic review.

Search Strategy

Relevant literature published from 2018 onward was identified through a structured and iterative search of

Table 1. Selection framework for studies included in the core narrative synthesis

Criterion	Included in the core synthesis	Excluded from the core synthesis
Publication period	Studies published from 2018 onward, thereby emphasizing contemporary experimental and intervention-related evidence.	Studies published before 2018 were not included in the core evidence table, although selected foundational literature could be used for theoretical or contextual discussion.
Study type	Randomized controlled trials, cluster-randomized trials, pilot randomized trials, quasi-experimental studies, controlled pre-post studies, pragmatic comparative trials, and structured experimental assessment studies with direct relevance to motor control or movement competence.	Systematic reviews, meta-analyses, scoping reviews, narrative reviews, conceptual papers, editorials, commentaries, protocols, validation studies, and general observational or correlational studies without intervention or relevant structured experimental assessment.
Population	Preschool children, school-aged children, adolescents, child athletes, physically active youth, or paediatric clinical populations when outcomes were directly relevant to movement competence, motor skills, physical fitness, exercise response, or physical education.	Adult or university populations and populations without a clear relationship to paediatric exercise, physical education, motor development, child sport, rehabilitation, or movement competence.
Intervention or experimental focus	Structured physical education, movement-based programmes, motor-competence training, structured physical activity, coordination training, guided play, balance-bike activity, resistance training, therapeutic exercise, injury-prevention programmes, sport-based activity, neuromuscular training, or structured experimental assessment directly examining motor-control processes such as strength-effort regulation.	Studies without a relevant intervention, experimental movement condition, structured assessment protocol, or direct contribution to the movement-competence question.
Comparator or experimental contrast	Control groups, usual physical education, free play, wait-list conditions, standard warm-up, regular school activity, active comparator groups, pre-post comparisons, or structured within-participant/age-group experimental comparisons.	Studies without a meaningful intervention, comparison, pre-post, or experimental contrast relevant to interpretation of the review question.
Outcome domains	Motor competence, fundamental movement skills, gross motor development, locomotor and object-control skills, balance, coordination, agility, force or effort regulation, muscular fitness, aerobic fitness, executive or cognitive-motor outcomes, physical activity, exercise capacity, and movement-related injury outcomes.	Outcomes without a meaningful relationship to motor competence, physical education, paediatric exercise, physical fitness, movement development, cognitive-motor control, or movement-related injury.
Context	Preschool, kindergarten, school physical education, youth sport, playground, after-school exercise, structured training, paediatric rehabilitation, and related child or adolescent exercise settings.	Contexts without a substantive movement, physical education, exercise, sport, rehabilitation, or motor-development component.
Language and accessibility	English-language publications with sufficient bibliographic and methodological information to permit interpretation of the design, participants, procedures, and principal outcomes.	Sources with insufficient methodological information, unclear publication details, non-traceable sources, or insufficient information for meaningful interpretation.
Role in synthesis	Studies meeting the above criteria and directly contributing experimental evidence were retained in the core characteristics table and narrative synthesis.	Conceptually relevant but non-core sources were used only to provide theoretical, historical, diagnostic, or interpretive context in the Introduction or Discussion.

academic databases, scholarly search platforms, publisher databases, and reference lists. Sources used during literature identification included PubMed, Google Scholar, ScienceDirect, Taylor & Francis Online, SpringerLink, MDPI, ResearchGate, and journal-specific sources relevant to physical education, sport pedagogy, motor development, rehabilitation, developmental psychology, and exercise science. Publisher and scholarly-network platforms were used to locate potentially relevant articles and bibliographic

information; decisions concerning inclusion in the core synthesis were based on the characteristics and content of the original scholarly publications.

Searches combined terms representing movement competence, motor development, physical education, children and adolescents, intervention or experimental activity, coordination, and related outcomes. Representative combinations included “physical education” AND “motor competence”; “physical education” AND “motor

coordination"; "fundamental movement skills" AND "children"; "motor development" AND "children" AND "school"; "developmental coordination disorder" AND "motor competence"; "movement-based intervention" AND "physical education"; "coordination" AND "children" AND "exercise"; "structured physical activity" AND "motor competence"; "strength effort" AND "children"; and "motor control" AND "youth." Conceptually related terms such as "movement competence," "gross motor skills," "coordination," "balance," "motor ability," "physical fitness," "executive function," "physical activity," "paediatric exercise," and "injury prevention" were also used where relevant. Reference lists of relevant articles, reviews, and book chapters were examined to identify additional studies directly aligned with the purpose of the narrative synthesis.

The search strategy was deliberately broader than would be expected for a narrowly defined intervention meta-analysis because the objective of the review was to integrate evidence across physical education, motor development, fitness, cognitive-motor, preventive, and paediatric exercise contexts. Nevertheless, only studies meeting the explicit selection framework presented in Table 1 were retained as core evidence for the narrative synthesis.

Source Selection

Potentially relevant sources identified during the literature search were examined according to title, abstract, keywords, study design, population, intervention or experimental condition, outcome domain, and full-text relevance where available. Sources were then classified according to their role in the manuscript. Studies satisfying the selection framework in Table 1 and contributing directly to the principal review domains were retained as the core evidence base. Publications that were useful primarily for theoretical background, diagnostic context, previous review evidence, or conceptual interpretation were not included in the main characteristics table and were used only in the Introduction or Discussion.

This process resulted in a core evidence set of 18 studies. Sixteen studies evaluated an intervention, programme, or comparative movement condition, including physical education-based motor-competence programmes, structured physical activity, guided play, coordinative exercise, balance-bike training, resistance training, therapeutic exercise, sport-based activity, and injury-prevention programming. Two additional studies (Ivashchenko et al., 2019; Choudhary et al., 2024) did not evaluate training effects but were retained as complementary structured experimental assessment studies because they directly examined the regulation and reproduction of muscular effort, a motor-control process relevant to the broader interpretation of movement competence. These two studies were therefore interpreted separately from intervention-effect evidence and were not used to support claims concerning intervention effectiveness. The number of studies included in the core synthesis should consequently be understood as the set of studies retained through the structured narrative selection framework rather than as an exhaustive estimate of every eligible publication in the international literature. Because the study was conceived as a narrative review, a PRISMA-style numerical screening flow was neither generated nor retrospectively reconstructed.

Critical Appraisal of the Evidence

Because this manuscript was designed as a narrative rather than systematic review, a formal systematic risk-of-bias instrument was not used to generate study-level risk-of-bias judgments or an overall quantitative quality score. Nevertheless, methodological quality was explicitly considered during interpretation of the evidence. Each core study was examined in relation to study design, sample size, presence and nature of a comparator, randomized or non-randomized allocation where reported, duration of intervention or observation, baseline comparability where relevant, outcome measurement, follow-up, and the extent to which the design supported causal interpretation. Randomized and cluster-randomised studies were considered to provide stronger evidence for intervention effects than uncontrolled or non-randomized comparisons, whereas pilot studies, small samples, convenience sampling, intact-group allocation, baseline inequalities, lack of longer-term follow-up, and absence of an appropriate control condition were treated as factors requiring more cautious interpretation. For structured experimental assessment studies without an intervention, conclusions were restricted to the motor-control phenomenon directly assessed and were not interpreted as evidence of training effectiveness. The purpose of this appraisal was not to rank studies numerically but to prevent findings from methodologically different designs from being treated as equivalent. Methodological strengths and limitations were therefore integrated directly into the narrative synthesis and Discussion when evaluating consistency, causal interpretation, generalizability, and transfer of effects.

Narrative Synthesis Procedure

The evidence was synthesized through an iterative thematic and comparative narrative process. First, the 18 core studies were classified according to study design, population, movement or intervention characteristics, comparator, outcome domain, and direction of findings. Second, studies were organized into six evidence domains: (1) physical education-based motor-competence interventions; (2) structured play and gross-motor-development programmes; (3) coordinative exercise and cognitive-motor outcomes; (4) physical fitness and resistance-training interventions; (5) injury-prevention and paediatric rehabilitation contexts; and (6) complementary experimental evidence concerning strength-effort regulation.

Third, findings were compared within and across domains to identify convergence, inconsistency, and outcome specificity. Particular attention was given to whether an intervention improved only the directly practised outcome or whether evidence suggested transfer to broader motor, cognitive, physical-activity, or health-related outcomes. Fourth, differences in study design, intervention duration, frequency, comparator condition, participant characteristics, and assessment method were considered as possible explanations for divergent findings. No pooled effect estimate was calculated because the evidence was heterogeneous in population, study design, intervention content, duration, comparator, and measurement approach. The final synthesis therefore emphasized cross-study

patterns, methodological interpretation, evidence of task specificity and transfer, unresolved inconsistencies, and implications for future physical education and paediatric exercise research.

Results

The core narrative synthesis comprised 18 studies that satisfied the structured selection framework described in Table 1. Sixteen studies evaluated structured interventions or comparative movement programmes, whereas two studies (Ivashchenko et al., 2019; Choudhary et al., 2024) used structured experimental assessment procedures to examine strength-effort regulation without implementing a training intervention. The latter were retained as complementary motor-control evidence and were interpreted separately from studies evaluating intervention effectiveness.

The intervention studies involved preschool children, school-aged children, adolescents, youth athletes, and a paediatric clinical population and included randomized controlled trials, cluster-randomized trials, pilot randomized trials, quasi-experimental studies, controlled repeated-measures studies, and pragmatic comparative designs. Intervention formats included physical education-based motor-competence programmes, structured movement activity, guided play, motor-skill programmes, balance-bike training, coordinative exercise, resistance training, therapeutic exercise, sport-based activity, and neuromuscular injury-prevention programmes. Table 2 summarizes the study designs, participants, intervention or experimental conditions, comparator conditions, principal quantitative findings, and direction of effects.

Critical Narrative Synthesis of Findings

The evidence was generally favourable toward structured movement-based programming, but the findings were neither uniform nor equally transferable across outcome domains. A central pattern was that the strongest effects tended to occur in abilities that were directly targeted by the intervention. Structured physical education and motor-skill programmes produced comparatively consistent improvements in motor competence and fundamental movement skills, whereas evidence for broader transfer to physical activity or cognitive outcomes was more variable. This distinction is important because improvement in a trained skill cannot automatically be interpreted as generalized improvement in motor development.

Physical education-based interventions provided some of the clearest evidence that intentionally structured instruction can improve motor competence. Mulvey et al. (2018), Palmer et al. (2019), Strotmeyer et al. (2021), and the studies by Navarro-Patón and colleagues generally demonstrated favourable changes following structured or specialist-led movement programmes. Nevertheless, the effects were domain-specific. Strotmeyer et al. (2021), for example, demonstrated an intervention advantage for object movement but not self-movement, whereas Palmer et al. (2019) reported substantial motor-skill gains without evidence that these gains translated into greater physical activity during subsequent outdoor free play. The evidence

therefore supports structured instruction more strongly for skill acquisition than for generalized behavioural transfer.

Structured play and gross-motor-development programmes showed a similar pattern. Kojić et al. (2024), Mačák et al. (2022), Navarro-Patón et al. (2024), Ren et al. (2025), and Tortella et al. (2022) demonstrated that structured or targeted movement experiences can improve selected motor and fitness outcomes. However, Tortella et al. (2022) found improvement in playground-specific tasks without significant change in broader standardized motor-competence measures. This finding provides an important counterpoint to the generally favourable evidence and suggests that practising a specific movement environment may improve performance within that environment without necessarily producing generalized motor competence.

Evidence concerning cognitive-motor outcomes was less consistent than evidence concerning physical outcomes. Mulvey et al. (2018) reported improvement in executive-function performance alongside motor improvement, whereas Şendil et al. (2024) and Başarır et al. (2025) reported favourable changes in selected motor or physical outcomes without consistent improvement in inhibitory control. These contrasting findings suggest that motor complexity alone may not guarantee cognitive transfer. The cognitive demands embedded within an intervention, including decision-making, response inhibition, stimulus discrimination, and adaptation to changing information, may be important, although the available studies are insufficient to establish which programme characteristics are necessary to produce such transfer.

Fitness-oriented evidence also demonstrated outcome specificity. Daily physical activity and structured resistance training improved selected fitness measures, but improvements did not occur uniformly across every measured variable. Choudhary and Choudhary (2025), for example, reported favourable changes in several strength, power, speed, and fitness outcomes without significant changes in BMI or flexibility. These findings reinforce the principle that adaptations should be interpreted in relation to the stimulus actually provided rather than assuming that a general exercise programme will influence all dimensions of health or fitness equally.

The injury-prevention and therapeutic-exercise studies extended the relevance of movement-based programming beyond conventional physical education. Al Attar et al. (2023) reported substantially lower injury incidence following the FIFA 11+ Kids programme, whereas Joschtel et al. (2022) demonstrated improvements in locomotor and object-control skills following play-based therapeutic exercise in children with non-cystic fibrosis bronchiectasis. These findings support the potential value of structured movement in preventive and rehabilitative settings but should be interpreted within their population-specific contexts.

The two strength-effort studies made a different contribution. Ivashchenko et al. (2019) and Choudhary et al. (2024) did not test movement interventions and therefore do not provide evidence regarding programme effectiveness. Instead, they suggest that children's ability to reproduce muscular effort varies according to the relative force level being reproduced. Their contribution to the present synthesis is consequently mechanistic and contextual, supporting the broader proposition that motor competence includes

Table 2. Characteristics of the core intervention and experimental-assessment studies included in the critical narrative synthesis (n = 18)

Study	Study design/Sample	Intervention Dose	Comparator / Control	Key Quantitative Findings	Direction of Effect
Mulvey et al. (2018)	Randomized controlled trial (RCT); 107 preschool children (Mean age = 5.14 years); intervention n = 50, control n = 57	6 weeks; 30-min sessions, twice weekly; total dose = 360 min	Business-as-usual recess (30 min/day, 5 days/week)	Significant interaction for gross motor skills (TGMD-2): $F(1,95) = 58.49, p < .001, \eta^2 = .38$; SKIP group improved significantly while control did not. Significant interaction for executive function (HTKS): $F(1,100) = 6.143, p = .015, \eta^2 = .058$; SKIP group showed higher posttest scores. Significant interaction for motor skills by condition and sex: $F(1,95) = 12.25, p < .001, \eta^2 = .11$	Positive effect on gross motor skills and executive function; no improvement observed in control group.
Ivashchenko et al. (2019)	Cross-sectional testing approach; This study analysed 86 boys: 22 aged 11 years, 31 aged 12 years, and 33 aged 13 years. Researchers used t-tests for paired observations to compare different effort levels and t-tests for independent samples to compare age group	Cross-sectional strength-effort assessment protocol. Participants first completed two attempts to determine right-hand maximum strength, with the best value recorded. They then reproduced dosed efforts at 1/3, 1/2, and 2/3 of maximum strength; reproduction error was calculated as a percentage.	Comparisons were made across age groups and within each age group across the three target effort levels.	Boys in all three age groups assessed effort most accurately at 2/3 of maximum strength, $p < .05$. No statistically significant age-group differences were observed for maximum hand strength or effort-assessment ability, $p > .05$. Among 13-year-olds, accuracy at 2/3 effort was 16.97% better than at 1/3 effort, $p = .001$. Correlations between reproduction accuracy at 1/3, 1/2, and 2/3 effort levels were not statistically significant.	Accuracy of strength-effort reproduction improved as the target effort increased from 1/3 to 2/3 of maximum strength. However, no clear age-related improvement was observed between 11 and 13 years.
Palmer et al. (2019)	Cluster randomized controlled trial; 102 preschoolers (mean age 4.4 years; 80% African American) from a single Head Start centre. Participants were assigned to an intervention group (n = 64) or a control group (n = 38).	5-week intervention (CHAMP) totalling 600 minutes. Sessions were held 3 days per week for 40 minutes each, including 32-35 minutes of autonomy-based motor skill engagement.	Outdoor free play (standard recess). Control children participated in their regular daily routine of 40-45 minutes of unstructured outdoor play.	Motor Skills: The CHAMP group significantly outperformed the control group at the late assessment in total motor skills ($p < 0.001, d = 2.7$). CHAMP children improved by 45 raw points compared to 9 points for the control group. Physical Activity (PA): There were no significant group differences in PA during outdoor free play. However, children in the CHAMP group significantly increased their MVPA during the intervention sessions over the 5-week period ($p = 0.003$).	Positive for fundamental motor skills (locomotor and ball skills) and Internal Positive for PA (improved PA behaviors occurred during the intervention but did not translate to outdoor recess settings).
Mačak et al. (2022)	Randomized controlled trial (RCT)	6-month intervention consisting of 45-minute organized physical activity sessions, 5 days per week. Activities focused on motor competence, muscle strengthening, and basic sport elements (gymnastics, athletics, soccer, etc.).	The control group (CG) followed their usual routine, which included 30-minute structured physical activity sessions 2 times per week.	The experimental group (EG) showed significantly greater improvements in grip strength (mean diff +1.70 kg vs. +1.08 kg in CG, $p < 0.01$) and sit-ups in 30s (mean diff +3.91 vs. +0.99 in CG, $p < 0.01$). Boys in the EG also saw significantly better results in the 4x10m shuttle run ($p < 0.01$) and standing long jump ($p = 0.04$) compared to the CG.	Positive (favourable) effect specifically on muscular strength and endurance. No significant differences between groups were found for cardiorespiratory fitness, speed-agility (in girls), or flexibility.

Table 2. Continued

Study	Study design/Sample	Intervention Dose	Comparator / Control	Key Quantitative Findings	Direction of Effect
Strotmeyer et al., (2021)	Longitudinal field study using a cluster-randomized design at the class level. The sample consisted of 200 children (58% girls, 42% boys) from third and fourth-grade classes with a mean age of 8.84 years.	The intervention consisted of 16 standardized units conducted once a week during regular physical education (PE) classes. Each unit lasted 45 minutes, with approximately 35 minutes of active time, and the program ran for roughly six months.	The comparison group (CG) participated in regular PE lessons instead of the structured intervention program.	The analysis of variance showed a significant interaction effect between time and group for object movement ($F(1,166)=7.52; p=0.007$; partial $\eta^2=0.04$), indicating the intervention group improved more than the control. However, there was no significant interaction effect for self-movement ($F(1,166)=0.25; p=0.619$), as both groups improved over time. Additionally, a significant interaction between time and sex was found in self-movement ($p=0.014$), where boys improved more than girls regardless of their group assignment.	The intervention had a positive effect on basic motor competencies in object movement. There was no differential effect (intervention vs. regular PE) for self-movement.
Navarro-Patón, Martín-Ayala et al. (2021)	Quasi-experimental design with pre- and post-test.	6-week program consisting of one 40-minute session per week (totalling 270 minutes of intervention). Sessions were led by a physical education (PE) specialist and included a warm-up, tasks for specific motor skills (dexterity, aiming, balance), and a cool-down.	Followed the traditional PE curriculum for pre-school education in Spain, led by non-specialist teachers. Exact duration and frequency for the control group were not recorded.	Intervention Group (IG) Improvements: Statistically significant increases in manual dexterity ($d = 2.63$), aiming and catching ($d = 1.13$), balance ($d = 1.68$), total test score ($d = 3.30$), and total percentile score ($d = 1.88$). IG vs. Control Group (Post-test): Significant differences found in manual dexterity ($p = 0.015$), aiming and catching ($p = 0.003$), balance ($p = 0.050$), and total percentile score ($p < 0.001$).	Positive: The structured intervention led to significant improvements in all motor competence dimensions, moving participants from a clinical range (percentile <5) to a normal range of motor competence (percentile >16).
Navarro-Patón, Brito-Ballester et al. (2021)	Quasi-experimental pre-post-test design	A six-week program consisting of one 40-minute session per week, totalling 240 minutes. The sessions were taught by a Physical Education (PE) specialist and replaced regular PE classes.	A control group of 76 students who continued with their regular PE programming taught by generalist preschool teachers. Their curriculum focused on general aspects such as body image, play, and personal health rather than specific motor competence (MC) training.	Post-intervention, the experimental group showed significantly higher scores than the control group in aiming and catching ($p < 0.001$), balance ($p < 0.001$), total test score ($p < 0.001$; Cohen's $d = 0.88$), and total percentile score ($p < 0.001$; Cohen's $d = 0.91$). Within the experimental group, significant improvements were seen across all dimensions: manual dexterity ($d = 0.45$), aiming and catching ($d = 0.84$), and balance ($d = 0.51$).	Positive improvement; the brief, specialist-led intervention significantly increased the motor competence levels of preschool children compared to standard PE classes.

Table 2. Continued

Study	Study design/Sample	Intervention Dose	Comparator / Control	Key Quantitative Findings	Direction of Effect
Al Attar et al. (2023)	Clustered Randomized Controlled Trial (CRCT)	The FIFA 11+ Kids program was performed as a warm-up during training and matches at least twice a week for one season (6 months). Each session lasted 15 to 20 minutes and consisted of seven exercises focusing on balance, coordination, and core/extremity strength.	The control group continued their usual or standard warm-up regimen.	Total Injuries: 43 injuries in the experimental group (0.85 per 1000 hours) vs. 86 in the control group (2.01 per 1000 hours). • Injury Risk Ratio (IRR): 0.43 (95% CI, 0.29-0.61), indicating a 57% reduction in overall injuries. • Initial Injuries: Significantly lower in the experimental group (IRR 0.43; 95% CI, 0.30-0.63). • Mechanism: Significant reductions in contact (IRR 0.50), noncontact (IRR 0.39), and overuse (IRR 0.27) injuries. • Recurrent Injuries: No significant difference (P = 0.52; IRR 0.34).	Favours the intervention. The FIFA 11+ Kids program significantly reduced overall, initial, and lower extremity injury rates compared to usual warm-ups.
Joschrel et al. (2022)	Pilot randomized controlled trial involving 21 children with non-cystic fibrosis bronchiectasis . The participants had a median age of 6.8 years (IQR: 5.3-8.8)	A 7-week play-based therapeutic exercise program consisting of 7 weekly 60-minute supervised sessions . This was supplemented by a home-based program to be performed two days per week.	A wait-list control group (n = 10) that received the intervention after the post-program assessments were completed for the exercise group.	Fundamental Movement Skills (FMS): The exercise group showed significant improvements in locomotor skills (pre 29.0 ± 2.0 to post 35.2 ± 2.2, p = 0.01) and object control skills (pre 27.0 ± 2.0 to post 35.5 ± 2.2, p = 0.01) • Cardiovascular Fitness: The exercise group saw a 6 percentage point decline in heart rate change (%ΔHR) during a treadmill test, compared to a marginal 0.9 percentage point decline in the control group (effect size d = 0.5), though this was not statistically significant • Secondary Outcomes: No significant group by time interactions were found for perceived competence, PedsQL (Quality of Life), or PC-QoL-8 (cough-specific QoL).	. Significant positive effect on locomotor and object control skills . There was a moderate positive effect on cardiorespiratory fitness . There was no significant effect on perceived competence or health-related quality of life.
Staiano et al. (2022)	Randomized controlled trial (RCT) with 72 children (aged 3-5 years; mean age 4.0 ± 0.8). Participants were randomized 1:1 to either the Motor Skills app (n=35) or the Free Play app (n=37).	12-week mobile app-based intervention delivering 12 hours of instruction. The goal was 12 minutes per day, 5 days per week of structured motor skills activity.	Free Play app: Parents received lessons/videos promoting unstructured physical activity (not parent-guided) for the same duration (12 min/day, 5 days/week).	Children in the Motor Skills group significantly improved their total TGMD-3 percentile (+13.7 vs. -5.3 for control, P < .01). Significant improvements were also seen in locomotor skills (+15.5 vs. -4.8, P < .01) and ball skills (+8.3 vs. -7.3, P < .01). Improvements were sustained at 24-week follow-up.	Positive: The parent-led mHealth intervention significantly improved motor skill proficiency compared to the control group.

Table 2. Continued

Study	Study design/Sample	Intervention Dose	Comparator / Control	Key Quantitative Findings	Direction of Effect
Navarro-Patón et al. (2024)	Quasi-experimental pre-post-test design. Sample: 98 preschool children (3.86 ± 0.91 years)	9-week structured balance bike program. Dose: 3 sessions per week, 50 minutes per session.	Control Group (CG): 39 students who followed the standard physical education curriculum in Spain without balance bike training.	Pre-intervention: CG significantly outperformed the experimental group (EG) in manual dexterity ($p < 0.001$), balance ($p = 0.003$), total test score ($p = 0.001$), and total percentile ($p < 0.001$). Post-intervention: Significant differences between groups disappeared (e.g., balance $p = 0.219$; total test score $p = 0.306$). The EG showed significant internal improvements in balance ($p < 0.001$), total test score ($p = 0.003$), and total percentile ($p = 0.007$).	Positive: The balance bike program significantly improved motor competence levels in preschoolers, regardless of gender, effectively closing the initial gap between the experimental and control groups.
Tortella et al. (2022)	pretest-post-test pragmatic comparison trial. The sample included 141 children aged 4-6 years from five kindergartens in Treviso, Italy. Participants were divided into three groups: a partly structured activity group ($n = 62$), a free-play group ($n = 43$), and a control group ($n = 36$).	The intervention consisted of 10 weekly sessions, each lasting one hour, conducted in a specific outdoor playground. The partly structured group received 30 minutes of planned activity (scaffolded by instructors) and 30 minutes of free play per session. The free-play group engaged in 60 minutes of unstructured play only.	The control group did not attend the playground activities and continued with their normal kindergarten routine. The free-play group also served as a comparator to determine the added value of structured versus unstructured play.	No significant differences were found between the groups in general motor competence as measured by the Test of Motor Competence (TMC) ($p \geq 0.68$) or the Movement Assessment Battery for Children (MABC-2) ($p > 0.05$). However, the partly structured activity group showed significant improvement in playground-specific tests (summarized playground and elastic platform scores) compared to both the free-play and control groups ($p < 0.001$).	Positive effect on task-specific balance skills (specifically on the equipment practiced) for the partly structured intervention group. The results showed a neutral effect (no significant change) regarding the transfer of these skills to broader, generalized motor competence batteries like the TMC and MABC-2.
Choudhary et al. (2024)	A descriptive design involving 75 sedentary girls. The participants were divided into three age groups: 10 years ($n = 20$ -24*), 11 years ($n = 25$), and 12 years ($n = 30$).	No intervention was implemented. The study focused on evaluating baseline handgrip strength and the participants' ability to accurately reproduce efforts at 1/3, 1/2, and 2/3 of their maximum strength.	The study used comparative analysis between age groups (10 vs. 11, 10 vs. 12, and 11 vs. 12) and within-group comparisons between the three different strength effort levels.	No significant age-related differences were found in maximum hand strength ($p > 0.70$) or in the accuracy of effort assessment between groups ($p > 0.05$). • The most accurate assessment for all groups occurred at 2/3 of maximum strength • Significant differences in assessment accuracy were found between 1/3 and 1/2 effort ($p \leq 0.001$) and between 1/3 and 2/3 effort ($p = 0.000$) for all ages.	Effort assessment precision improves as the percentage of maximum strength increases, with accuracy being highest at the 2/3 threshold. • The ability to assess these efforts remains stable and consistent across the age range of 10 to 12 years.
Kojić et al. (2024)	Controlled two-group, repeated-measures experimental study. Sample of 53 preschool children (24 boys, 29 girls), mean age 6.22 ± 0.43 years.	6-month intervention, with sessions conducted 3 times per week for 35 minutes each.	Free play activity (FRP) group.	The SMA group showed significant improvements in obstacle course backwards (OCB; -24.75%, ES=1.24), plate tapping (PTT; +29.42%, ES=1.24), and standing long jump (SLJ; +7.21%, ES=0.45), and shuttle run (SRT; -27.15%, ES=0.84). The FRP group improved significantly only in OCB (-2.88%, ES=0.47). ANCOVA showed significant group × time interactions favoring SMA for coordination, agility, and speed.	Positive (favouring SMA). Structured movement activities were significantly more effective than free play for developing motor coordination, agility, and speed of movement.

Table 2. Continued

Study	Study design/Sample	Intervention Dose	Comparator / Control	Key Quantitative Findings	Direction of Effect
Şendil et al., (2024)	A non-randomized study using convenience sampling consisting of 41 kindergarten children (27 boys and 14 girls) aged 5-6 years. Participants were divided into an exercise group (n = 18) and a control group (n = 23).	A structured coordinative exercise program focusing on locomotor and balance skills (e.g., side-stepping, jumping, running) for 30 minutes, 2 days a week, for 8 weeks.	The control group followed their normal kindergarten curriculum and did not receive the specific exercise intervention.	Mixed measures ANOVA revealed a significant group-by-time interaction effect for the exercise group in: • Static balance ($F(1-39) = 6.993, p = 0.012$). • KTK sideways jump ($F(1-39) = 6.443, p = 0.015$). • KTK eye-hand coordination ($F(1-39) = 8.180, p = 0.007$). No significant effect was found for inhibitory control ($p > 0.05$).	Positive effect on specific elements of physical fitness and motor competence; no significant effect on inhibitory control.
Choudhary & Choudhary, (2025)	Controlled quasi-experimental pre-post design using intact class allocation. The sample consisted of 99 healthy adolescents (52 boys and 47 girls) aged 13-16 years.	12-week program consisting of three 60-minute sessions per week on non-consecutive days. Training included bodyweight and circuit-based exercises (squats, lunges, push-ups, planks, and plyometric jumps) with progressive increases in sets, repetitions, and intensity (RPE 5 to 8).	The control group (CG) continued with the standard school physical education curriculum, which included two 40-minute sessions per week of callisthenics, aerobic games, and flexibility exercises, but no structured resistance training.	Significant Group $\times$ Time interactions were found for: • Standing Broad Jump: $\eta^2 = 0.26$ (Large effect), $p < 0.001$. • Sit-ups: $\eta^2 = 0.23$ (Large effect), $p < 0.001$. • Push-ups: $\eta^2 = 0.19$ (Large effect), $p < 0.001$. • 20-m Sprint: $\eta^2 = 0.14$ (Large effect), $p < 0.001$. • CMJ Height: $\eta^2 = 0.12$ (Medium effect), $p = 0.001$. • Flexibility and BMI: No significant changes ($p > 0.05$).	Improvement in the intervention group across multiple fitness domains, including muscular endurance, power, speed, coordination, and aerobic capacity, while the control group showed minimal or no changes.
Başarır et al. (2025)	Randomized experimental design involving 51 preschool children (27 boys, 24 girls) aged 5 to 6 years ($M = 6.03$) from a preschool in Turkey. The children were typically developing with no cardiovascular, neurological, or orthopedic illnesses.	An 8-week coordination-based training program consisting of two 25-minute sessions per week. The program used a game-based format focusing on basic movement patterns that progressed from simple to complex.	A control group (CG; n = 25) that continued their routine preschool activities and scheduled lessons without any additional coordination-based training.	The exercise group (EG) showed a significantly higher score increase than the CG in vertical jumping ($F(1-49) = 14.569, p < 0.001$) and KTK Balancing Backwards ($F(1-49) = 14.051, p < 0.001$). Conversely, the CG showed a significantly higher score increase than the EG in KTK Moving Sideways ($F(1-49) = 9.984, p < 0.01$). No statistically significant differences were found between groups for static balance, agility, jumping sideways, hand-eye coordination, or inhibition control (accuracy and response time).	The intervention had a positive effect on lower extremity strength and dynamic balance (as measured by KTK BB) in preschool children. However, it had a neutral effect on cognitive inhibition control, which authors suggest might be due to the low frequency of the intervention (2 days/week).

Table 2. Continued

Study	Study design/Sample	Intervention Dose	Comparator / Control	Key Quantitative Findings	Direction of Effect
Ren et al. (2025)	Three-group quasi-experimental pretest-posttest design. The sample included 45 children aged 3-6 years (15 per group) recruited from a training institution in Shenzhen, China.	12-week intervention consisting of sessions held twice weekly, each lasting 60 minutes.	This was a comparative study between three active groups: Roller Skating (RS), Basketball (BT), and Physical Training (PT). There was no no-intervention control group.	Total Gross Motor Score: Significant interaction effect ($F_{2,42}=8.00, p=0.001, \eta^2=0.276$). All groups improved ($p<0.01$), but BT and PT outperformed RS post-intervention ($p<0.01$). Locomotor Skills: Significant main effect of time ($F_{1,42}=179.11, p<0.001$), with all groups showing improvement. Object Control Skills: Significant interaction effect ($F_{2,42}=11.89, p<0.001$); BT and PT showed significantly greater gains than RS ($p<0.01$).	Positive effect across all groups for gross motor development. However, Basketball and Physical Training were associated with broader and more pronounced improvements in motor skills compared to Roller Skating.

Note. RCT = randomized controlled trial; CRCT = cluster randomized controlled trial; n = sample size/number of participants; PE = physical education; IG = intervention group; EG = experimental group; CG = control group/comparison group; PA = physical activity; MVPA = moderate-to-vigorous physical activity; FMS = fundamental movement skills; MC = motor competence; TGMD-2 = Test of Gross Motor Development, Second Edition; HTKS = Head-Toes-Knees-Shoulders task; CHAMP = Children's Health Activity Motor Program; FIFA 11+ Kids = Fédération Internationale de Football Association 11+ Kids injury-prevention programme; IRR = injury rate ratio/incidence rate ratio; CI = confidence interval; IQR = interquartile range; HR = heart rate; Δ HR = percentage change in heart rate; PedsQL = Pediatric Quality of Life Inventory; PC-QoL-8 = Parent Cough-Specific Quality of Life Questionnaire, 8-item version; TMC = Test of Motor Competence; MABC-2 = Movement Assessment Battery for Children, Second Edition; KTK = Körperkoordinations test für Kinder/Body Coordination Test for Children; KTK BB = KTK Balancing Backwards; OCB = obstacle course backwards; PTT = plate tapping test; SLJ = standing long jump; SRT = shuttle run test; SMA = structured movement activity; FRP = free play activity; RPE = rating of perceived exertion; CMJ = countermovement jump; BMI = body mass index; RS = roller skating; BT = basketball training; PT = physical training; ANOVA = analysis of variance; ANCOVA = analysis of covariance; F = F-statistic; p = probability value/statistical significance level; η^2 = eta squared; η^2 = partial eta squared; ES = effect size; d = Cohen's d; M = mean; SD = standard deviation.

regulation and grading of force as well as visible movement execution.

Taken collectively, the evidence suggests that structured movement experiences are generally more reliable for improving directly targeted outcomes than for producing broad developmental transfer. Differences in programme design, dose, progression, comparator condition, age group, measurement approach, and methodological strength appear to contribute to variation between studies. This pattern informed the critical interpretation developed in the Discussion.

Discussion

The principal finding of this critical narrative synthesis is not simply that movement-based interventions produce favourable outcomes, but that their effects appear to be governed by three interrelated characteristics: structure, specificity, and transfer. Across the included literature, intentionally organized and progressively delivered movement experiences generally produced more favourable outcomes than usual practice, free play, or less targeted comparison conditions. At the same time, the strongest effects were usually observed in outcomes closely aligned with the content of the intervention, whereas evidence that these gains generalized to broader motor competence, habitual physical activity, or cognitive functioning was substantially less consistent. This distinction provides a more cautious interpretation of the literature than a general conclusion that all forms of movement intervention are universally beneficial.

Structure: Guided Movement Appears More Reliable Than Exposure Alone

A recurring pattern across the evidence was the advantage of structured, developmentally appropriate movement experiences over less directed exposure. Physical education and motor-skill programmes involving deliberate practice, task progression, feedback, and targeted skill development repeatedly produced improvements in directly assessed motor outcomes (Mulvey et al., 2018; Navarro-Patón, Brito-Ballester, et al., 2021; Navarro-Patón, Martín-Ayala, et al., 2021; Palmer et al., 2019; Strotmeyer et al., 2021). Structured movement activity was also more effective than free play for several measures of coordination, agility, and speed in Kojić et al. (2024).

The implication is not that free play lacks developmental value, but that opportunity to move and systematic development of motor competence are not equivalent. Children may receive considerable physical activity exposure without repeatedly practising the specific movement patterns, control strategies, and progressive challenges needed to develop proficiency. From this perspective, the role of the physical educator is not merely to provide activity time but to organize movement experiences so that learners encounter appropriate challenge, repetition, variation, and feedback.

Specificity: Intervention Effects Closely Follow the Trained Stimulus

The second cross-study pattern was outcome specificity. The interventions were generally most successful for the

physical or motor abilities explicitly addressed by programme content. Resistance training predominantly improved strength-, power-, and performance-related outcomes; balance-bike training improved selected dimensions of motor competence and balance; neuromuscular warm-up training reduced injury incidence; and therapeutic exercise improved specific locomotor and object-control abilities. Conversely, outcomes not directly targeted by the intervention were less consistently affected.

This principle is illustrated particularly clearly by findings in which some outcomes improved while others did not. Strotmeyer et al. (2021) observed differential effects for object movement and self-movement. Choudhary and Choudhary (2025) reported substantial improvements across several fitness measures but no significant changes in BMI or flexibility. Başarır et al. (2025) demonstrated improvements in selected jumping and dynamic-balance outcomes while several other coordination and inhibition outcomes remained unchanged. Such findings argue against describing movement interventions as producing a single generalized developmental effect. Instead, programme effectiveness should be interpreted in relation to the match between the intervention stimulus and the outcome being assessed. This has important implications for both research and practice: an intervention should first specify the developmental characteristic it intends to influence and then provide sufficient task exposure, progression, and measurement sensitivity to evaluate that characteristic.

Transfer: Improvement in Practised Skills

The third and perhaps most important finding concerns transfer. Several studies demonstrated substantial improvement in directly practised or closely related outcomes without equivalent improvement in broader or less directly trained domains. Tortella et al. (2022), for example, found improvements in playground-specific performance but not in generalized motor competence measured through broader test batteries. Palmer et al. (2019) demonstrated marked improvements in fundamental motor skills, yet the intervention did not produce corresponding between-group differences in physical activity during outdoor free play.

These results indicate that intervention success should be considered at different levels. The first is direct learning of the practised task. The second is near transfer to related but untrained motor abilities. The third is far transfer to broader outcomes such as habitual physical activity, generalized motor competence, executive function, participation, or long-term physical literacy. The present evidence provides comparatively strong support for direct task improvement and some evidence for near transfer, but substantially less consistent evidence for far transfer.

This distinction is important because movement competence is often discussed as a pathway toward broader physical activity and health outcomes. Although such developmental relationships are theoretically plausible and supported by broader literature, individual intervention studies cannot establish them merely by demonstrating improvement in a specific motor test. Future research should therefore assess transfer directly rather than infer it from improvements in trained skills.

Cognitive-Motor Benefits

The evidence concerning cognitive outcomes was particularly inconsistent. Mulvey et al. (2018) demonstrated an improvement in executive-function performance alongside motor-competence gains. In contrast, coordination-based interventions reported by Şendil et al. (2024) and Başarır et al. (2025) did not produce consistent improvements in inhibitory control despite improvements in selected motor or fitness outcomes.

These findings suggest that improving motor coordination does not automatically result in cognitive improvement. One possible explanation is that cognitive adaptation depends upon the cognitive demands embedded within the movement task. Activities requiring response selection, inhibition, anticipation, memory, perceptual discrimination, or adaptation to unpredictable information may provide a different stimulus from repetitive coordination activities even when both are physically demanding. Intervention frequency, duration, developmental stage, and sensitivity of cognitive assessment may also contribute to the inconsistent findings.

The present evidence is therefore insufficient to support broad claims that movement-based intervention improves executive functioning in general. A more defensible conclusion is that selected cognitively demanding movement programmes may influence specific cognitive outcomes, but the conditions necessary to produce reliable cognitive transfer remain uncertain.

Intervention Dose Cannot Be Interpreted Solely as Programme Duration

Considerable variation was evident in intervention duration and frequency. Some programmes lasted only several weeks, whereas others extended for several months. Importantly, longer programmes were not uniformly superior across all outcomes, and comparatively brief specialist-led interventions sometimes produced substantial improvements.

This suggests that intervention dose should not be conceptualized solely in terms of number of weeks or sessions. Active practice time, task repetitions, movement complexity, progression, instructional quality, feedback, participant engagement, and fidelity may all contribute to the effective dose received by participants. Two interventions of equal duration may therefore provide markedly different developmental stimuli.

The current evidence base does not permit identification of an optimal dose for motor-competence development. Future research should report the active components of interventions more precisely and directly compare alternative frequencies, durations, and progression strategies.

Methodological Differences Affect the Strength of the Evidence

The generally favourable direction of findings should also be considered in relation to methodological heterogeneity. The evidence base included randomized controlled trials, cluster-randomized designs, pilot trials, quasi-experimental studies, pragmatic comparisons, and structured experimental

assessments. These designs do not provide equivalent levels of causal evidence. Randomized and cluster-randomized trials provide comparatively stronger protection against selection-related explanations than non-randomized designs. In contrast, several quasi-experimental studies used intact groups, convenience sampling, or populations with initial between-group differences. Navarro-Patón et al. (2024), for example, reported several significant baseline differences before the balance-bike intervention. The pilot trial by Joschtel et al. (2022) involved only 21 participants, making its findings important for feasibility and preliminary effect estimation but less suitable for broad generalization. Similarly, Ren et al. (2025) included only 15 participants in each of three active intervention groups and did not include a no-intervention control condition.

Outcome measurement was another source of heterogeneity. Some studies used established motor-development assessments, whereas others evaluated fitness tests, task-specific outcomes, cognitive tasks, or injury incidence. Consequently, apparent differences between programmes may reflect not only intervention effectiveness but also differences in what was measured and how closely the assessment corresponded to the intervention.

These methodological differences do not negate the positive findings, but they require caution when making generalized causal statements. The literature is more convincing in demonstrating that structured programmes can improve selected proximal outcomes than in establishing that such improvements persist over time or generalize across developmental domains.

Complementary Evidence on Strength-Effort Regulation

The experimental strength-effort studies should be interpreted separately from the intervention literature. Ivashchenko et al. (2019) and Choudhary et al. (2024) did not evaluate training programmes; accordingly, they cannot establish whether movement intervention improves motor competence. Their relevance lies instead in demonstrating that children must regulate and reproduce graded levels of muscular force and that accuracy appears to differ according to the relative effort required.

This evidence broadens the conceptual interpretation of motor competence by highlighting force regulation as a component of movement control. Effective performance in throwing, jumping, landing, pushing, pulling, balancing, and many sport-specific skills depends not only on producing force but on scaling force appropriately to the task. Strength-effort regulation therefore represents a potentially relevant but comparatively underexplored motor-control dimension. Future intervention research could determine whether this ability is trainable and whether improvements transfer to functional movement performance.

Original Conceptual Contribution: A Structure-Specificity-Transfer Perspective

The principal conceptual contribution emerging from this synthesis is a structure-specificity-transfer perspective for interpreting movement-based interventions. Structure refers to the recurring advantage of intentionally organized, progressive, and guided movement experiences over

exposure alone. Specificity refers to the tendency for the strongest improvements to occur in outcomes closely aligned with the training stimulus. Transfer refers to the less consistent evidence that improvements extend beyond directly practised abilities to generalized motor competence, physical activity, cognition, or other distal developmental outcomes.

This perspective should not be interpreted as a formally validated theoretical model. Rather, it represents an evidence-informed interpretation generated through comparison of the included studies. Its value lies in preventing an overly broad conclusion that any structured movement intervention will automatically produce multidimensional developmental benefits.

The current evidence more strongly supports the proposition that appropriately structured programmes can improve specific targeted capabilities. Whether these improvements subsequently generalize depends on task variability, programme content, developmental characteristics, measurement approach, and potentially the duration and quality of exposure. Future research should therefore ask not only whether an intervention works, but what it improves, why it improves that outcome, whether the improvement transfers, and whether the effect persists after the intervention ends.

Practical Implications for Physical Education and Paediatric Exercise

The findings have direct implications for physical education teachers, coaches, paediatric exercise specialists, and rehabilitation professionals. First, motor competence should be treated as a central learning outcome within physical education rather than as an assumed by-product of general participation. Evidence from PE-based interventions indicates that children improve when they receive structured practice in locomotor, object-control, balance, coordination, and body-management tasks (Mulvey et al., 2018; Navarro-Patón, Martín-Ayala, et al., 2021; Palmer et al., 2019; Strotmeyer et al., 2021). These skills should therefore be systematically embedded within preschool and school PE curricula. Second, early screening and monitoring of motor competence should be strengthened. Children with low motor competence, developmental coordination difficulties, overweight, or low physical confidence may require adapted instruction and additional support. Tools such as the Movement Assessment Battery for Children-2 and related checklists have been widely used for identifying motor difficulties and monitoring developmental progress (Serbetar et al., 2019). Screening is especially important because developmental coordination disorder may affect school function, participation, physical activity, and psychosocial well-being (Wang et al., 2009). Third, physical education should combine structured instruction with play-based exploration. The evidence suggests that free play alone may not always produce broad motor development, whereas partly structured activity, balance-bike training, structured movement activities, and guided gross motor programmes can produce meaningful improvements (Kojić et al., 2024; Navarro-Patón et al., 2024; Ren et al., 2025; Tortella et al., 2022). Teachers should therefore design lessons that preserve enjoyment and autonomy while also

ensuring progression, repetition, feedback, and skill variety. Fourth, coordination-based and cognitively enriched activities should be used more deliberately in PE lessons. Activities involving decision-making, response inhibition, sustained attention, perceptual discrimination, rhythm, spatial orientation, and rapid adjustment may support both motor and cognitive-motor development (Başarır et al., 2025; Şendil et al., 2024). This is particularly relevant for physical literacy, which includes physical, cognitive, affective, and social dimensions. Fifth, age-appropriate resistance training and neuromuscular exercises should be integrated into adolescent PE and after-school programmes. Choudhary & Choudhary (2025) showed that structured resistance training can improve muscular endurance, power, speed, aerobic capacity, balance, and coordination. Such programmes should emphasize technique, progression, supervision, bodyweight control, and safe exercise habits rather than maximal loading. Sixth, youth sport settings should include structured injury-prevention warm-ups. The FIFA 11+ Kids evidence suggests that neuromuscular warm-up programmes can reduce injury rates among child soccer players when implemented consistently (Al Attar et al., 2023). These programmes are practical because they can be integrated into regular training and match preparation without requiring complex equipment. Finally, paediatric rehabilitation and adapted PE programmes should use task-oriented and goal-directed movement activities. Evidence from DCD intervention research supports the value of motor-based, task-oriented, and participation-focused approaches (Smits-Engelsman et al., 2018; Thornton et al., 2016; J. J. Yu et al., 2018). For children with clinical conditions or motor delays, therapeutic exercise should be playful, functional, progressive, and connected to everyday movement participation.

Limitations

Several limitations should be considered when interpreting this narrative synthesis. First, although a structured search and explicit selection framework were used to increase transparency, the study was conceived as a narrative review and was not designed to provide exhaustive identification of all potentially eligible literature. Consequently, the 18 core studies should be understood as a deliberately selected contemporary evidence base rather than as a complete census of all studies in the field.

Second, the review was restricted to English-language and sufficiently accessible scholarly publications from 2018 onward. Relevant non-English, older, regional, or less accessible evidence may therefore not have been represented. The decision to emphasize contemporary literature improves the relevance of the synthesis to current physical education and paediatric exercise practice but limits historical comprehensiveness.

Third, considerable methodological and clinical heterogeneity existed across the core studies. Populations ranged from preschool children to adolescents, youth athletes, and a paediatric clinical population. Study designs included randomized, cluster-randomized, pilot, quasi-experimental, pragmatic, and structured assessment approaches. Intervention duration, frequency, instructional format, comparator conditions, and outcome measures

also varied considerably. These differences limit direct comparison between studies.

Fourth, methodological quality was evaluated narratively rather than by means of a formal systematic risk-of-bias instrument. This approach was consistent with the narrative design of the review but does not provide domain-level risk-of-bias judgments comparable with those expected in a systematic review. The findings should therefore be interpreted as critical narrative integration rather than as evidence graded according to a formal certainty framework.

Fifth, several studies had methodological characteristics requiring cautious interpretation, including small samples, non-randomized allocation, convenience sampling, baseline between-group differences, limited information concerning long-term follow-up, and heterogeneous assessment procedures. Such limitations reduce the strength with which causal and generalized conclusions can be drawn.

Sixth, not all reported improvements represented broader transfer. Some interventions produced substantial changes in directly practised or task-specific outcomes without corresponding improvements in generalized motor competence, physical activity, or cognitive measures. Future studies should therefore distinguish direct training effects from near and far transfer.

Finally, two of the 18 core studies were structured experimental assessment studies rather than intervention trials. These studies were deliberately retained because they provided complementary information concerning strength-effort regulation as a motor-control process, but they were interpreted separately and should not be considered evidence of intervention effectiveness.

Future Research Directions

Future research should move beyond establishing whether movement-based programmes produce statistically significant pre-post improvements and focus more explicitly on intervention mechanisms, specificity, transfer, and sustainability. Larger and methodologically rigorous randomized and cluster-randomized trials are required, particularly in school-based settings. Studies should clearly report allocation procedures, participant flow, adherence, intervention fidelity, assessor procedures, and prespecified primary outcomes.

A major priority should be to distinguish directly trained improvement from broader transfer. Future studies should include outcomes representing the practised task, related but untrained motor abilities, and more distal outcomes such as habitual physical activity, participation, cognitive functioning, psychosocial well-being, or physical literacy. This would make it possible to determine whether interventions improve only what children practise or whether their effects generalize meaningfully beyond the intervention context.

Intervention dose also requires more precise investigation. Researchers should report not only programme duration and weekly frequency but also active practice time, movement repetitions, task complexity, progression, feedback, participant engagement, and instructor characteristics. Comparative studies examining different doses and instructional structures would help determine which programme components are responsible for observed improvements.

Greater consistency in assessment would also strengthen the field. Use of common, validated motor-competence outcome measures alongside intervention-specific assessments would make it easier to distinguish task learning from generalized developmental improvement and would facilitate future quantitative synthesis.

The inconsistent cognitive findings require particular attention. Future studies should describe the perceptual and cognitive demands embedded within movement programmes and determine whether activities involving decision-making, inhibition, anticipation, working memory, or stimulus-response adaptation produce different outcomes from predominantly repetitive coordination training.

Long-term follow-up should be incorporated wherever feasible to determine whether improvements persist after structured intervention ends. Future research should also include more diverse populations, particularly children with low motor competence, developmental coordination difficulties, disabilities, overweight or obesity, and clinical conditions.

Finally, the complementary findings concerning strength-effort regulation suggest a further research direction. Experimental intervention studies should determine whether force-regulation accuracy can be systematically trained and whether improvement in effort grading contributes to broader movement competence, sport skill, or functional motor performance.

Conclusions

This critical narrative synthesis indicates that structured movement-based interventions can improve motor competence and selected related outcomes in children and adolescents, but the available evidence does not support the assumption of a uniform effect across all developmental domains. The most consistent benefits were observed when activities were intentionally structured, progressively delivered, and closely aligned with the outcomes being assessed.

Cross-study comparison suggests three important principles. First, structured and guided movement experiences generally appear more reliable for targeted motor development than exposure or unstructured activity alone. Second, intervention effects are frequently specific to the abilities directly addressed by programme content. Third, transfer from practised skills to broader motor competence, habitual physical activity, or cognitive functioning is less consistent and should be demonstrated rather than assumed. These patterns support a structure-specificity-transfer perspective for interpreting movement-based programming. Although this perspective requires further empirical testing, it offers a more cautious explanation of why some programmes produce substantial improvements in selected outcomes while showing limited effects elsewhere. Methodological heterogeneity, variation in participant characteristics, mixed study designs, differences in assessment, and limited long-term follow-up restrict the strength of broad causal conclusions. The two experimental strength-effort studies additionally provide complementary rather than intervention-effect evidence and highlight force regulation as an underexplored aspect of motor control. For physical education teachers, coaches, and paediatric

exercise professionals, the practical implication is that movement programmes should be designed around clearly defined developmental objectives and should incorporate appropriate structure, progression, variation, and feedback. Future research should determine not only whether movement programmes produce improvement, but whether those gains persist, generalize beyond the trained task, and ultimately contribute to broader physical literacy and sustained participation in physical activity.

Ethics Approval

Not applicable.

Informed Consent

Not applicable.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

AI Transparency Statement

The authors used Paperpal solely to improve the language, grammar, spelling, and readability of the manuscript. The scientific content, literature selection, data synthesis, interpretation of findings, and conclusions were developed and verified by the authors. The authors reviewed and approved the final manuscript and take full responsibility for its content.

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Conflicts of Interest

The authors declare no conflict of interest.

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Рухово-орієнтовані втручання та рухова компетентність у контексті фізичного виховання та рухової активності дітей і підлітків: наративний синтез експериментальних доказів

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

Реферат. Стаття: 18 с., 2 табл., 36 джерел.

Мета. Рухова компетентність є фундаментальною складовою фізичного виховання, фізичної грамотності та тривалої участі у фізичній активності. У цьому критичному наративному синтезі проаналізовано сучасні експериментальні та інтервенційні дані щодо рухово-орієнтованих втручань у дітей і підлітків з акцентом на спрямованість, узгодженість, специфічність, переносимість ефектів та методологічні обмеження отриманих результатів.

Матеріали та методи. Для виявлення та критичного узагальнення літератури, опублікованої з 2018 року, застосовано структурований наративний огляд. Під час відбору досліджень враховували популяцію, дизайн, спрямованість втручан-

ня або експерименту, наявність групи порівняння, сферу оцінюваних результатів, контекст, мову та відповідність дослідницькому питанню. Основну доказову базу становили 18 досліджень: 16 інтервенційних або порівняльних досліджень і два структуровані експериментальні дослідження, присвячені регуляції м'язових зусиль як компоненту рухового контролю. Дані синтезували тематично з урахуванням методологічних переваг, обмежень, суперечностей і ефектів переносу.

Результати. Структуровані програми фізичного виховання та розвитку рухової компетентності загалом сприяли поліпшенню безпосередньо тренуваних грубих рухових і фундаментальних рухових навичок. Структурована гра, тренування на баланс-велосипеді, програми фізичної активності та спортивно-орієнтовані заняття покращували окремі показники рухової підготовленості та фізичної працездатності, однак ці зміни не завжди переносилися на ширшу рухову компетентність. Координаційні втручання позитивно впливали на низку показників рівноваги, стрибкових здібностей і координації, тоді як результати щодо гальмівного контролю та інших когнітивних показників були неоднозначними. Силові тренування покращували окремі показники м'язової підготовленості та фізичної працездатності, терапевтичні вправи — окремі фундаментальні рухові навички у педіатричній клінічній популяції, а програма FIFA 11+ Kids знижувала загальну частоту травм на 57% (IRR = 0,43; 95% ДІ: 0,29–0,61). Дослідження регуляції м'язових зусиль також засвідчили, що точність відтворення зусилля може залежати від відносної величини відтворюваного зусилля.

Висновки. Сучасні дані підтверджують ефективність структурованого та відповідного віковому розвитку рухового досвіду для покращення рухової компетентності й окремих пов'язаних із нею показників у дітей і підлітків. Водночас ефекти часто мають специфічний характер, тому поліпшення безпосередньо тренуваних здібностей не слід автоматично трактувати як перенесення на загальну рухову компетентність, фізичну активність або когнітивне функціонування. На величину спостережуваних ефектів, імовірно, впливають структура втручання, специфічність завдань, прогресування навантаження, характеристики учасників і методи оцінювання. У майбутніх дослідженнях необхідно чітко розмежовувати безпосередні тренувальні ефекти та ширший розвитковий перенос.

Ключові слова: рухова компетентність, фізичне виховання, рухово-орієнтоване втручання, фізичні вправи у педіатрії, фундаментальні рухові навички, фізична грамотність, нарративний огляд, руховий розвиток.

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Biomechanical Parameters of Attacking Throws as a Basis for Technical Training in Judo

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Abstract

Objectives. The development of school physical education requires effective means for improving motor skills, coordination, and speed-strength qualities. Judo is one such means, and the effectiveness of teaching its technical actions depends on the objective assessment of movement biomechanics. This study aimed to determine the biomechanical parameters of the O-goshi throw in highly trained schoolchildren, develop an original biomechanical model based on tensodynamometric indicators and correlation analysis, and identify the most informative characteristics of its movement structure.

Materials and Methods. The study involved 77 male high school students aged 15–16 years. The general group (n = 63) consisted of beginners in judo, while the model group (n = 14) included advanced athletes (Candidates for Master of Sports of Ukraine and medalists of Ukrainian championships). Biomechanical parameters of O-goshi were recorded using a force plate. Force (Fzmax, Fmax, Fmax/P, GRAD, I), time (Tps, Tmax, Tmax+To, Tsum), and spatial (Hmax) parameters were analyzed. The biomechanical model was developed from the model-group data using correlation analysis and normalization of the sums of absolute correlation coefficients. Each participant performed three trials, and the mean values were analyzed.

Results. The highest relative contribution to the biomechanical model was observed for force gradient (11.13%). High informational value was also found for maximum vertical reaction force (Fzmax, 10.37%), resultant maximum force (Fmax, 10.28%), and force impulse (10.17%). Strong correlations between force and force-time parameters indicated their close interaction during O-goshi execution.

Conclusions. The developed biomechanical model identified the most informative force, time, and force-time characteristics of O-goshi in highly trained schoolchildren. The findings may be used for biomechanical monitoring and comparative assessment of performance across different training levels.

Keywords: judo, biomechanics, force-time characteristics, O-goshi, biomechanical model, schoolchildren.

Introduction

In the curriculum "Physical Education: 10–11 Grades. Standard Level," approved by the Ministry of Education and Science of Ukraine, the "Judo" elective module is designed to develop specific motor skills and abilities, as well as coordination, speed-strength motor qualities, balance, and the ability to effectively perform technical movements under varying conditions of physical activity (Ministry of Education and Science of Ukraine, 2022). The use of judo techniques in the physical education of high school students contributes to the development of specific motor skills necessary for mastering throwing techniques, as confirmed by the results of recent domestic studies (Filina, 2025).

Judo is a highly dynamic Olympic martial art in which the effectiveness of offensive techniques is largely determined by the rational spatial and temporal organization of movements, the ability to quickly generate force, and the optimal utilization of the athlete's strength during a throw.

Neuromuscular performance and lower-limb power have been identified as critically important factors in judo performance. It has been shown that improving lower-limb power and counter-movement jump (CMJ) parameters contributes to better performance on the Special Judo Fitness Test and improved throwing performance (Ho et al., 2025). Furthermore, repeated competitive bouts significantly influence the development of force impulse and indicators of bilateral strength deficit, highlighting the sensitivity of strength and strength-time characteristics to the onset of fatigue (Kons et al., 2026).

Contemporary biomechanical studies of specific judo techniques are of considerable interest. For example, a kinematic analysis of the Uchi-mata technique showed that higher-level athletes demonstrate greater center-of-mass velocity and more effective coordination of movements during the preparatory phase of the throw (Hamaguchi et al., 2024). Furthermore, it has been established that the kinematic characteristics of the lower limbs during the execution of the Uchi-mata throw differ significantly between judokas who specialize in this technique and those who do not. This confirms the existence of specific biomechanical characteristics of individual judo techniques and the need for their individual research (Brito et al., 2025). A biomechanical assessment of the Sode-tsurikomi-goshi and Tsurikomi-goshi techniques also revealed significant differences in acceleration and velocity metrics, confirming the value of using quantitative biomechanical metrics to analyze throwing techniques (Pantelidou et al., 2025).

Beyond technique-specific descriptions, recent work indicates that skill level in judo is expressed through the coordination of center-of-mass motion, segmental rotation, and momentum transfer. In seoi-nage, elite judokas demonstrate greater relative forward velocity of the whole-body center of mass than collegiate athletes (Ishii et al., 2018). More recent three-dimensional analyses combining motion capture and force platforms have identified center-of-mass control, linear and angular momentum, and rotational force generation as objective characteristics of technically proficient execution (Ishii & Koshida, 2025, 2026). These findings support the use of integrated biomechanical indicators rather than isolated variables when describing the structure of a judo throw.

Domestic studies indicate that the teaching of complex technical movements should be based on the step-by-step development of motor skills, systematic pedagogical monitoring, and objective assessment of the quality of movement execution (Krutsevich et al., 2017; Platonov, 2004). For the technical training of judokas, the use of model characteristics is of great importance, as they allow for the objectification of the process of monitoring and refining technique (Platonov, 2004). The development of biomechanical models for individual technical techniques enables a comprehensive quantitative description of their force, time, and force-time characteristics, thereby providing a scientific basis for the objective evaluation of technique and its further improvement.

An important area of contemporary research is the use of biomechanical monitoring to quantitatively assess athletes' technical readiness. The use of force-measurement methods makes it possible to determine the force and force-time characteristics of technical movements, as well as to develop model indicators of technique for athletes of various skill levels (Harkusha, 2016). At the same time, the effectiveness of mastering complex technical movements depends to a large extent on the level of development of motor coordination skills, which ensure the synchronization of movement phases and the stability of technical execution (Nosko et al., 2023).

Force-platform studies also show that interaction with the support surface is directly related to the mechanical effectiveness of throwing actions. In Harai-goshi, advanced judokas differ from novices in the horizontal force applied by the supporting leg and in sweeping-leg velocity (Pucsok et al., 2001). In osoto-gari, higher technical proficiency is associated with greater segmental angular velocities

and angular momentum transfer (Liu et al., 2024), while ground-reaction-force components and ankle-joint kinetics are related to sweeping-leg velocity at contact (Liu et al., 2025). Thus, force, temporal, and force-time characteristics can be considered complementary components of the same movement organization.

Advances in modern biomechanical analysis tools and wearable sensor systems are expanding the possibilities for objective, quantitative assessment of the kinetic and kinematic characteristics of technical movements in martial arts (Xue et al., 2025). At the same time, modern concepts of athletic training indicate that high performance in judo is achieved through the complex interaction of technical, neuromuscular, coordinative, and psychological components (Schoof et al., 2024). However, most current studies focus on specific judo techniques, physiological characteristics, or the evaluation of training program effectiveness, while the development of biomechanical models for individual throws and the comprehensive analysis of their force, time, and force-time characteristics remain under-explored.

In adolescent judo athletes, the interpretation of biomechanical and performance characteristics also requires attention to training experience and maturation. Somatic maturation, body size, and training experience contribute to variation in neuromuscular and judo-specific performance in young athletes (Detanico et al., 2020), and higher competitive level in youth judo is associated with greater training experience and superior strength- and power-related performance (Detanico et al., 2022). Accordingly, biomechanical model characteristics for school-age judokas are most informative when interpreted within comparable age and training contexts.

Thus, an analysis of current research indicates that, despite the active development of biomechanical methods for assessing the technical readiness of judo athletes, comprehensive studies aimed at developing a biomechanical model of the O-goshi throw based on an integrated analysis of its force, time, and force-time characteristics remain limited. This necessitates the research of the biomechanical parameters of this throw and the development of its biomechanical model as a basis for objectively assessing technique execution and further refining the methods of technical training for judo athletes.

The purpose of this research is to develop an original biomechanical model of the attacking throw in high-level school athletes based on tensodynamometric data and correlation analysis, and to identify the most informative biomechanical characteristics of the movement under research.

Materials and Methods

Participants

Educational research was conducted to examine the biomechanical parameters of the attacking throw in judo. The preparatory phase included selecting the sample, standardizing research procedures, and ensuring safe experimental conditions.

The research was conducted at the T. H. Shevchenko National University "Chernihiv Colehium" in a specialized biomechanical laboratory equipped with instruments for

conducting biomechanical research and high-precision measurement of force and time parameters of motor activity.

The general group (hereinafter – “GG”) consisted of 63 students aged 15–16 – pupils from general secondary schools in Chernihiv who were practicing judo at the beginner level. The model group (hereinafter – MG) included 14 high-level school students aged 15–16, among whom were candidates for the title of Master of Sports of Ukraine and medalists of Ukrainian championships.

The model group consisted of 10th-grade students from general secondary schools in Chernihiv and Kyiv, aged 15–16, who regularly practice judo and train at leading sports schools and clubs, including: the Chernihiv City Council Sports Wrestling Center, the “Fortuna” Children’s and Youth Sports School, Children’s and Youth Sports School No. 2, the “Yavara” Sports Club, the “JC Ippon Kyiv” Sports Club, and the “Young Spartak” Sports Club. The model group consisted of schoolchildren with a high level of training (Candidate Masters of Sports, prize winners of Ukrainian championships), which made it possible to determine the model biomechanical parameters for performing an attacking throw and to use them to construct an original biomechanical model of the technical action under research and for further comparative analysis.

All participants were informed of the research’s purpose, objectives, and procedures and provided written informed consent to participate. Since all participants were minors at the time of the research, written informed consent was also obtained from their parents or legal guardians. The research included schoolchildren of the same age and weight categories, which ensured the homogeneity of the sample and minimized the impact of anthropometric differences on the research results. The research was conducted in accordance with generally accepted ethical principles for educational research involving schoolchildren. Before the experiment began, all participants underwent a preliminary medical examination and received detailed instructions on how to perform the research procedures.

Research Design

The research procedure consisted of a preparatory phase and an experimental phase, each of which had clearly defined objectives and was designed to ensure the reliability and reproducibility of the results obtained.

All participants performed the same technical movement – the throw over the hip (O-goshi).



Fig. 1. Execution of the throw over the hip (O-goshi): a – starting position and grip; b – the initial phase of the throw, involving a step-in and bringing the hip under the opponent’s center of gravity

All participants performed a throw over the hip (O-goshi) on a standard training dummy, whose weight corresponded to that of the schoolchild performing the technique. Each participant performed three trials under identical experimental conditions following a standard warm-up. To minimize the impact of random variations and increase the reliability of the results, the subsequent statistical analysis used the average values of the biomechanical parameters obtained from the three trials of each participant.



Fig. 2. Experimental setup for researching the biomechanical characteristics of the O-goshi throw on a training dummy using a force plate

Force and time parameters were recorded using a calibrated force plate, which ensured highly accurate measurement of the reaction force during the execution of the movement. The force plate automatically recorded the “force-time” curves during each throw.

For further analysis, all recorded parameters were grouped into three categories: force parameters, time parameters, and combined force-time parameters.

Specifically, the maximum thrust force relative to the vertical axis (F_{zmax}) was $1,544.48 \pm 123.41$ N, and the maximum resultant force (F_{max}) was $1,549.53 \pm 129.37$ N. The relative force ratio (F_{max}/P) was 2.66 ± 0.21 . The force gradient (GRAD), which characterizes the rate of increase in muscle effort, was $5,945.82 \pm 442.18$ N/s. The force impulse (I) was 208.71 ± 17.86 N·s. The temporal characteristics of the movement were as follows: takeoff time (T_{ps}) – 0.09 ± 0.01 s; time to reach maximum force (T_{max}) – 0.16 ± 0.02 s. The total time of the push-off phase ($T_{max}+T_o$) was 0.21 ± 0.02 s, and the total time of the movement (T_{sum}) was 0.43 ± 0.04 s.

The maximum height of the center of mass (H_{max}) was 0.08 ± 0.01 m, which characterizes the vertical displacement of the body during the performance of the movement under research.

Based on the obtained data, a graphical biomechanical model was constructed (Fig. 3), which reflects the relative contribution of biomechanical characteristics to the structure of the throw under research, expressed as a percentage.

The author’s graphical biomechanical model demonstrates the relative contribution of individual parameters to the structure of the throw under research. The highest values of relative contribution were found for the force gradient (GRAD), relative maximum force (F_{max}/P), takeoff time (T_{ps}), and maximum force characteristics (F_{zmax} , F_{max}). Other indicators are also represented in

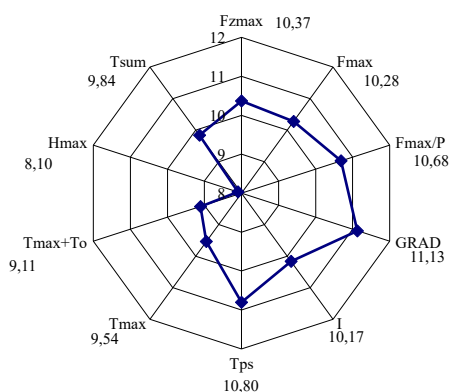


Fig. 3. The author's graphical model of the biomechanical parameters of throws over the hip in highly trained schoolchildren

the model's structure and characterize the temporal, spatial, and force-time characteristics of the movement's execution. The resulting distribution indicates the complex nature of the interrelationships among the biomechanical parameters under research during the execution of the throw over the hip (O-goshi).

Statistical Analysis

Statistical analysis of the obtained data was performed using SPSS software (IBM Corp., USA).

Descriptive statistics (mean and standard deviation) were calculated for all biomechanical parameters, which allowed us to characterize the central tendency and variability of the studied parameters.

To determine the relationships between biomechanical parameters, correlation analysis was performed using Pearson's correlation coefficient (r). The strength of the correlations was interpreted in accordance with generally accepted statistical approaches.

A comparative analysis of the indicators for the general and model groups was performed using Student's t -test for independent samples.

To construct the author's biomechanical model, a data normalization method was used. In the first stage, for each indicator, the sum of the absolute values of the correlation coefficients (Σr) was calculated, which characterized the degree of its integration into the system of interrelationships among the studied parameters. In the second stage, the obtained values were normalized relative to the total sum of the correlation coefficients of all indicators, followed by the determination of their percentage contribution to the structure of the author's biomechanical model.

The level of statistical significance was set at $p < 0.05$.

Results

Descriptive characteristics of biomechanical parameters.

Analysis of the tensodynamometric data and the results of the correlation analysis made it possible to determine the relative contribution of individual biomechanical parameters to the structure of the authors' model of the throw over the hip (O-goshi) in highly trained schoolchildren (Fig. 4).

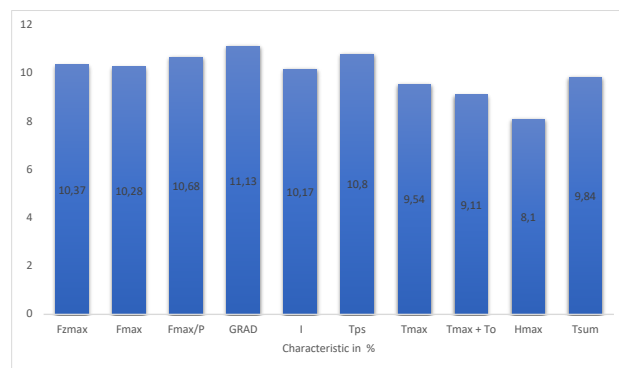


Fig. 4. Biomechanical parameters of attacking throws among highly trained schoolchildren (%)

The obtained values ranged from 8.10 % to 11.13 %, indicating a relatively uniform distribution of the contributions of the studied biomechanical parameters to the structure of the authors' model.

The highest relative contribution was demonstrated by the force gradient (GRAD), which amounted to 11.13 %. High values were also characteristic of relative maximum force (Fmax/P) – 10.68 %, preparatory phase time (Tps) – 10.80 %, maximum vertical ground reaction force (Fzmax) – 10.37 %, and resultant maximum force (Fmax) – 10.28 %.

The force impulse index (I) was 10.17 %. The time characteristics had the following contribution values: time to reach maximum force (Tmax) – 9.54 %, total duration of the push-off phase (Tmax+To) – 9.11 %, and total duration of the movement (Tsum) – 9.84 %. The smallest relative contribution was found for the maximum vertical displacement of the center of mass (Hmax), which was 8.10 %.

The resulting distribution indicates the comprehensive nature of the biomechanical model developed, within which all studied parameters are characterized by relatively similar values of relative contribution and reflect various aspects of the force, time, and force-time structures of the throw over the hip (O-goshi).

Comparative Analysis of Biomechanical Parameters in Schoolchildren of Different Fitness Levels

To verify the validity of the author's biomechanical model, a comparative analysis was conducted of the performance metrics of highly trained students in the model group (MG, $n = 14$) and students who were at the initial stage of judo training (CG, $n = 63$). The results of the comparison are presented in Table 4 and Figure 4.

The analysis revealed statistically significant differences in all biomechanical parameters studied ($p < 0.05$). The greatest intergroup differences were observed in the force gradient (GRAD) parameter, which was 47.56 % higher in the model group than in the general group. Significant differences were also found in the indicators of maximum center-of-mass displacement (Hmax) – 41.82 %, force impulse (I) – 38.99 %, relative maximum force (Fmax/P) – 38.54 %, and time to reach maximum force (Tmax) – 38.46 %.

The values for maximum vertical reaction force (Fzmax) and maximum resultant force (Fmax) among students in the model group were 35.49 % and 35.19 % higher, respectively,

Table 1. Biomechanical parameters of attacking throws in beginner at beginner and highly trained schoolchildren

No.	Characteristics	Unit of measur.	GG (n = 63)	MG (n = 14)	Diff. in %	P (темп.)
1	Fzmax	N	1139.94 ± 98.56	1544.48 ± 123.41	35.49	< 0.05 (15.634)
2	Fmax	N	1146.15 ± 103.16	1549.53 ± 129.37	35.19	< 0.05 (14.876)
3	Fmax/P	-	1.92 ± 0.17	2.66 ± 0.21	38.54	< 0.05 (16.751)
4	GRAD	N/s	4029.43 ± 321.59	5945.82 ± 442.18	47.56	< 0.05 (21.110)
5	I	Ns	150.16 ± 12.76	208.71 ± 17.86	38.99	< 0.05 (16.027)
6	Tps	s	0.14 ± 0.01	0.09 ± 0.01	35.71	< 0.05 (22.361)
7	Tmax	s	0.26 ± 0.02	0.16 ± 0.02	38.46	< 0.05 (22.361)
8	Tmax+To	s	0.32 ± 0.02	0.21 ± 0.02	34.38	< 0.05 (24.597)
9	Hmax	m	0.06 ± 0.01	0.08 ± 0.01	41.82	< 0.05 (10.286)
10	Tsum	s	0.67 ± 0.05	0.43 ± 0.04	35.82	< 0.05 (24.623)

compared to students at the beginner level of training. At the same time, students with a high level of training exhibited lower values for the time parameters Tps, Tmax, Tmax+To, and Tsum, indicating a faster realization of force potential during the execution of attacking technical actions.

A visual analysis of the profiles presented in Table 1 reveals significant differences in the structure of force-time characteristics between the groups. The profile of the model group is characterized by higher values of force indicators (Fzmax, Fmax, Fmax/P, GRAD, I) and lower values of time parameters (Tps, Tmax, Tmax+To, Tsum), reflecting a more efficient organization of the movement and a higher level of utilization of speed-strength capabilities during the execution of attacking throws.

The results obtained indicate significant differences in the biomechanical organization of attacking throws among schoolchildren of varying fitness levels. The indicators of the model group can be considered as indicative model characteristics of the biomechanical profile of attacking throws in schoolchildren with a high level of fitness and can be used for biomechanical monitoring and comparative analysis of schoolchildren's fitness levels.

A comprehensive analysis of the results showed that the average magnitude of intergroup differences across all biomechanical parameters studied was 38.20 %, in favor of the students in the model group. This indicates significant differences in the structure of the force-time characteristics of attacking throws between students with a high level of training and those with a beginner level of training. The greatest differences were recorded for the force gradient (47.56 %), while the smallest were for the resultant maximum force (35.19 %). The data confirm that the level of training is accompanied by complex changes in both the force and time components of the motor action.

Correlation Analysis

Correlation analysis made it possible to determine the nature of the relationships between the biomechanical parameters of attacking throws studied in highly trained schoolchildren (Table 1).

Numerous statistically significant, strong correlations were found between the force, time, and force-time characteristics of the motor action. The strongest positive

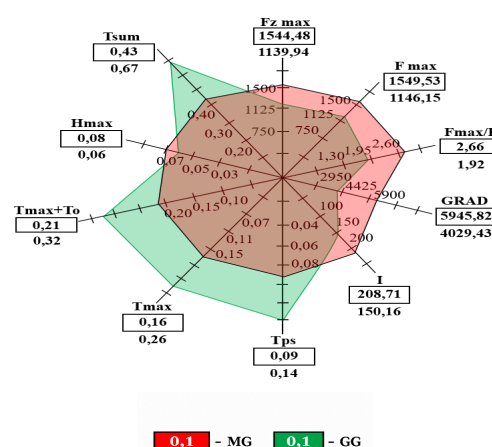


Fig. 5. Biomechanical profile of the throws over the hip in elementary school students (GG) and highly trained schoolchildren (MG)

correlations were found between the force gradient (GRAD) and the maximum vertical ground reaction force (Fzmax; $r = 0.998$), as well as between the force gradient and the force impulse (I ; $r = 0.998$). A very strong positive correlation was found between the maximum vertical ground reaction force and the resulting maximum force ($r = 0.938$), between force impulse and relative maximum force ($F_{\max}/P$; $r = 0.926$), as well as between force impulse and maximum vertical ground reaction force ($r = 0.925$).

An analysis of the time parameters revealed strong positive correlations between the preparatory phase time (Tps) and the total movement duration (Tsum; $r = 0.992$), between the preparatory phase time and the time to reach maximum force (Tmax; $r = 0.916$), as well as between the preparatory phase duration and the total duration of the push-off phase (Tmax+To; $r = 0.914$). This indicates a high level of coordination in the temporal structure of attacking technical actions.

Strong inverse correlations prevailed between force and time measures. Specifically, a correlation of $r = -0.988$ was found between the force gradient and the duration of the preparatory phase; $r = -0.967$ between the force gradient and the time to reach maximum force; and $r = -0.876$ between the force impulse and the duration of the preparatory phase. The

Table 2. Correlation matrix of biomechanical parameters of attacking throws in highly trained schoolchildren, with the specified level of statistical significance ($p < 0.05$)

Throw	Fzmax	Fmax	Fmax/P	GRAD	I	Tps	Tmax	Tmax+To	Hmax	Tsum
Fzmax	1									
Fmax	0.938	1								
Fmax/P	0.918	0.893	1							
GRAD	0.998	0.925	0.864	1						
I	0.925	0.922	0.926	0.998	1					
Tps	-0.918	-0.916	-0.926	-0.988	-0.876	1				
Tmax	-0.907	-0.905	-0.926	-0.967	-0.874	0.916	1			
Tmax+To	-0.736	-0.758	-0.924	-0.951	-0.731	0.914	0.634	1		
Hmax	-0.698	-0.695	-0.783	-0.797	-0.634	0.792	0.532	0.628	1	
Tsum	-0.869	-0.886	-0.989	-0.998	-0.867	0.992	0.615	0.672	0.615	1
Sum r	7.91	7.84	8.15	8.49	7.75	8.24	7.27	6.95	6.17	7.50
%	10.37	10.28	10.68	11.13	10.17	10.80	9.54	9.11	8.10	9.84
Rank	4	5	3	1	6	2	8	9	10	7

results indicate that higher indicators of strength potential are accompanied by a reduction in the duration of individual phases of the movement.

The sum of the correlation coefficients for each indicator was used to determine its integral informativeness within the structure of the author's biomechanical model.

The highest integral values were found for the force gradient ($\Sigma r = 8.49$), the duration of the preparatory phase ($\Sigma r = 8.24$), and relative maximum force ($\Sigma r = 8.15$). Based on the normalized values of the sums of correlation coefficients, the relative contribution of each indicator to the overall structure of the author's biomechanical model was determined, which made it possible to rank the studied parameters according to their degree of integration into the system of attacking technical actions.

The resulting correlation structure confirms the integrated nature of the biomechanical organization of attacking throws and indicates a close interrelationship between force, time, and force-time characteristics in highly trained schoolchildren.

Discussion

The purpose of this research was to develop an original biomechanical model of the throw over the hip (O-goshi) in highly trained schoolchildren based on tensodynamometric measurements and correlation analysis.

The force gradient index (11.13 %) demonstrated the highest relative contribution to the model's structure. The results obtained are consistent with data from recent biomechanical studies, which emphasize the importance of rapid muscle force development during the execution of judo techniques. For example, Hamaguchi et al. (2024) note that the characteristics of the preparatory phases (kuzushi and tsukuri) are associated with the acceleration characteristics of movement and the transfer of force impulse. The results of the present research complement these findings, demonstrating the high integration of the force rise rate indicator within the model structure.

Maximum force values (Fzmax – 10.37 %; Fmax – 10.28 %; Fmax/P – 10.68 %) were also characterized by high relative contribution values. Similar conclusions have been reported in biomechanical studies of the Sode-tsurikomi-goshi and Tsurikomi-goshi techniques, where peak accelerations and kinematic parameters of movement were associated with a high level of athletic proficiency (Pantelidou et al., 2025). In contrast to these studies, which focused primarily on segmental kinematics, the results of this research complement them with data on the role of support reaction parameters in the structure of the biomechanical model.

The high contribution of maximum force variables is also consistent with findings from other judo throwing techniques. Pucsok et al. (2001) showed that advanced performers of Harai-goshi differed from novices in support-leg force application, whereas Liu et al. (2025) reported significant relationships between ground-reaction-force components and sweeping-leg velocity in osoto-gari. Although the mechanical structure of these techniques is not identical to O-goshi, the common pattern is that proficient throwing requires effective conversion of support forces into rapid whole-body and segmental motion. In the present research, the higher Fzmax, Fmax, Fmax/P, and GRAD values in the model group are consistent with this broader biomechanical pattern.

Force impulse (10.17 %) also demonstrated a high level of integration within the system of parameters under research. Previous studies have established a link between impulse characteristics and indicators of sport-specific performance in judo (Ho et al., 2025). The results of this research complement these findings, demonstrating the relationship between force impulse and the force and force-time characteristics of the throw over the hip.

The time parameters (Tps, Tmax, Tmax+To, Tsum) were characterized by relative contribution values ranging from 9.11 % to 10.80 %. The results obtained are consistent with multidimensional concepts of athletic performance in judo, which emphasize the integration of neuromuscular, technical, and coordinative components (Schoof et al., 2024).

The temporal differences observed between the groups should therefore be interpreted together with the spatial and rotational organization of the movement. Ishii et al. (2018) found that elite seoi-nage performers generated greater relative forward center-of-mass velocity, while Liu et al. (2024) reported larger angular momentum and segmental angular velocities in black-belt than in white-belt judokas. Recent studies of seoi-nage further identify center-of-mass control, propulsion, and angular momentum transfer as objective markers of proficient throwing performance (Ishii & Koshida, 2025, 2026). From this perspective, the inverse correlations between force and time parameters in the present research may reflect a more compact and coordinated realization of force during the throw rather than an isolated reduction in movement duration.

The use of force plate analysis is in line with the current trend toward objective, quantitative assessment of biomechanical parameters (Xue, Han & Zhu, 2025). Unlike wearable sensor systems, the force platform provides highly accurate measurements of ground reaction forces and temporal characteristics of movement, which enables the development of integrated biomechanical models.

It is important to note that the relatively narrow range of normalized contributions (8.10–11.13 %) indicates the systemic nature of the biomechanical organization of the throw over the hip.

The practical significance of the author's model lies in the ability to use the obtained biomechanical indicators for biomechanical monitoring, comparative analysis of the characteristics of the throw over the hip (O-goshi) among schoolchildren of different fitness levels, further research of the biomechanical structure of technical movements in judo, and the development of the author's technical training methodology. The obtained values of force gradient, maximum force indicators, and force impulse can be used as indicative model characteristics.

For application in school-age athletes, the proposed values should be treated as reference characteristics for comparable age and training groups rather than as universal normative thresholds. Research in youth judo has shown that maturation, growth, and training experience contribute to neuromuscular and judo-specific performance (Detanico et al., 2020, 2022). Moreover, competitive level in judo can be differentiated by a combination of biomechanical, anthropometric, and sport-specific performance variables rather than by a single indicator (Teixeira et al., 2022). This supports using the proposed O-goshi profile as a multidimensional monitoring tool and interpreting changes in relation to the athlete's developmental and training context.

The limitations of the research include the relatively small sample size ($n = 14$), the analysis of only one technical movement (O-goshi), the use of force-measurement data without simultaneous assessment of the kinematic characteristics of the movement, and the inclusion of only male schoolchildren aged 15–16 years.

A separate limitation is the absence of a direct assessment of the technical effectiveness of the throw using expert evaluation, performance indicators, or other objective criteria of technical proficiency. Therefore, the results obtained characterize only the biomechanical features of the O-goshi throw and do not provide a basis for a direct assessment of the technical preparedness of school-age judo athletes.

The proposed biomechanical model can be used as a tool for the quantitative description and comparative analysis of the biomechanical characteristics of the movement, whereas establishing their relationship with technical effectiveness requires further research using additional evaluation criteria and the development of technical training methods based on the identified biomechanical patterns.

Conclusions

The research developed an original authors' biomechanical model of the throw over the hip (O-goshi) in highly trained schoolchildren based on tensodynamometric and correlation analysis. It was found that the greatest relative contribution to the structure of the developed model comes from the indicators of force rate of increase, maximum ground reaction force, and force impulse, which are characterized by a high degree of correlation with other biomechanical parameters of the movement under study.

An analysis of normalized contributions showed that the highest values of relative contribution are characteristic of the indicators of force rise rate, relative maximum force, maximum ground reaction force, and force impulse. The obtained results reflect the characteristics of the distribution of force, time, and force-time characteristics within the structure of the authors' biomechanical model.

The model group's measurements differed statistically significantly from those of schoolchildren at the initial stage of judo training across all biomechanical parameters studied ($p < 0.05$). The model characteristics obtained by the authors can be used for a comparative analysis of the biomechanical parameters of the throw over the hip (O-goshi) in schoolchildren of varying levels of training and for further research into the biomechanical structure of movement actions in judo.

Informed Consent

All participants were informed about the purpose, procedures, and conditions of the study before participation. Written informed consent was obtained from all participants. For participants under 18 years of age, additional written informed consent was obtained from their parents or legal guardians.

AI Transparency Statement

The authors declare that artificial intelligence tools were not used in the design of the study, data collection, data analysis, statistical processing, interpretation of the results, or formulation of scientific conclusions. ChatGPT (OpenAI, USA) was used exclusively for linguistic editing and grammatical improvement of the manuscript. The authors reviewed and approved all AI-assisted revisions and take full responsibility for the accuracy, integrity, and scientific content of the final manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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Біомеханічні параметри атакувальних кидків як основа технічної підготовки в дзюдо

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Мета дослідження. Сучасний розвиток фізичного виховання школярів потребує ефективних засобів удосконалення рухових навичок, координаційних і швидко-силових здібностей. Одним із таких засобів є дзюдо, ефективність навчання технічних дій якого значною мірою залежить від об'єктивного оцінювання біомеханіки рухів. Метою дослідження було визначити біомеханічні параметри кидка O-goshi у школярів високої спортивної кваліфікації, розробити оригінальну біомеханічну модель на основі тензодинамометричних показників і кореляційного аналізу та визначити найбільш інформативні характеристики структури руху.

Матеріали та методи. У дослідженні взяли участь 77 учнів старшого шкільного віку чоловічої статі 15–16 років. Загальну групу (n = 63) становили початківці в дзюдо, тоді як модельну групу (n = 14) — спортсмени високої кваліфікації (кандидати у майстри спорту України та призери чемпіонатів України). Біомеханічні параметри кидка O-goshi реєстрували за допомогою тензодинамометричної платформи. Аналізували силові (Fzmax, Fmax, Fmax/P, GRAD, I), часові (Trs, Tmax, Tmax+To, Tsum) та просторові (Hmax) параметри. Біомеханічну модель розроблено на основі даних модельної групи із застосуванням кореляційного аналізу та нормування сум абсолютних значень коефіцієнтів кореляції. Кожен учасник виконував три спроби; для аналізу використовували середні значення показників.

Результати. Найбільший відносний внесок у біомеханічну модель мав градієнт сили (11,13%). Високу інформативність також встановлено для максимальної вертикальної сили реакції опори (Fzmax — 10,37%), результуючої максимальної сили (Fmax — 10,28%) та імпульсу сили (10,17%). Сильні кореляційні зв'язки між силовими та силово-часовими параметрами свідчать про їх тісну взаємодію під час виконання кидка O-goshi.

Висновки. Розроблена біомеханічна модель дала змогу визначити найбільш інформативні силові, часові та силово-часові характеристики кидка O-goshi у школярів високої спортивної кваліфікації. Отримані результати можуть бути використані для біомеханічного контролю та порівняльного оцінювання техніки виконання кидка спортсменами різного рівня підготовленості.

Ключові слова: дзюдо, біомеханіка, силово-часові характеристики, О-гоші, біомеханічна модель, школярі.

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Sport for Inclusive Education: Effects on Motor and Socio-Relational Skills

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Abstract

Objectives. This exploratory feasibility study aimed to evaluate the applicability and effects on motor and socio-relational skills of an inclusive educational-motor intervention based on the game of bocchia in lower secondary school.

Materials and Methods. The study involved 80 students divided into a control group (n=40) and an experimental group (n=40). In particular, the experimental group participated in a 12-week program, structured into 24 sessions, designed according to the principles of Physical Literacy, Universal Design for Learning, inclusive physical education and cooperative learning. Conversely, the control group followed the standard school physical education curriculum. Both groups underwent baseline, post-intervention, and follow-up assessments using the Movement Assessment Battery for Children – Second Edition (MABC-2) for motor competence and the Social Skills Improvement System (SSIS) for social skills. Additionally, structured observations were conducted throughout the intervention to monitor participation, peer interactions, and inclusive behaviors.

Results. The findings demonstrated the feasibility of the protocol within the school context and indicated potential improvements in motor competence, active participation, and peer relational dynamics in the intervention group.

Conclusions. Therefore, the program based on bocchia emerges as a valuable educational strategy capable of promoting inclusive motor environments and supporting the overall development of students.

Keywords: inclusion, special educational needs, motor competence, inclusive physical education.

Introduction

Motor activities can perform a function not only oriented towards the development of physical abilities, but also an educational function, promoting social learning and inclusive participation (Nzuza & Chitiyo, 2024; Özkan & Kale, 2023). Although the available evidence indicates that structured physical activity may contribute to cognitive functioning, academic achievement, and well-being (Latino et al., 2025b; Kliziene et al., 2023), school-based research also highlights the relevance of the timing and organisation of movement for cognitive performance (Latino et al., 2025a). Further studies are therefore needed to examine interventions capable of simultaneously acting on motor and

socio-relational outcomes. Particular attention is directed towards students with Special Educational Needs (SEN) who, however, may encounter barriers to participation related to motor competence, communication, social interaction, or behavioural regulation, with the potential effect of limiting involvement in group activities and opportunities to establish relationships with peers (Schürer & van Ophuysen, 2022; Martin Ginis et al., 2016; Haegele & Sutherland, 2015). Therefore, inclusive physical education and sport contexts require attention to equity, individual needs, and appropriate adaptations (Ainscow, 2020; Di Palma & Tafuri, 2016; Jardinez & Natividad, 2024), while structured cooperative activities, peer support, and appropriately adapted tasks may facilitate participation and social interaction among students with and without disabilities (Liu et al., 2025; Dalgaard et al., 2022). Motor activity therefore represents a fundamental component of the development of children and adolescents,

contributing to physical health and motor competence (Beni et al., 2017; Burton et al., 2023; Logan et al., 2012), as well as to psychological well-being, social interaction, and participation in everyday life contexts (Fu et al., 2025; Wade et al., 2026). In the school context, physical education constitutes an important setting for promoting inclusive experiences, as movement-based activities can foster cooperation, peer relationships, and a sense of belonging (Qi & Ha, 2012; Kuspratiwi et al., 2026; Ojeda-Troncoso & Campos-Campos, 2025). From a broader health perspective, consideration of physical, behavioural, and physiological dimensions can support a multidimensional understanding of well-being and health-related outcomes (Di Maio et al., 2026). In light of these considerations, the present study aimed to explore the feasibility and preliminary effectiveness of a structured inclusive motor intervention, based on *boccia*, aimed at lower secondary school students; more precisely, the study analysed changes in motor competence, assessed through the Movement Assessment Battery for Children–Second Edition (MABC-2) (Brown, 2021), and in socio-relational skills, assessed through the Social Skills Improvement System (SSIS) (Elliott & Gresham, 2021), at the three assessment time points (T0, T1, and T2), while simultaneously monitoring participation and peer-oriented behaviours through a structured observational checklist. In this regard, a motor-educational programme based on the discipline of *boccia* was structured, particularly suitable for this purpose due to its high degree of adaptability and the potential involvement of students with different levels of motor ability. *Boccia* in fact requires the integration of skills such as precision, planning, movement control, and decision-making, which can nevertheless be exercised through differentiated strategies and levels of difficulty; in particular, playing distances, equipment, rules, and participation roles can be adapted according to the characteristics and individual needs of the students, allowing shared objectives to be maintained within heterogeneous groups. These characteristics make *boccia* a potentially appropriate context for promoting participation, cooperation, and peer interaction in an inclusive motor environment.

Materials and Methods

Study Design

The study was designed as a feasibility and exploratory preliminary effectiveness study, with a controlled pre-post design and an 8-week follow-up assessment. It involved 80 students attending lower secondary school, divided into an experimental group ($n = 40$), which participated in the inclusive motor activity program, and a control group ($n = 40$), which continued the usual school activities included in the curriculum. Among the participants, 20 students had Special Educational Needs (SEN), equally divided between the two groups. The specific objective of the work was to evaluate the feasibility of an inclusive motor activity program based on the game of *bocce* in lower secondary school, analyzing participants' adherence, the feasibility of the protocol and participation during the activities and, in parallel, the secondary objective was to explore the potential effects of the intervention on students' motor coordination and socio-relational skills. The study was classified as a feasibility and

exploratory preliminary effectiveness study rather than as a definitive effectiveness trial because the primary purpose was to assess the practicality, acceptability, adherence, retention, and implementation of the intervention and to obtain preliminary estimates of its potential effects. This approach is consistent with methodological recommendations for randomised pilot and feasibility studies, which emphasize the assessment of feasibility, acceptability, implementation, retention, and preliminary estimates of outcomes before a definitive trial (Eldridge et al., 2016). The controlled design was adopted to provide preliminary information on outcome variability, intervention-related changes, and the suitability of the assessment procedures for informing future adequately powered studies; accordingly, the effectiveness analyses were considered exploratory, and the findings were interpreted as preliminary estimates rather than as confirmatory evidence of intervention efficacy. Precisely, the assessments were carried out at three specific time points, an initial time (T0) representing the baseline, at the end of the intervention (T1) and a third time interval represented by the follow-up (T2) 8 weeks after the conclusion of the program. More precisely, the exploratory outcomes were assessed through the Movement Assessment Battery for Children (MABC-2) for motor coordination and the Social Skills Improvement System (SSIS) for socio-relational skills and the feasibility of the intervention was assessed through the participation rate in the sessions, adherence to the program, completion of the planned assessments and structured observation of participation during the activities.

Participants

The study involved 80 participants from lower secondary school, all regularly attending school activities. The mean age of the sample was 12.1 ± 0.8 years; more precisely, the experimental group consisted of 22 males (55%) and 18 females (45%), while the control group included 21 males (52.5%) and 19 females (47.5%). Overall, 20 students, representing a heterogeneous sample, presented Special Educational Needs (SEN), including specific learning disorders, attention deficit/hyperactivity disorder, neurodevelopmental disorders and other certified conditions, equally distributed between the experimental group and the control group ($n = 10$ per group). Given the relatively small size and heterogeneity of the SEN subgroup, separate inferential analyses were not considered sufficiently robust for the purposes of the present exploratory study; therefore, the SEN subgroup was described in terms of its distribution across the experimental and control groups, while no separate estimates of intervention effects were calculated for students with SEN. This approach was adopted to avoid potentially unstable or misleading subgroup estimates arising from the limited sample size. The sample size was determined a priori based on the feasibility and exploratory objectives of the study. In accordance with methodological recommendations for pilot studies, the sample size was intended to provide sufficient information on recruitment, participation, adherence, assessment completion, retention, and preliminary estimates of outcome variability and effect sizes rather than to provide definitive evidence of intervention efficacy (Julious, 2005). Accordingly, a target sample of 80 students, equally allocated between the experimental

and control groups ($n = 40$ per group), was considered appropriate for evaluating the feasibility of implementing the intervention in the school setting and for informing the design of future adequately powered studies. No formal *a priori* power calculation was therefore performed, as the study was not designed to provide definitive evidence of intervention efficacy. The estimates obtained from this study may inform the sample-size planning of future adequately powered controlled studies. Specifically, the inclusion criteria comprised regular school attendance, the ability to participate in the proposed motor activities and the availability of informed consent signed by parents or legal guardians; whereas the exclusion criteria included medical or physical conditions that prevented safe participation in the activities included in the study protocol, as well as the unavailability of informed consent. Therefore, before the start of the activities, signed informed consents from parents or legal guardians were collected for participation and all procedures were conducted in compliance with the ethical principles of educational research.

Procedure

Following recruitment and eligibility screening, participants were individually randomly allocated in a 1:1 ratio to the experimental or control group using a simple randomization procedure, the random allocation sequence was generated in Microsoft Excel using a random-number function, and participants were assigned to the experimental or control group according to the resulting sequence. The allocation was performed before the beginning of the intervention, with 40 participants initially allocated to each group and among the 20 students identified as having Special Educational Needs (SEN), 10 were allocated to the experimental group and 10 to the control group as a result of the random allocation.

The intervention lasted 12 weeks, with two weekly 60-minute sessions (24 sessions; 24 hours). A follow-up assessment was conducted 8 weeks after completion. The intervention took place in the school gym during regular school hours. The control group carried out the usual motor education activities included in the school curriculum, while the experimental group participated in the structured intervention protocol. Before the beginning of the intervention, all participants underwent a baseline assessment (T0) under the same standardized conditions. The assessment protocol included the Movement Assessment Battery for Children–Second Edition (MABC-2) for motor competence and the Social Skills Improvement System (SSIS) for social skills and behavioural characteristics related to peer interaction. At the end of the 12-week intervention period, both groups were reassessed (T1) using the same procedures, instruments, and administration conditions adopted at baseline. An additional follow-up assessment (T2) was conducted eight weeks after the conclusion of the intervention using the same instruments and standardized procedures to explore the short-term maintenance of changes observed after the intervention.

Throughout the intervention, students' participation, engagement and social interactions during motor activities were monitored through structured observational procedures. Attendance, completion of assessment

procedures, and adverse events were recorded throughout the study. In addition, the intervention instructor maintained a session diary documenting attendance, activities implemented, adaptations introduced, and relevant descriptive observations concerning participation and interaction. These records supported the evaluation of feasibility and implementation. UDL-based adaptations concerned task difficulty, playing space, equipment, rules, scoring, and participation roles. Each session followed the same four-part structure: (i) general motor activation (10 minutes); (ii) development of bocchia-specific skills (20 minutes); (iii) inclusive and cooperative game situations (20 minutes); and (iv) feedback and reflection (10 minutes). Across the 12 weeks, activities progressed from familiarization and basic participation to technical skill development, strategic and cooperative problem-solving, consolidation and autonomous participation, and a final inclusive event. The detailed progression is reported in Table 1. The intervention was informed by Physical Literacy, Inclusive Physical Education, Universal Design for Learning (UDL) and cooperative learning principles (Catama, 2025; Zach et al., 2023; Latino et al., 2025b). Accordingly, tasks, equipment, rules, playing distances and participation roles were adapted when necessary to allow students with different abilities (Di Palma & Tafuri, 2016; Kasari, et al., 2012) to work toward shared objectives within the same activity environment (Valle-Muñoz et al., 2025).

Intervention

The intervention was structured as a progressive inclusive educational-motor programme based on bocchia, designed to promote motor learning, participation, and peer collaboration, the programme was organized into sequential phases, with specific objectives and activities tailored to progressively develop students' motor and social skills, as summarized in Table 1.

Measures

Assessments were carried out at three time points: before the beginning of the intervention (T0), at the end of the 12-week intervention (T1), and at follow-up (T2), conducted eight weeks after the conclusion of the program. Consistent with the feasibility and exploratory nature of the study, the outcomes were categorized as feasibility outcomes, process outcomes, and exploratory effectiveness outcomes. The primary outcomes concerned the feasibility of implementing the inclusive motor activity program within the school context. Feasibility was assessed through the participation rate, calculated as the percentage of completed sessions out of the total number of scheduled sessions, the completion rate of the assessment procedures at T0, T1, and T2, participant retention throughout the study, and the occurrence of adverse events during the intervention. Process outcomes were assessed through a structured observation checklist developed for the purposes of the present study based on indicators described in the literature on inclusive physical education, participation, and adapted motor activity (Roberts & Fairclough, 2012; Cairney et al., 2019; Gilmore et al., 2019). The checklist was developed to capture observable dimensions of participation and social interaction that were

Table 1. Structure of the inclusive educational-motor intervention based on boccia

Phase	Period	Main objectives	Planned activities
1. Familiarization and construction of the inclusive context	Weeks 1–2	To promote knowledge of the discipline, create a positive group climate, and encourage the participation of all students. To develop initial skills in equipment manipulation and control.	Presentation of boccia and fundamental rules; free and guided exploration of materials; exercises involving grasping, carrying, and throwing; individual and pair activities; cooperative games without scoring aimed at promoting mutual knowledge and peer collaboration.
2. Development of specific motor skills	Weeks 3–5	To enhance the motor components involved in boccia: hand-eye coordination, force control, precision, and movement planning.	Progressive throwing exercises towards static and dynamic targets; variation of distances from the jack; activities aimed at regulating throwing force and direction; precision tasks with individualized feedback; adaptation of space, materials, and difficulty according to students' ability levels.
3. Application of skills and strategic development	Weeks 6–8	To integrate technical skills with cognitive and social processes such as decision-making, problem-solving, and communication with teammates.	Simplified game situations progressively increasing in complexity; pair and small-group activities; selection of throwing strategies according to the position of the boccia balls; discussion of possible solutions; cooperative exercises with differentiated roles (player, observer, peer support).
4. Consolidation, autonomy, and inclusive participation	Weeks 9–11	To promote autonomy in game management, a sense of responsibility, and active participation within the group.	Adapted matches with heterogeneous teams based on ability levels; progressive autonomous management of rules; role rotation; team strategies; peer feedback activities; use of cooperative scoring systems to value the contribution of each participant.
5. Final event and reflection on the experience	Week 12	To consolidate the acquired motor and social learning outcomes and enhance the inclusive pathway developed throughout the intervention.	Implementation of a final inclusive boccia tournament with adapted rules; collaborative game activities; guided final discussion on the experiences lived; individual and group reflection on motor, relational, and participatory aspects.

Note: UDL principles were applied throughout the intervention through adaptations of tasks, environment, materials, and participation roles.

considered directly relevant to the feasibility and inclusive implementation of the intervention. Four behavioural domains were included: (i) active participation in activities; (ii) collaboration with peers; (iii) spontaneous interaction with peers; and (iv) compliance with rules and turn-taking. These indicators were selected because they represent observable behaviours associated with active participation, peer interaction, cooperation, and engagement in inclusive motor activities. The checklist was completed during the intervention sessions by two independent observers, who independently rated the observed behaviours. Each indicator was scored on a 5-point Likert scale ranging from 1 to 5 (1 = never; 2 = rarely; 3 = sometimes; 4 = often; 5 = always). An overall checklist score was calculated as the mean of the four indicator scores, with higher scores indicating greater observed participation and more frequent socially inclusive behaviours. For process evaluation purposes, observations were conducted during the initial phase of the intervention (sessions 1–3) and during the final phase (sessions 22–24),

allowing changes in observed participation and interaction to be described over the course of the intervention. The checklist was not intended to function as a psychometrically validated outcome measure and was therefore used exclusively as a process and feasibility assessment tool, complementing the standardized MABC-2 and SSIS measures. To assess the consistency of ratings between observers, interobserver agreement was evaluated using the Intraclass Correlation Coefficient (ICC 2,1). The exploratory effectiveness outcomes included motor coordination and socio-relational skills, which were assessed at T0, T1, and T2 using standardized instruments. Motor competence was assessed using the Movement Assessment Battery for Children–Second Edition (MABC-2), a standardized instrument assessing manual dexterity, ball skills, and balance. Socio-relational skills were assessed using the Social Skills Improvement System (SSIS), a standardized measure of social skills and adaptive behaviours, including social interaction, cooperation, self-control, and peer relationships.

Data Analysis

Statistical analyses were conducted using a two-sided significance level of $p < 0.05$. Descriptive statistics (mean, standard deviation, frequencies and percentages) were calculated for all study variables. Because the study included three assessment occasions (T0, T1 and T2) and repeated observations within the same participants, the primary longitudinal analysis was performed using linear mixed-effects models (LMMs). Separate LMMs were fitted for MABC-2 and SSIS scores, with Group (experimental vs. control), Time (T0, T1 and T2) and the Group $\times$ Time interaction specified as fixed effects and participant specified as a random intercept to account for the correlation among repeated observations within participants. The Group $\times$ Time interaction was prespecified as the principal test of whether the trajectories of change differed between the experimental and control groups. This approach was selected because it allows all three measurement occasions to be modeled simultaneously, accounts for within-participant dependence, and provides a direct test of differential change between groups over time. Estimated marginal means, model-based contrasts and 95% confidence intervals were used to characterize the longitudinal pattern of change. Before the parametric analyses, the distribution of the outcome variables and model residuals was assessed using visual inspection of Q-Q plots and histograms and the Shapiro-Wilk test. Homogeneity of variance across group-by-time cells was examined using Levene's test. The assumptions were considered acceptable when no substantial departure from normality or heteroscedasticity was observed. In addition, residual diagnostics were inspected after model fitting. Baseline group characteristics were examined descriptively. Changes from baseline to post-intervention were also expressed as change scores ($\Delta = T1 - T0$) to facilitate descriptive interpretation of pre-post differences. The change scores were not considered the primary inferential evidence of intervention effectiveness, which was assessed using the longitudinal linear mixed-effects models and the Group $\times$ Time interaction. Pearson's correlation coefficient was used as an exploratory analysis to examine the association between changes in MABC-2 and SSIS scores ($\Delta = T1 - T0$). Feasibility indicators and observational checklist scores were analyzed descriptively; the initial-versus-final observational comparison was treated as a process evaluation. Interobserver reliability was assessed using ICC(2,1).

Results

Longitudinal analysis

Longitudinal changes were examined using linear mixed-effects models, with Group, Time, and the Group $\times$ Time interaction specified as fixed effects and participant included as a random intercept. The Group $\times$ Time interaction was considered the primary test of whether the longitudinal trajectory differed between the experimental and control groups. For MABC-2, the model showed a significant Group $\times$ Time interaction, $\chi^2_{(2)} = 6.78$, $p = 0.034$, indicating that changes across the three assessment occasions differed between the experimental and control groups. The estimated

between-group difference in change was significant at T1 ($\beta = 3.80$, $SE = 1.46$, 95% CI [0.94, 6.66], $p = 0.011$), whereas the corresponding estimate at T2 remained positive but did not reach conventional statistical significance ($\beta = 3.30$, $SE = 1.89$, 95% CI [-0.40, 7.00], $p = 0.085$). For SSIS, the model also showed a significant Group $\times$ Time interaction, $\chi^2_{(2)} = 6.18$, $p = 0.046$. The estimated between-group difference in change was significant at T1 ($\beta = 3.70$, $SE = 1.49$, 95% CI [0.78, 6.62], $p = 0.015$), whereas the corresponding T2 estimate remained positive but was not statistically significant ($\beta = 2.90$, $SE = 1.83$, 95% CI [-0.69, 6.49], $p = 0.118$).

Motor Competence (MABC-2)

Table 2. MABC-2 scores at baseline, post-intervention, and follow-up in the experimental and control groups

Group	T0	T1	T2	Δ T1-T0
Experimental	64.2 $\pm$ 8.9	68.7 $\pm$ 9.1	67.9 $\pm$ 8.7	+4.5
Control	63.8 $\pm$ 9.2	64.5 $\pm$ 9.0	64.2 $\pm$ 8.7	+0.7

Note. The primary inferential analysis was the linear mixed-effects model. The Group $\times$ Time interaction was significant, $\chi^2_{(2)} = 6.78$, $p = 0.034$. The estimated between-group difference in change was $\beta = 3.80$ ($SE = 1.46$, $p = 0.011$) at T1 and $\beta = 3.30$ ($SE = 1.89$, $p = 0.085$) at T2.

Socio-relational Skills (SSIS)

Table 3. SSIS scores at baseline, post-intervention, and follow-up in the experimental and control groups

Group	T0	T1	T2	Δ T1-T0
Experimental	87.3 $\pm$ 10.5	92.1 $\pm$ 10.8	91.5 $\pm$ 10.6	+4.8
Control	86.9 $\pm$ 10.1	88.0 $\pm$ 10.3	88.2 $\pm$ 10.4	+1.1

Note. The primary inferential analysis was the linear mixed-effects model. The Group $\times$ Time interaction was significant, $\chi^2_{(2)} = 6.18$, $p = 0.046$. The estimated between-group difference in change was $\beta = 3.70$ ($SE = 1.49$, $p = 0.015$) at T1 and $\beta = 2.90$ ($SE = 1.83$, $p = 0.118$) at T2.

Feasibility indicators

The intervention showed favorable feasibility indicators. The mean session participation rate was 88.5% in the experimental group, and no adverse events were recorded during implementation. Assessment completion was 100% at baseline (T0), 96.2% at post-intervention (T1), and 93.7% at follow-up (T2). These completion rates indicate good retention and feasibility of the assessment procedures throughout the study period. The observed participation and completion rates, together with the absence of adverse events, provide preliminary evidence that the intervention protocol could be implemented within the regular school context over the study period. At T1, 38/40 experimental participants and 39/40 control participants completed the assessment (77/80 overall). At T2, 37/40 experimental participants and 38/40 control participants completed the assessment (75/80 overall). The three T1 non-completions

(two experimental and one control) and the two additional T2 non-completions (one experimental and one control) were treated as missing observations; no values were imputed.

Results of Structured Observation

The structured observational checklist was used as a process evaluation measure to characterize students' participation, peer interaction, and inclusive behaviours during the intervention. The analysis showed a descriptive increase in behaviours associated with participation and social inclusion between the initial and final sessions. Inter-rater agreement was good, with an ICC of 0.84 (95% CI = 0.78–0.89). The four observed indicators showed higher descriptive values during the final sessions compared with the initial sessions (Table 4). Because the checklist was developed specifically for process evaluation and was not intended as a psychometrically validated outcome measure, these findings are reported as descriptive implementation indicators rather than independent evidence of intervention efficacy.

Table 4. Structured observation checklist scores

Indicator	Initial sessions	Final sessions
Active participation	3.35 ± 0.54	3.92 ± 0.51
Peer cooperation	3.21 ± 0.56	4.02 ± 0.48
Spontaneous peer interaction	3.02 ± 0.60	3.78 ± 0.55
Compliance with rules and turn-taking	3.54 ± 0.49	4.10 ± 0.43

Note. Checklist data were used exclusively as process indicators and were not treated as a primary efficacy outcome.

Exploratory Correlation Analysis

An exploratory correlation analysis examined the association between changes in motor competence and socio-relational skills from T0 to T1 among participants with complete T0–T1 data for both MABC-2 and SSIS ($n = 77$). The three participants who did not complete the T1 assessment were therefore excluded from this complete-case analysis. No missing values were imputed. The change in MABC-2 scores was moderately and positively correlated with the change in SSIS scores ($r = 0.34$, $p = 0.002$). This finding indicates that greater improvements in motor competence were associated with greater improvements in socio-relational skills during the intervention period. However, because this analysis was correlational, it does not establish a causal relationship between changes in the two domains.

Discussion

The present feasibility and exploratory study examined the potential contribution of a structured inclusive motor intervention based on boccia to the development of motor competence and socio-relational skills among lower secondary school students. The presence of a Group $\times$ Time interaction for MABC-2 and SSIS scores also indicates that the trajectories of change over time differed between

students who participated in the boccia-based intervention and those who continued with regular school activities. Moreover, the improvement observed in motor competence can be interpreted in relation to the specific characteristics of boccia and, although it is an activity accessible to students with different levels of motor ability, effective participation requires the integration of precision, force regulation, visuomotor coordination, postural control, anticipation, and movement planning (Herlitz et al., 2020; Qu, 2022; Hale et al., 2021). Therefore, the progressive organisation of the intervention provided students with repeated opportunities to practise these components through appropriately structured situations of increasing difficulty. From a Physical Literacy perspective, repeated and meaningful engagement in motor tasks may contribute not only to the development of motor competence, but also to greater confidence and willingness to participate in physical activities (Stodden et al., 2008; Piotrowski et al., 2025). The results concerning socio-relational skills are also particularly relevant when considered in relation to the educational structure of the intervention and, in this regard, boccia was not proposed exclusively as a motor activity, but as a cooperative learning environment in which students were required to communicate, share decisions, alternate roles, and pursue common goals. These characteristics may have created repeated opportunities for peer interaction, cooperation, and self-regulation. The improvement observed in SSIS scores may therefore be interpreted in relation to the social organisation of the intervention, rather than being considered exclusively as a consequence of participation in a sporting activity. This interpretation is consistent with previous evidence highlighting the role of inclusive physical education and meaningful cooperative experiences in promoting social interaction and participation among students with and without disabilities (Qi & Wang, 2018; Bertills et al., 2019; Sedláčková et al., 2025). A particularly relevant feature of the intervention was the possibility of maintaining common educational objectives while, at the same time, adapting the conditions of participation; therefore, playing distances, equipment, rules, task difficulty, and participation roles could be modified according to individual characteristics, without excluding students from the shared activity. From this perspective, the findings highlight the potential of boccia as a practical tool for applying the principles of Inclusive Physical Education and Universal Design for Learning within regular school activities. The observed association between changes in MABC-2 and SSIS scores also provides an interesting indication of the possible relationship between the motor and socio-relational dimensions. Although the correlational nature of this finding does not allow a causal relationship to be established, this evidence is consistent with a conception of motor activity as a multidimensional educational experience, in which physical, social (Wang et al., 2025), and relational processes may develop in an interconnected manner. Structured observations provided complementary information on participation and peer interaction during implementation. Another relevant aspect concerns the inclusion of students with Special Educational Needs within the same intervention framework. The participation of students with SEN in the same motor programme highlights the practical feasibility of implementing a common activity within a heterogeneous school population. Although the

small size of the subgroup does not allow specific conclusions to be drawn regarding differential intervention effects in relation to the presence of SEN, the possibility of involving these students in the same structured activities represents a relevant aspect of the programme and supports the need for future research involving larger samples of students with SEN. The follow-up assessment also provides a preliminary indication of the evolution of the changes observed after the end of the intervention; indeed, at T2, the experimental group maintained numerically favourable values compared with baseline in both assessment domains, although the magnitude of the differences was reduced compared with the post-intervention assessment. Future studies could therefore investigate whether longer programmes or maintenance-oriented interventions may contribute to consolidating the effects observed at the end of the intervention. In light of the exploratory nature of the study, however, some limitations should be taken into account when interpreting the findings. First, the sample size, although considered appropriate for the feasibility objectives, provided limited statistical power for a definitive assessment of effectiveness, and no formal a priori power calculation was performed because the study was designed primarily to assess feasibility and provide preliminary estimates of intervention effects. Second, the school context may have introduced variability related to students' previous motor experiences, previous opportunities for physical activity, and exposure to organised sports, which could not be systematically controlled. Overall, the findings provide preliminary support for the feasibility of an inclusive boccia-based motor intervention in the school context and suggest its potential to promote both motor competence and socio-relational development.

Conclusions

The present study supports the feasibility and potential effectiveness of an inclusive motor intervention in promoting motor competence and social inclusion in the school context, in line with the objectives and outcomes of the study. From a pedagogical perspective, these findings support the value of motor education as a context for promoting active participation, peer collaboration and an inclusive classroom climate, with opportunities for shared learning and meaningful participation.

Ethics Approval

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the University of Naples Parthenope (DiSMMeB, Prot. No. 88592/2024).

Informed Consent

Informed consent was obtained from all participants involved in the study.

Data Availability Statement

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

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Conflicts of Interest

The authors declare no conflicts of interest.

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Спорт для інклюзивної освіти: вплив на рухові та соціально-реляційні навички

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

Реферат. Стаття: 10 с., 4 табл., 42 джерела.

Мета дослідження. Це пошукове дослідження доцільності мало на меті оцінити застосування та вплив інклюзивної освітньо-рухової інтервенції на основі гри в бочку на рухові та соціально-реляційні навички учнів молодших класів середньої школи.

Матеріали та методи. У дослідженні взяли участь 80 учнів, які були розділені на контрольну групу (n=40) та експериментальну групу (n=40). Зокрема, експериментальна група брала участь у 12-тижневій програмі, структурованій із 24 занять. Цю програму було розроблено відповідно до принципів фізичної грамотності (Physical Literacy), Універсального дизайну в освіті (UDL), інклюзивного фізичного виховання та кооперативного навчання. Натомість контрольна група займалася за стандартною шкільною програмою з фізичної культури. Обидві групи пройшли первинне, постінтервенційне, а також повторне оцінювання через певний час за допомогою Батарей тестів для оцінки рухової активності дітей – друге видання (MABC-2) з метою визначення рухової компетентності та Системи вдосконалення соціальних навичок (SSIS) для оцінки соціальних навичок. Крім того, протягом усього періоду інтервенції проводилися структуровані спостереження для моніторингу рівня залученості, взаємодії з однолітками та інклюзивної поведінки.

Результати. Отримані дані продемонстрували доцільність впровадження протоколу в умовах шкільного контексту, а також вказали на потенційне покращення рухової компетентності, активної залученості та реляційної динаміки з однолітками в інтервенційній групі.

Висновки. Таким чином, програма на основі гри в бочку виступає як цінна освітня стратегія, здатна забезпечувати інклюзивне рухове середовище та підтримувати всебічний розвиток учнів.

Ключові слова: інклюзія, особливі освітні потреби, рухова компетентність, інклюзивне фізичне виховання.

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Determinants of Competency Development in Physical Education: The Mediating Role of Motivation and Engagement

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Abstract

Objectives. This study tested a serial mediation model examining how pedagogical feedback and prior sport experience are associated with the development of perceived competencies in physical education (PE) through the sequential mediating roles of motivation and engagement.

Materials and Methods. Participants were 248 undergraduate students (Year 1: n = 91; Year 2: n = 92; Year 3: n = 65; 125 males, 123 females) enrolled in a Bachelor's degree program in Physical Education and Sport at the École Normale Supérieure of Martil, Abdelmalek Essaâdi University, Morocco. Data were collected via an online, cross-sectional questionnaire comprising five eight-item Likert scales measuring motivation, perceived pedagogical feedback, engagement, prior sport experience, and perceived competency development, all self-reported by participants. Internal consistency was excellent for all scales (Cronbach's $\alpha > .91$). Two serial mediation models were tested using bootstrap resampling (5,000 iterations, 95% percentile confidence intervals).

Results. Both perceived pedagogical feedback and prior sport experience were significantly associated with perceived competency development. These relationships were partially accounted for by motivation and engagement (67% and 47% of the total association, respectively). Engagement emerged as the mediator most strongly associated with perceived competency development in both models. Notably, the indirect association through motivation alone was not significant for prior sport experience. No substantial differences were found across academic years, whereas prior competition participation correlated significantly with all five self-reported constructs. Given the cross-sectional, self-report design, these associations should not be interpreted causally.

Conclusions. Motivation and engagement operate as sequential, partially distinct mediators of the association between pedagogical feedback, prior sport experience, and perceived competency development. These findings offer important theoretical and practical implications for physical education teacher training, particularly regarding feedback design and differentiated support based on students' competitive backgrounds.

Keywords: engagement, feedback, motivation, physical education, self-efficacy, serial mediation, teacher training.

Introduction

The development of competencies in physical education (PE) among pre-service teachers constitutes a central issue in initial teacher training, insofar as the quality of this learning directly conditions their future professional practice. Teachers who enter the profession with well-developed technical, pedagogical, and reflective competencies are better equipped to design effective learning experiences, to

adapt their teaching to diverse student needs, and to sustain their own professional engagement over time. Conversely, gaps in competency development during training tend to persist into early career practice, making the identification of the levers that support this development during the university years a priority for teacher education research and policy alike.

While the literature agrees on the importance of student motivation and engagement in this process, the pathways through which contextual and experiential factors are associated with competency development remain insufficiently documented in the specific context of university-level PE teacher training. Much of the existing

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evidence on motivation and engagement in PE has been produced with school-age pupils rather than with pre-service teachers themselves, leaving open the question of whether, and how, the same motivational and experiential associations hold once students are the ones being trained to teach the subject. This gap is compounded by recent observational evidence suggesting that pedagogical competencies among PE pre-service teachers do not necessarily progress in a linear fashion across the years of training (Mellado-Berenguer & Monfort-Pañego, 2026; Salin, Huhtiniemi, Watt, Sääkslahti, & Jaakkola, 2025), which raises the question of which psychological factors, rather than seniority alone, are most closely associated with competency gains during PE teacher education.

Self-determination theory (Deci & Ryan, 1985, 2000) posits that the satisfaction of basic psychological needs — autonomy, perceived competence, and relatedness — fosters autonomous motivation, which is in turn a key determinant of engagement in learning. Vallerand's (1997) hierarchical model of intrinsic and extrinsic motivation complements this view by proposing that motivation operates at global, contextual, and situational levels, and that contextual factors specific to a given domain of activity — such as the feedback students receive during PE coursework — shape contextual motivation, which in turn cascades down to situational engagement in specific learning tasks. Pedagogical feedback, when perceived as informational rather than controlling, has been identified as a major lever supporting the sense of competence and, through it, autonomous motivation (Hattie & Timperley, 2007). This informational function of feedback has since been confirmed specifically within PE: a systematic review of feedback effects on motor skill learning concluded that descriptive, progress-oriented feedback consistently outperforms purely evaluative feedback in supporting PE learners (Zhou, De Shao, & Wang, 2021), while broader evidence on teachers' interpersonal behavior in PE similarly links supportive, informational styles to better learning outcomes (Tian & Shen, 2023).

Engagement itself is best understood as a multidimensional construct encompassing behavioral, cognitive, and emotional components, to which more recent work has added an agentic dimension reflecting students' proactive contribution to their own learning conditions (Fredricks, Blumenfeld, & Paris, 2004; Reeve, 2012; Reeve & Tseng, 2011). A recent conceptual refinement of the construct has further clarified this multidimensionality, distinguishing learning engagement from broader school engagement and addressing longstanding concerns of definitional overlap across the behavioral, cognitive, emotional, and agentic dimensions (Wong & Liem, 2022). This multidimensionality is theoretically important for the present study: it is precisely because engagement captures observable participation, sustained attention, and self-regulated effort — rather than a purely internal motivational state — that it is theorized to be the construct most proximal to perceived competency development, downstream from motivation itself.

In parallel, self-efficacy theory (Bandura, 1997) suggests that students' prior sport experience constitutes a source of mastery experiences likely to strengthen their engagement in physical activities, independently of its effect on motivation. This primacy of mastery experience among the sources of self-efficacy has recently received renewed empirical support

outside the PE context, in a study ranking the relative importance of Bandura's four sources of self-efficacy for physical activity and confirming mastery experience as the strongest predictor (Egele, Klopp, & Stark, 2025). Unlike feedback, which is a contextual factor delivered by the teacher within the training program, prior sport experience is a personal, biographical resource that students bring with them into training. Theoretically, these two predictors are therefore expected to operate through partially different pathways: feedback should act primarily through the motivational route described by self-determination theory, whereas sport experience should act more directly on engagement through the mastery-based mechanisms described by self-efficacy theory and by Harter's (1978) competence motivation framework.

Within the Moroccan and broader Maghreb context, research specifically addressing PE teacher training remains comparatively limited, although a growing body of work is beginning to fill this gap. Recent Moroccan research on the motivational dimension of PE has noted that empirical studies on the motivational dynamics of PE students remain scarce and scattered, despite increasing scholarly interest in the topic (Moumen & Koutaya, 2026). Direct evidence on the professional competencies of Moroccan PE student teachers points in a similar direction: an observational study of second-year PE trainees at the Faculty of Education Sciences in Rabat found only limited mastery of core professional competencies — didactic knowledge, communication, lesson planning, and learning management — highlighting a persistent gap between training objectives and trainees' actual classroom-ready skills (Mousmi, 2026). In neighboring Tunisia, the introduction of the LMD (Licence-Master-Doctorat) reform into PE teacher training institutes has similarly been described as a largely top-down process, implemented with limited empirical grounding in the realities of trainees' experience (Fraj, Desbiens, & Bali, 2023), and even the measurement of engagement itself among Maghrebi PE and sport students has only recently been placed on solid psychometric footing, with the first Arabic-language validation of a university student engagement inventory carried out on a large Tunisian PE and sport student sample (Tannoubi et al., 2023). Taken together, this regional literature underscores both the relevance and the timeliness of empirically grounded research into the psychological and experiential factors that shape competency development among Maghrebi PE trainees — a gap the present study seeks to help address.

Despite the richness of these theoretical frameworks, few studies have simultaneously tested the mediating role of motivation and engagement in the relationship between, on the one hand, pedagogical feedback and prior sport experience, and on the other hand, the development of perceived competencies in PE. A systematic review of the broader relationship between perceived teacher support and student engagement in PE confirmed a significant positive association across the available literature, while also noting that the underlying mediating mechanisms remain insufficiently tested (Guo et al., 2023). The closest antecedents to the present design come from two very recent studies among Chinese college PE students, which modeled teacher support as acting on engagement through self-efficacy and autonomous motivation (Guo et al., 2025) or through self-

efficacy and sport task orientation (Xu, Tan, Abdullah, & Baker, 2025). While these studies confirm that support-type variables operate on PE engagement through sequential psychological mechanisms, neither examined pre-service PE teachers specifically, neither combined a contextual predictor (feedback) with a biographical predictor (prior sport experience) within the same serial model, and neither tested motivation and engagement — as conceptually distinct from self-efficacy or task orientation — as sequential mediators. Existing research has, more broadly, often examined pedagogical feedback and prior sport experience separately, or has modeled motivation and engagement as parallel rather than sequential mediators, which limits the ability to test whether motivation is a necessary step toward engagement or whether the two constructs are independently associated with the effects of distal predictors. Moreover, this question has rarely been addressed within the specific population of PE teacher trainees, whose profile — combining formal academic training with often extensive personal sporting backgrounds — makes the relative contribution of pedagogical versus experiential factors a particularly relevant empirical question.

The present study aims to address this gap by testing a serial mediation model among undergraduate PE students, in which pedagogical feedback and prior sport experience are modeled as distal predictors, motivation and engagement as sequential mediators, and the development of perceived competencies in physical education as the outcome. Based on this theoretical framework, the following hypotheses were formulated:

H1: Pedagogical feedback positively predicts students' motivation.

H2: Prior sport experience positively predicts students' motivation and engagement.

H3: Motivation positively predicts engagement.

H4: Motivation and engagement serially mediate the association between (a) pedagogical feedback, (b) prior sport experience, and the development of perceived competencies in physical education.

Materials and Methods

Participants

The target population consisted of students enrolled in the Bachelor's degree program in Physical Education and Sport (Year 1 to Year 3) at the École Normale Supérieure of Martil, affiliated with Abdelmalek Essaâdi University. The actual number of students enrolled and actively pursuing their PE-BA training for the 2025–2026 academic year was 632 (Year 1: $n = 176$; Year 2: $n = 258$; Year 3: $n = 198$). The questionnaire, distributed electronically with the agreement of the department's academic coordinators, collected 261 responses, corresponding to a response rate of 41.3%. After data cleaning (see Results), the final analyzed sample comprised $N = 248$ PE undergraduate students (Year 1: $n = 91$; Year 2: $n = 92$; Year 3: $n = 65$; 125 males, 123 females).

Study Design

A cross-sectional survey design was used. A non-probability convenience sampling method was applied: the

questionnaire was distributed electronically (Google Forms) to students, with the agreement of the relevant academic coordinators, between March and July 2026. Participation was voluntary and anonymous.

Procedures and Instruments

The questionnaire included a profile section (age, sex, year of study, regular sport practice, prior competition participation, practice frequency) followed by five scales of eight items each, measuring respectively motivation, perceived pedagogical feedback, engagement, prior sport experience, and perceived competency development in physical education. All five scales are self-report measures: they capture students' own perceptions and self-assessments rather than externally observed or objectively assessed behaviors or skills. In particular, the outcome variable — referred to throughout as “competencies” for brevity in tables and figures — reflects students' perceived or self-reported development of competencies, not an observer-rated or performance-based assessment of actual motor or pedagogical competence; this terminology is used consistently throughout the manuscript. Each item was rated on a five-point Likert scale (1 = Strongly disagree; 5 = Strongly agree).

Data were collected via an online form. An information notice specified the scientific purpose of the study, the anonymous nature of the responses, and their strictly academic use. Participants' consent was implicit upon submission of the form, consistent with usual practice for minimal-risk, non-interventional surveys in educational science.

Because the data are cross-sectional and self-reported, all statistical relationships reported in this manuscript — including regression coefficients, correlations, and indirect/direct paths in the mediation models — are interpreted as associations rather than as evidence of causal influence. Terms such as “predictor,” “indirect effect,” and “direct effect” are used in their standard statistical sense, as conventionally defined in the mediation analysis literature (Hayes, 2018), and do not imply a causally verified sequence of events.

Instrument Development

The five scales were developed specifically for this study rather than adapted from previously validated instruments. Item generation was guided by the theoretical frameworks described in the Introduction: self-determination theory (Deci & Ryan, 1985, 2000) for the motivation scale, with items addressing interest, enjoyment, effort, and persistence; the feedback literature (Hattie & Timperley, 2007) for the pedagogical feedback scale, with items addressing the frequency, clarity, and perceived usefulness of teacher feedback; multidimensional engagement models (Fredricks, Blumenfeld, & Paris, 2004; Reeve, 2012) for the engagement scale, with items addressing behavioral participation, attention, and initiative; self-efficacy theory (Bandura, 1997) for the sport experience scale, with items addressing prior mastery experiences and their perceived transfer to PE learning; and general competency-development frameworks in PE teacher education for the outcome scale, with items addressing technical, reflective, and self-

regulatory competencies. This item-generation, review, and pilot-testing sequence follows the early stages of established scale-development guidelines for the health, social, and behavioral sciences (Boateng, Neilands, Frongillo, Melgar-Quinonez, & Young, 2018), although, as noted in the Limitations, the later psychometric stages of that framework (exploratory/confirmatory factor analysis, independent expert content-validity indexing) were not conducted for the present instrument. The initial item pool was reviewed by the co-authors and the first author's doctoral supervisor for clarity, relevance, and alignment with the intended theoretical dimensions, and items identified as ambiguous or redundant were revised accordingly. The revised questionnaire was then piloted with a small group of PE students who did not take part in the main study, to check item comprehension, wording, and completion time; minor wording adjustments were made based on this pilot feedback before the questionnaire was distributed to the full sample. The complete item set for all five scales, in their original French version and in English translation, is provided in the Appendix as supplementary material.

Statistical Analysis

The analyses were conducted in several steps: (1) data cleaning and verification of response consistency; (2) calculation of internal consistency (Cronbach's alpha) for each of the five scales; (3) calculation of composite scores (mean of items) and descriptive statistics; (4) Pearson correlation analysis among the five constructs; (5) testing of a serial mediation model via successive regressions on standardized variables, following established recommendations for regression-based mediation analysis (Hayes, 2018), with bootstrap estimation (5,000 resamples, 95% percentile confidence intervals) of indirect effects (Preacher & Hayes, 2008), tested separately for each of the two distal predictors (pedagogical feedback, sport experience); (6) complementary analyses (ANOVA, t-tests) to explore the effect of profile variables. All analyses were performed in Python (pandas, pingouin, and statsmodels libraries).

Results

Participants and Data Cleaning Procedure

The initial sample comprised 261 responses. Thirteen responses (5.0%) showed inconsistent multiple selections on the categorical profile variables (age, year of study, or practice frequency), likely due to a form artifact, and were excluded. The final analyzed sample comprised $N = 248$ PE undergraduate students (Year 1: $n = 91$; Year 2: $n = 92$; Year 3: $n = 65$; 125 males, 123 females). All items across the five 8-item scales (motivation, pedagogical feedback, engagement, sport experience, competency development) were set as mandatory fields in the online form; consequently, no missing data occurred on any of these 40 items in the final analytic sample of $N = 248$.

A chi-square goodness-of-fit test was conducted to verify the representativeness of the final sample relative to the actual distribution of the 632 students enrolled in the PE-BA program for the 2025–2026 academic year (Year 1: 27.8%; Year 2: 40.8%; Year 3: 31.3%). This test revealed a significant discrepancy between the observed distribution in the sample

(36.7% / 37.1% / 26.2%) and the expected distribution, $\chi^2_{(2)} = 9.89$, $p = .007$, with Year 1 being overrepresented and Year 3 underrepresented. This limitation is discussed further below.

Table 1. Sample distribution by year of study relative to the reference population

Year	Population (%)	Sample (%)	Sample n
Year 1	27.8	36.7	91
Year 2	40.8	37.1	92
Year 3	31.3	26.2	65

Note. $\chi^2_{(2)} = 9.89$, $p = .007$. Reference population: 632 students enrolled in the PE-BA program, 2025–2026 academic year.

Reliability and Descriptive Statistics

Internal consistency for each of the five scales (8 items, 1–5 Likert format) proved excellent, with Cronbach's alpha coefficients all above .91 (Table 2). Because a very high alpha can itself signal item redundancy rather than pure reliability (Taber, 2018), this uniformly high internal consistency is interpreted with appropriate caution alongside the other psychometric indicators reported below. The distributions show pronounced negative skewness across all scales, indicating a ceiling effect (overall high scores), which is noted as a methodological limitation.

Table 2. Descriptive statistics and internal consistency of the five scales

Scale	M	SD	Skewness	Cronbach's α	95% CI
Motivation	4.23	0.76	-1.66	.926	[.912, .939]
Pedagogical feedback	3.92	0.76	-0.82	.915	[.898, .930]
Engagement	4.18	0.72	-1.46	.915	[.898, .930]
Sport experience	4.14	0.79	-1.46	.931	[.917, .943]
Competencies	4.04	0.78	-1.44	.934	[.921, .946]

Note. M = mean; SD = standard deviation; scale from 1 to 5. $n = 248$.

Correlations Among Constructs

All correlations among the five constructs were positive and significant (Table 3), with coefficients ranging from .689 to .844, confirming the existence of associations sufficiently strong to justify a mediation model.

Table 3. Correlations among the five constructs

Variable	1	2	3	4	5
1. Motivation	—				
2. Feedback	.738**	—			
3. Engagement	.826**	.786**	—		
4. Sport experience	.740**	.689**	.809**	—	
5. Competencies	.764**	.772**	.844**	.844**	—

Note. ** $p < .001$. $n = 248$.

Table 4. Serial mediation model — pedagogical feedback as distal predictor

Effect	β	p	95% Bootstrap CI
Direct effect: Feedback $\rightarrow$ Motivation (a_1)	.738	< .001	—
Direct effect: Feedback $\rightarrow$ Engagement (a_2)	.387	< .001	—
Direct effect: Motivation $\rightarrow$ Engagement (d_{21})	.540	< .001	—
Direct effect: Motivation $\rightarrow$ Competencies (b_1)	.142	.017	—
Direct effect: Engagement $\rightarrow$ Competencies (b_2)	.530	< .001	—
Residual direct effect: Feedback $\rightarrow$ Competencies (c')	.251	< .001	—
Total effect: Feedback $\rightarrow$ Competencies (c)	.772	< .001	—
Indirect via Motivation only	.105	—	[.007, .212]
Indirect via Engagement only	.205	—	[.125, .290]
Serial indirect (Motivation $\rightarrow$ Engagement)	.211	—	[.134, .300]
Total indirect	.521	—	[.395, .640]

Note. Standardized coefficients (β). CI = bootstrap confidence interval (5,000 resamples, percentile method). $n = 248$.

Table 5. Serial mediation model — prior sport experience as distal predictor

Effect	β	p	95% Bootstrap CI
Direct effect: Experience $\rightarrow$ Motivation (a_1)	.740	< .001	—
Direct effect: Experience $\rightarrow$ Engagement (a_2)	.436	< .001	—
Direct effect: Motivation $\rightarrow$ Engagement (d_{21})	.504	< .001	—
Direct effect: Motivation $\rightarrow$ Competencies (b_1)	.111	.038	—
Direct effect: Engagement $\rightarrow$ Competencies (b_2)	.393	< .001	—
Residual direct effect: Experience $\rightarrow$ Competencies (c')	.444	< .001	—
Total effect: Experience $\rightarrow$ Competencies (c)	.844	< .001	—
Indirect via Motivation only	.082	—	[-.013, .184] (n.s.)
Indirect via Engagement only	.171	—	[.095, .262]
Serial indirect (Motivation $\rightarrow$ Engagement)	.147	—	[.078, .219]
Total indirect	.400	—	[.284, .518]

Note. n.s. = not significant (the confidence interval includes zero). $n = 248$.

Serial Mediation Model — Pedagogical Feedback

A first serial mediation model (Pedagogical feedback $\rightarrow$ Motivation $\rightarrow$ Engagement $\rightarrow$ Competencies) was tested via successive OLS regressions on standardized variables, with bootstrap estimation (5,000 resamples, 95% percentile confidence intervals) of the indirect effects (Table 4). All three indirect pathways were statistically significant, as was the residual direct association, consistent with partial mediation: a substantial proportion of the total association between pedagogical feedback and perceived competency development (67%, .521/.772) was statistically accounted for by motivation and engagement jointly.

Serial Mediation Model — Prior Sport Experience

A second model tested prior sport experience as the distal predictor (Table 5). The indirect association via motivation alone was not significant (the interval includes zero), but the indirect associations via engagement alone and via the full serial pathway were significant, as was the residual direct association (partial mediation, 47% of the total association).

Complementary Analyses

Group comparisons enriched the interpretation of the model. No significant difference was observed according to year of study (Year 1/2/3) on any of the five constructs (Table 6), suggesting that these variables do not progress linearly across the curriculum as measured here. Similarly, regular sport practice (yes/no) and sex showed no significant differences. By contrast, prior competition participation significantly distinguished students on all five constructs, with a medium effect size, following Cohen's (1988) conventional benchmarks, for perceived sport experience ($d = 0.59$) and for competencies ($d = 0.41$) (Table 6).

Summary of Hypotheses

H1 (Feedback $\rightarrow$ Motivation): confirmed. H2 (Sport experience $\rightarrow$ Motivation and Engagement): confirmed. H3 (Motivation $\rightarrow$ Engagement): confirmed. H4 (mediation via Motivation and Engagement): confirmed for both predictors, with partial mediation in both cases and a significant serial pathway. However, the mediation via motivation alone was not significant for sport experience, which qualifies H4 for this specific predictor.

Table 6. Differences by year of study, prior competition participation, and regular sport practice

Year of Study (one-way ANOVA)					
Variable	Year 1 (M)	Year 2 (M)	Year 3 (M)	F(2, 245)	p
Motivation	4.25	4.22	4.22	0.04	.966
Feedback	3.99	3.82	3.95	1.21	.300
Engagement	4.21	4.17	4.15	0.17	.842
Sport experience	4.15	4.12	4.14	0.05	.951
Competencies	4.08	3.96	4.10	0.77	.462
Prior Competition Participation (independent-samples t-test)					
Variable	M Yes	M No	t	p	Cohen's d
Motivation	4.30	4.09	2.016	.046	0.27
Feedback	3.96	3.82	1.406	.161	0.18
Engagement	4.27	4.00	2.743	.007	0.37
Sport experience	4.28	3.84	4.335	< .001	0.59
Competencies	4.15	3.84	3.136	.002	0.41
Regular Sport Practice (independent-samples t-test)					
Variable	M Yes	M No	t	p	Cohen's d
Motivation	4.23	4.23	0.006	.995	0.00
Feedback	3.93	3.82	0.757	.453	0.15
Engagement	4.20	4.05	1.089	.281	0.21
Sport experience	4.17	3.97	1.326	.191	0.25
Competencies	4.07	3.90	1.139	.260	0.22

Note. $n = 248$. Effect sizes (Cohen's d) interpreted following Cohen's (1988) conventional benchmarks (small = 0.20, medium = 0.50, large = 0.80).

Discussion

The aim of this study was to test a serial mediation model examining how motivation and engagement statistically account for the association between, on one hand, pedagogical feedback and prior sport experience, and on the other hand, the development of perceived competencies in physical education. Overall, the results are consistent with this model and offer three main contributions to the literature on PE teacher training: (1) they clarify the motivational pathway associated with feedback in relation to perceived learning, (2) they reveal that prior sport experience follows a partially different pattern of association from that of feedback, being more closely linked to engagement than to motivation, and (3) they show that the variable most strongly associated with students' profiles is not seniority in the program but prior competitive experience. As the data are cross-sectional and self-reported, all interpretations below describe patterns of statistical association rather than demonstrated causal processes.

The Pivotal Role of Pedagogical Feedback

Consistent with H1, perceived pedagogical feedback was strongly associated with students' motivation ($\beta = .738$). This result is consistent with self-determination theory (Deci & Ryan, 1985, 2000; Ryan & Deci, 2020), which posits that informational feedback — perceived as support for progress rather than as judgment — nurtures the psychological need for competence, theorized as a driver of autonomous

motivation. It also aligns with Hattie and Timperley's (2007) review describing feedback as one of the most robust pedagogical correlates of learning in the educational science literature, as well as with extensions of this framework to the specific context of physical education (Ntoumanis, 2001), where the motivational climate established by the teacher has been associated with students' investment.

The specific contribution of the present study is to show that this association is not limited to a direct feedback-motivation link: two-thirds of the total association between feedback and perceived competency development (67%) was statistically accounted for by the motivation-engagement chain. This pattern suggests that the association between feedback quality and students' self-reported competencies may operate largely through their motivation, which is in turn linked to greater self-reported engagement in learning tasks — although this sequential interpretation reflects the structure of the theoretical model tested and cannot be confirmed as a causal sequence given the cross-sectional design (see Limitations). This result is nonetheless consistent with the idea, often stated in general terms in the literature, that feedback may be more closely tied to an indirect than to a direct correlate of self-reported motor learning.

A Distinct Pattern of Association for Prior Sport Experience

The second model tested reveals a more nuanced pattern. Although prior sport experience was significantly associated with motivation ($\beta = .740$) and engagement ($\beta = .436$),

consistent with H2, the indirect association estimated via motivation alone did not reach significance (95% CI = [-.013, .184]), unlike what was observed for feedback. This result invites a distinction between two theoretical explanations that are conceptually close but distinct: self-determination theory, relevant for interpreting the association involving feedback, and Bandura's (1997) self-efficacy theory, more relevant for interpreting that involving sport experience. Students with a richer sporting background were not necessarily more motivated to learn, but reported higher engagement, a pattern consistent with the possibility that mastery experiences accumulated through sport may be associated with engagement independently of motivation. This distinction is consistent with Harter's (1978) work on competence motivation, which proposes that a sense of mastery can be linked to behavioral engagement independently of the initial motivational state.

This differentiation between the two distal predictors constitutes one of the most original contributions of the study: it suggests that motivation and engagement, although strongly correlated ($r = .826$), are not simple proxies for one another but are associated with partially distinct antecedents — a distinction that parallel mediation models, more common in the literature, might have obscured.

Engagement as the Central Proximal Mediator

In both models tested, engagement was the mediator most strongly associated with perceived competency development ($\beta = .530$ for the feedback model; $\beta = .393$ for the sport experience model), more so than motivation itself ($\beta = .142$ and $.111$, respectively). This result is consistent with contemporary models of academic and sport engagement (Reeve, 2012; Reeve & Tseng, 2011), which describe engagement — behavioral, cognitive, and agentic — as the construct most proximally linked to effective learning in theoretical accounts of the motivational process. In the present data, motivation alone was not sufficient: engagement — reflected in active participation, sustained attention, and persistence in the task — showed the stronger association with perceived competency development. This pattern of associations (motivation linked to engagement, which in turn is more strongly associated with perceived competencies, rather than motivation relating to competencies directly) suggests a pedagogical implication, developed further below: training programs may benefit from explicitly targeting engagement behaviors, and not only the desire to learn.

Unexpected Findings That Enrich the Interpretation

Two unanticipated findings deserve detailed discussion. First, the absence of any significant difference between Year 1, Year 2, and Year 3 students on the five constructs is surprising given the implicit assumption of curricular progression. This pattern is, however, less isolated than it might first appear: recent observational research on pre-service PE teachers likewise found only minimal differences in teaching competencies across cohorts, concluding that initial teacher education contexts may not substantially enhance pedagogical competence throughout the degree (Mellado-Berenguer & Monfort-Pañego, 2026), and a

related study similarly found that teaching efficacy among pre-service PE teachers was shaped more by accumulated teaching experience than by year level per se (Salin et al., 2025). Several interpretations are possible. It may be that PE training, as currently structured, is not differentially associated with motivation or engagement across years — in which case this finding directly calls into question the pedagogical design of the curriculum. It is also possible that cohort effects (classes that otherwise differ) mask a genuine progression effect, or that the cross-sectional design fails to capture change that occurs more at the intra-individual level than between year groups. Only a longitudinal follow-up of the same students across the three years would allow these hypotheses to be disentangled.

Second, prior participation in sport competitions proved to be the most discriminating profile variable, with effect sizes ranging from small to medium across constructs ($d = .18$ to $.59$), whereas regular sport practice — although conceptually close — showed no significant difference. This contrast suggests that perceived competency development in PE may be more closely associated with the qualitatively specific nature of competitive experience than with the frequency of physical practice per se: exposure to performance pressure, social evaluation of skill level, and the structured technical coaching characteristic of competitive sport. This distinction between recreational and competitive practice, rarely made in the literature on PE teacher training, offers a useful avenue for refining the diagnostic criteria used to identify support needs at entry into training.

Theoretical Contribution and Positioning

Taken as a whole, this study extends the existing literature in three respects. On a theoretical level, it proposes an empirical articulation between self-determination theory and self-efficacy theory within a single model, showing that these two frameworks are associated with distinct patterns of association depending on the nature of the predictor (contextual/pedagogical for SDT, experiential/personal for self-efficacy). This articulation is particularly meaningful in a teacher-training population, since self-efficacy beliefs formed during initial training are widely regarded as a distinct and especially consequential construct compared with self-efficacy in other domains, given their documented links to teachers' persistence, instructional behavior, and career-long professional engagement (Tschannen-Moran & Woolfolk Hoy, 2001). On a methodological level, the use of a serial mediation model, rather than a simple correlational analysis or multiple regression, makes it possible to document not only that these variables are related, but the sequential pattern of association among them that is consistent with the proposed theoretical model — while acknowledging that causal order cannot be established with cross-sectional data (see Limitations). Finally, on an applied level, it provides concrete, hierarchized levers for reflection for PE teacher training, discussed below.

Limitations

Several limitations should be considered when interpreting these findings, and each has direct implications for how the results should be read. First, and most

importantly, the cross-sectional design does not allow causal relationships between variables to be established. All associations reported — including the direct, indirect, and total paths in the two mediation models — describe patterns of statistical association among variables measured at a single point in time. The sequence postulated in the theoretical model (feedback/experience → motivation → engagement → competencies) reflects the order suggested by theory and was used to structure the regression equations, but it remains a working hypothesis rather than a demonstrated causal chain: the same data pattern would be equally consistent with alternative orderings (for example, engagement reinforcing motivation over time, or perceived competency development itself reinforcing engagement) that a cross-sectional design cannot rule out. Readers, and the authors themselves in the interpretation offered above, should therefore treat terms such as “mediation,” “indirect association,” and “pathway” as descriptions of a statistical model consistent with theory, not as evidence that one variable causally produced change in another. Only an experimental or longitudinal design could adjudicate between competing causal orderings. Second, all five constructs were measured through student self-report, which introduces at least two distinct concerns. The first is social desirability bias — a distortion documented even for ostensibly non-sensitive constructs such as physical activity and lifestyle habits in large survey samples (Teh et al., 2023) — reinforced by the pronounced negative skewness (ceiling effect) observed across all five scales, which may have compressed the observed correlations and attenuated the ability to detect weaker associations. The second concern is a shared-method artifact: because all constructs were measured with the same self-report format at the same time, part of the observed associations among motivation, engagement, feedback, and perceived competencies may reflect common method variance rather than substantive association. Neither concern can be fully ruled out with the present design, and both underscore why the outcome variable is described throughout as “perceived” or “self-reported” competency development rather than as an objective, observer-rated, or performance-based measure of motor or pedagogical competence. Third, the sample shows a representativeness imbalance by year of study, with Year 1 overrepresented and Year 3 underrepresented relative to the actual population ($\chi^2 = 9.89, p = .007$). This raises the possibility of differential non-response bias — for example, if students who felt more or less engaged in their training were differentially likely to respond depending on their year of study. This concern is partly, though not fully, mitigated by the absence of a significant difference between years on any of the five constructs (Table 6), which suggests that the imbalance is unlikely to have systematically distorted the associations reported in the main mediation models. Fourth, the sample was drawn from a single institution (the École Normale Supérieure of Martil), which limits the generalizability of the findings to other PE teacher training programs, particularly those with different admission criteria, curricula, or national contexts. A multi-site replication, ideally spanning several Moroccan or Maghrebi institutions, would be needed to assess whether the pattern of associations observed here holds more broadly. Fifth, although the five measurement scales were grounded in established theoretical frameworks and reviewed by the co-authors and doctoral supervisor

prior to piloting (see Instrument Development), they have not yet undergone a formal psychometric validation beyond internal consistency testing: no exploratory or confirmatory factor analysis was conducted to verify the intended factor structure, and no independent expert content-validity index was computed. While internal consistency was excellent for all five scales ($\alpha > .91$), this means that factorial and convergent validity have not yet been formally established. Future use of these scales should include such validation steps. The complete item set is provided in the Appendix to allow readers and future researchers to evaluate, refine, and further validate them.

Pedagogical and Institutional Implications

If corroborated by future longitudinal or experimental research, these results would argue for strengthening PE teacher training in the practice of constructive, individualized feedback centered on progress rather than solely on evaluation, rather than for simply extending the duration of training. Structured teacher-training programs designed to increase autonomy-supportive, informational feedback have already demonstrated feasibility and effectiveness with in-service PE teachers (Cheon, Reeve, & Moon, 2012), and a comparable module embedded within PE teacher education curricula could plausibly extend similar benefits to pre-service teachers themselves. Since engagement was the mediator most strongly associated with perceived competency development in the present model, trainers may also benefit from designing activities that explicitly call for active participation, sustained attention, and student initiative, rather than limiting themselves to interventions aimed solely at fostering motivation or interest. Finally, since it is prior competitive experience, rather than year of study or regular practice, that was most clearly associated with students' profiles, an entry-level diagnostic specifically addressing students' competitive background could help target differentiated support — particularly technical confidence-building programs for students without competitive experience — rather than standardized content by year of study.

Future Research Directions

Three extensions appear particularly promising. A longitudinal design, following the same cohort of students from Year 1 to Year 3, would help resolve the question of actual competency progression across the curriculum, which the cross-sectional design of the present study cannot settle. A mixed-methods approach, combining self-assessment with observational measures of actual motor competencies, would reduce the risk of social desirability and shared-method bias identified above. Finally, a replication of the tested model in other PE teacher training institutions, in Morocco or in other national contexts, would help assess the generalizability of the distinction observed between the motivational (feedback) and experiential (sport competition) correlates of perceived competency development.

Conclusions

This study set out to test whether motivation and engagement serially mediate the association between

pedagogical feedback and prior sport experience, on one hand, and the development of perceived competencies in physical education among pre-service PE teachers, on the other. The results are consistent with all four hypotheses: pedagogical feedback and prior sport experience were both associated with motivation and engagement, motivation was associated with engagement, and the two constructs jointly and partially accounted for the association between both distal predictors and perceived competency development (67% and 47% of the total association, respectively). Engagement, rather than motivation, was the mediator most strongly associated with perceived competency development, and the pattern linking sport experience to the outcome operated largely independently of motivation, consistent with a self-efficacy rather than a self-determination account. As the design is cross-sectional and all measures are self-reported, these findings should be read as a coherent pattern of statistical association consistent with the proposed theoretical model, not as demonstrated causal pathways. With this caveat in mind, the findings speak to the study's purpose by clarifying how feedback and prior sport experience are associated with perceived competency gains through a sequential pattern involving motivation and engagement, and they lend support to prioritizing feedback quality and engagement-oriented teaching practices, together with differentiated support based on students' competitive background, in PE teacher training programs.

Ethics Approval

This study involved an anonymous, voluntary, minimal-risk online survey of enrolled university students, with no experimental manipulation and no collection of identifying or sensitive personal data. In accordance with the institution's policy for this category of minimal-risk, non-interventional educational research, formal approval from an institutional ethics committee was not required. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki.

Informed Consent

An information notice preceding the online questionnaire specified the scientific purpose of the study, the anonymous nature of the responses, and their strictly academic use. Participants' informed consent was obtained implicitly upon voluntary submission of the questionnaire, consistent with standard practice for minimal-risk, non-interventional surveys in educational science. As all participants were enrolled Bachelor's-degree university students, parental/guardian consent was not applicable.

Data Availability Statement

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

AI Transparency Statement

The authors used AI-assisted tools (Claude, Anthropic) for spelling and grammar correction and for language rephrasing during the preparation of this manuscript. The authors reviewed all content and take full responsibility for its scientific accuracy and conclusions.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix: Complete Measurement Scales

All items were rated on a five-point Likert scale (1 = Strongly disagree; 5 = Strongly agree). The original questionnaire was administered in French; the English translations below are provided for the international readership of this journal.

Motivation Scale

1. I am motivated to learn in physical education.
2. I feel enjoyment during physical education practical lessons.
3. I make efforts to progress in physical activities.
4. I am interested in the content taught in physical education.
5. I wish to improve my competencies in physical education.
6. I actively involve myself in practical lessons.
7. I persevere even when tasks are difficult.
8. I seek to improve my physical performance.

Pedagogical Feedback Scale

1. The teacher provides regular feedback during physical education lessons.
2. The feedback I receive helps me improve my performance.

3. The corrections given are clear and understandable.
4. The teacher effectively guides me in learning motor skills.
5. I understand my mistakes thanks to the explanations given.
6. The feedback is adapted to my level in physical education.
7. The teacher acknowledges and values my progress.
8. The instructions given are precise and useful.

Engagement Scale

1. I actively participate in physical education lessons.
2. I am attentive during practical sessions.
3. I involve myself in the activities proposed.
4. I practice physical activities outside of class.
5. I make consistent efforts to progress.
6. I remain focused during exercises.
7. I take initiative during physical activities.
8. I follow the instructions given by the teacher.

Prior Sport Experience Scale

1. My sport experience facilitates my learning in physical education.

2. My sport practice helps me understand exercises more quickly.
3. My sporting background improves my competencies in physical education.
4. I feel comfortable in the physical activities proposed.
5. I have already acquired technical foundations in sport.
6. My sport experience strengthens my confidence in physical education.
7. I adapt easily to new physical activities.
8. I master several sport-specific motor skills thanks to my experience.

Perceived Competency Development Scale

1. I develop my technical competencies in physical education.
2. I progress in my physical performance.
3. I become more autonomous in physical activities.
4. I better understand the objectives of physical education lessons.
5. I am able to analyze my performance.
6. I correct my mistakes autonomously.
7. I become more competent in sport activities.
8. I develop my learning abilities in physical education.

Детермінанти розвитку компетентності у фізичному вихованні: медіативна роль мотивації та залученості

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

Реферат. Стаття: 13 с., 6 табл., 32 джерела.

Мета дослідження. У дослідженні протестовано модель послідовної медіації для вивчення того, як педагогічний зворотний зв'язок і попередній спортивний досвід асоційовані з розвитком суб'єктивно сприйманих компетентностей у фізичному вихованні (ФВ) через послідовні медіативні ролі мотивації та залученості.

Матеріали та методи. Учасниками дослідження були 248 студентів бакалаврату (1-й курс: n = 91; 2-й курс: n = 92; 3-й курс: n = 65; 125 осіб чоловічої статі, 123 особи жіночої статі), які навчалися за бакалаврською програмою з фізичного виховання та спорту в Вищій нормальній школі Мартіля (École Normale Supérieure of Martil) Університету Абдельмалека Ессааді, Марокко. Збір даних здійснювали за допомогою онлайн-опитувальника з використанням методу поперечного зрізу, що містив п'ять восьмипунктових шкал Лайкерта для вимірювання мотивації, суб'єктивно сприйманого педагогічного зворотного зв'язку, залученості, попереднього спортивного досвіду та розвитку суб'єктивно сприйманої компетентності; усі дані базувалися на самозвітах учасників. Внутрішня узгодженість була відмінною для всіх шкал (альфа Кронбаха > .91). Дві моделі послідовної медіації було протестовано з використанням бутстреп-вибірки (5000 ітерацій, 95% перцентильні довірчі інтервали).

Результати. Як суб'єктивно сприйманий педагогічний зворотний зв'язок, так і попередній спортивний досвід значущо асоційовані з розвитком суб'єктивно сприйманої компетентності. Ці взаємозв'язки частково пояснювалися мотивацією та залученістю (67% та 47% від загального зв'язку, відповідно). Залученість виявилася медіатором, найбільш сильно асоційованим із розвитком суб'єктивно сприйманої компетентності в обох моделях. Зокрема, непрямий зв'язок через саму лише мотивацію був статистично незначущим для попереднього спортивного досвіду. Не було встановлено суттєвих відмінностей залежно від курсу навчання, тоді як попередній досвід участі у змаганнях значущо корелював з усіма п'ятьма конструктами самозвіту. З огляду на поперечний дизайн дослідження та використання методу самозвіту, ці зв'язки не слід інтерпретувати як причинно-наслідкові.

Висновки. Мотивація та залученість діють як послідовні, частково відокремлені медіатори зв'язку між педагогічним зворотним зв'язком, попереднім спортивним досвідом та розвитком суб'єктивно сприйманої компетентності. Отримані результати мають важливе теоретичне та практичне значення для підготовки викладачів фізичного виховання, зокрема щодо розробки зворотного зв'язку та диференційованої підтримки з урахуванням змагального досвіду студентів.

Ключові слова: залученість, зворотний зв'язок, мотивація, фізичне виховання, самоефективність, послідовна медіація, підготовка викладачів.

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Motor Skill Adaptations to a School-Based Basketball Training Program in Upper Secondary School Students

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Abstract

Objectives. The study aimed to determine the effects of an eight-week school-based basketball training programme on dribbling and shooting performance in upper secondary school students and to examine accompanying changes in motor awareness, perceived self-efficacy, motivation, and peer collaboration.

Materials and Methods. Eighteen students aged 15–17 years participated in a single-group pre-test–post-test pilot study. The intervention consisted of two 60-minute sessions per week for eight weeks and included progressive technical exercises, pair and small-group tasks, simplified game situations, formative feedback, and reflection activities. Basketball-specific performance was assessed using the AAHPERD Control Dribble Test and Speed Spot Shooting Test. Qualitative data were obtained using a technical-motor observational rubric and a semi-structured focus group. Pre–post differences were analysed using paired-samples t-tests, and effect sizes were calculated using Cohen's d.

Results. Control Dribble Test performance improved from 25.51 ± 2.84 s to 21.76 ± 2.37 s, with a mean difference of -3.75 s (95% CI: -4.52 to -2.98 ; $t_{(17)} = -10.28$; $p < .001$; $d = 2.42$). Speed Spot Shooting Test scores increased from 4.78 ± 1.21 to 6.56 ± 1.18 successful shots, with a mean difference of 1.78 shots (95% CI: 1.27 – 2.29 ; $t_{(17)} = 8.00$; $p < .001$; $d = 1.89$). Qualitative analysis indicated improvements in movement control, technical awareness, perceived self-efficacy, motivation, error management, and peer collaboration.

Conclusions. The eight-week basketball programme was associated with substantial improvements in dribbling and shooting performance in upper secondary school students. Positive changes were also observed in students' awareness of movement execution and engagement in the learning process. Given the small sample size and the absence of a control group, the findings should be interpreted as preliminary.

Keywords: basketball, physical education, motor learning, dribbling, shooting, adolescents.

Introduction

Basketball represents a particularly relevant discipline within school physical education, as it allows the development of fundamental motor skills to be integrated with cognitive, relational, and decision-making competences (Mocanu, & Murariu, 2024). Unlike activities based mainly on repetitive or isolated motor execution, basketball requires students to constantly adapt their actions to changing situations,

coordinate their movements in relation to space, time, the ball, and other players, and make rapid decisions under dynamic conditions. In upper secondary school, this sport therefore constitutes a rich and multifaceted educational environment, in which motor learning is closely connected to perception, attention, communication, cooperation, and self-regulation. Students are not only required to perform technical gestures, but also to understand when, how, and why to use them in relation to the context of play. For this reason, basketball can be considered a particularly suitable activity for promoting meaningful learning in physical education, especially when it is taught through structured, progressive, and reflective didactic pathways (Pocius, & Malinauskas, 2025).

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Within this framework, the technical fundamentals of dribbling and shooting play a central role. Dribbling enables students to manage the ball while moving, orient themselves in space, protect possession, change direction, vary rhythm, and maintain motor control under variable conditions. It involves coordination between upper and lower limbs, control of posture, use of gaze, spatial orientation, and the ability to regulate force and timing. Shooting, on the other hand, represents one of the most complex and meaningful technical gestures in basketball, as it requires balance, segmental coordination, precision, postural stability, concentration, and the ability to self-regulate the movement (Kioumourtzoglou et al., 1998). An effective shot does not depend solely on arm strength or final accuracy, but on the coordination of several components: foot position, lower-limb drive, trunk stability, shoulder-elbow-wrist alignment, ball release, and final follow-through. From an educational point of view, working on dribbling and shooting therefore means helping students to develop not only sport-specific skills, but also broader motor competences related to body control, movement awareness, attention, and intentionality.

Recent literature highlights that school physical education should not be reduced to the mere technical execution of movements, but should instead be understood as a context for promoting physical literacy (Latino et al., 2025a,b). Physical literacy refers to an integrated set of physical, cognitive, emotional, and motivational competences that enable individuals to participate consciously, confidently, and sustainably in motor and sports activities across the lifespan (Graudusius et al., 2024). This perspective is particularly important in adolescence, a developmental phase in which students' relationship with the body, movement, sport, and perceived competence may strongly influence their future participation in physical activity. In this sense, physical education has the responsibility to offer learning experiences that are not only technically effective, but also inclusive, motivating, and capable of strengthening students' confidence in their own abilities. A basketball workshop designed around progressive tasks, formative feedback, peer collaboration, and reflection can contribute to this goal by transforming technical learning into an opportunity for broader personal and educational development.

This approach is also consistent with the recommendations of the World Health Organization, according to which children and adolescents should regularly engage in moderate- to vigorous-intensity physical activity, including through meaningful and inclusive school-based experiences (Bull et al., 2020; Di Maio et al., 2026). School represents a privileged setting for promoting physical activity, because it can reach all students, including those who may not participate in organised sport outside school. However, for physical education to be truly effective, it is not sufficient to simply increase movement time; it is also necessary to design activities that support participation, motivation, perceived competence, and the progressive acquisition of motor skills. In this regard, basketball offers significant educational potential, because it combines physical engagement with playful, cooperative, and decision-making dimensions. When properly adapted to students' levels, it can involve both more skilled students and those who initially feel less confident, allowing each participant to experience improvement and contribute to the group.

Furthermore, the concept of Quality Physical Education promoted by UNESCO emphasises the need to design motor learning environments capable of supporting not only physical development, but also psychosocial well-being, participation, responsibility, and collaboration (UNESCO, 2021). From this perspective, the value of a basketball workshop does not lie exclusively in the acquisition of technical fundamentals, but in the possibility of creating a learning environment in which students can cooperate, observe one another, accept feedback, manage errors, and recognise progress. The educational quality of the intervention therefore depends on the way in which the teacher structures the tasks, differentiates the levels of difficulty, provides feedback, and promotes a positive climate. In particular, the use of small-group activities, simplified game situations, and peer observation can help students to develop both technical competence and social responsibility (Gaggioli et al., 2013).

Within this framework, basketball can be interpreted as a didactic device capable of promoting complex motor learning, especially when teaching combines progressive technical exercises, simplified game situations, formative feedback, peer observation, and moments of reflection. The transition from analytical exercises to game-based situations allows students to first consolidate the basic elements of the movement and then apply them in more authentic and dynamic contexts. This progression is particularly relevant in the learning of dribbling and shooting, since both skills require not only technical precision, but also adaptation to changing spatial and temporal conditions. A purely repetitive approach may improve isolated execution, but it does not always support transfer to real or semi-real game situations. Conversely, an approach that alternates technical practice, contextualised tasks, and reflection may help students understand the functional meaning of the gesture and improve their ability to use it appropriately.

Recent studies on the Sport Education Model show that approaches centred on active participation, student responsibility, and cooperative dynamics can improve attitudes, motivation, and engagement in physical education contexts (Zhang et al., 2024). This is particularly relevant for upper secondary school students, who may show different levels of motivation, competence, and confidence in sports activities. A workshop organised through progressive challenges, shared responsibilities, and peer support can reduce the distance between students with different initial skill levels and promote a more inclusive form of participation. At the same time, research on motor feedback confirms that the learning of technical skills is more effective when students receive timely, specific instructions oriented towards improving the movement, rather than generic judgments on performance (Treschman et al., 2024; Zhou et al., 2021). Feedback, in this sense, becomes not only a corrective tool, but also an educational strategy that helps students understand errors, regulate their actions, and develop greater awareness of their own learning process.

In light of these premises, the present pilot study aimed to analyse the effects of a basketball workshop involving 18 upper secondary school students, with the goal of improving the fundamental skills of dribbling and shooting. The main objective was to verify whether a short, structured intervention, methodologically oriented towards technical progression, could produce observable changes both

quantitatively, through pre- and post-intervention motor tests, and qualitatively, through systematic observations and students' reflections. More specifically, the study sought to examine whether a workshop based on gradual progression, formative feedback, differentiated tasks, peer observation, and simplified game situations could improve students' technical performance while also promoting motor awareness, motivation, perceived self-efficacy, and collaboration within the class group. In this sense, the research was not limited to measuring performance outcomes, but also aimed to explore the educational processes activated by the intervention and the extent to which basketball can function as a meaningful learning environment in school physical education.

Materials and Methods

Study Design

This pilot study adopted a convergent mixed-methods design involving a single experimental group assessed before and after a school-based basketball instructional programme. The quantitative component was used to examine changes in basketball-specific technical performance, whereas the qualitative component explored movement quality, motor awareness, perceived improvement, difficulties encountered, motivation, error management, peer collaboration, and students' perceptions of the learning experience. Quantitative and qualitative data were collected during the same intervention period and were subsequently integrated to provide a more comprehensive interpretation of the educational and motor outcomes.

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the University of Naples Parthenope, Department of Medical, Motor and Wellness Sciences (DiSMMeB Prot. No. 88592/2024). Participation was voluntary. Students received age-appropriate information concerning the study objectives, procedures, assessments, and confidentiality of the collected data. Written informed consent was obtained from the parents or legal guardians of participants under 18 years of age, together with assent from the students. Where applicable, participants who had reached the age of legal consent provided their own written informed consent.

Outcome Measures

Quantitative Outcome Measures

Basketball-specific technical performance was assessed using two subtests selected from the AAHPERD Basketball Skills Test proposed by Hopkins, Shick, and Plack (1984): the Control Dribble Test and the Speed Spot Shooting Test. These tests were selected because they were directly aligned with the two technical skills addressed during the instructional programme.

The Control Dribble Test was used to assess dynamic dribbling control. Participants were required to complete a standardised cone-marked course while maintaining control of the ball during forward movement, changes of direction, and variations in movement rhythm. Performance was recorded in seconds using a digital stopwatch. A lower

completion time at post-test, provided that the course was completed correctly and without loss of ball control, indicated improved dribbling performance.

The Speed Spot Shooting Test was used to evaluate shooting speed and accuracy under dynamic conditions. Participants were required to shoot from predetermined positions, retrieve the ball, and move rapidly to the subsequent shooting location. Performance was expressed as the number of successful shots completed within the prescribed test duration. A higher post-test score indicated improved shooting performance.

Both quantitative tests were administered twice, during the week preceding the beginning of the instructional programme and after completion of the eight-week intervention. The same testing procedures, equipment, court arrangement, instructions, and scoring criteria were used at pre-test and post-test.

Qualitative Outcome Measures

Movement quality was assessed using a Technical-Motor Observational Rubric for Dribbling and Shooting developed specifically for the educational objectives of the workshop. The rubric was intended as a systematic observational instrument and was not treated as a standardised psychometric measure. Performance was classified according to four levels of mastery: initial, basic, intermediate, and advanced.

For dribbling, the rubric considered ball control, continuity of movement, body posture, gaze orientation, use of the dominant and non-dominant hand, ability to change direction, and ball management while moving. For shooting, the observed indicators included foot position, body balance, coordination between the lower and upper limbs, shoulder-elbow-wrist alignment, movement fluidity, final wrist follow-through, and the ability to maintain concentration during execution.

The rubric was completed during the initial and final assessments and was supplemented by intermediate observations conducted during the instructional sessions. These intermediate observations were used to monitor learning progression and guide instructional feedback rather than to generate additional quantitative outcomes.

At the end of the intervention, a semi-structured focus group was conducted using open-ended questions concerning perceived technical improvement, difficulties encountered, motivation, error management, peer collaboration, motor awareness, and the overall learning experience. Students' responses were examined through thematic analysis. Recurring units of meaning were identified and grouped into themes related to motor learning, participation, perceived self-efficacy, technical awareness, and group climate.

Participants

The study involved 18 students aged between 15 and 17 years who attended the same pre-existing upper secondary school class. The entire class participated in the basketball workshop and was therefore treated as a single experimental group. The observed age range reflected the ordinary variability within the class associated with differences in birth dates and individual educational trajectories.

The inclusion criteria were established before the intervention and comprised regular participation in physical education classes, medical eligibility for school-based physical activity, absence of injuries or medical conditions incompatible with the proposed exercises, attendance at a minimum of 80% of the scheduled instructional sessions, willingness to complete both the initial and final assessments, and provision of the required informed consent.

Students were excluded from the analysis when they were fully exempt from practical physical education, had prolonged absences during the intervention, did not complete either the pre-test or post-test assessment, or practised basketball continuously at a competitive level. The latter criterion was introduced to reduce the possible influence of substantially advanced previous basketball experience on the observed outcomes.

For the exploratory analysis requested according to age, participants were divided on the basis of chronological age at baseline into younger adolescents aged 15–16 years and older adolescents aged 17 years. This classification distinguished students in the intermediate phase of adolescence from those approaching the end of upper secondary education and a later stage of biological and psychomotor maturation. Because of the pilot nature of the study and the small number of participants, the subgroup analysis was considered exploratory and was intended to identify possible age-related patterns rather than establish definitive differences between age categories.

Procedures

The study was conducted within the students' regular school setting between February and April 2025, during the regular physical education curriculum. Before the intervention, eligible students and their families received information concerning the study, and the required consent procedures were completed. Participants then underwent baseline assessment using the Control Dribble Test, the Speed Spot Shooting Test, and the Technical-Motor Observational Rubric.

Following the pre-test assessment, all participants completed the same eight-week basketball instructional programme. The intervention comprised two 60-minute sessions per week, corresponding to 16 instructional sessions and a total scheduled duration of 16 hours. Sessions were conducted in the same school sports environment and using the same basketball equipment and instructional framework.

The intervention was delivered throughout the eight weeks by the same (physical education teacher/instructor), who had (specify academic or professional qualification and years of teaching or coaching experience). Using the same instructor throughout the programme was intended to ensure consistency in task presentation, verbal instructions, feedback, progression criteria, and session organisation.

All participants received an identical core instructional programme in terms of session frequency, duration, technical content, sequence of learning objectives, and overall training volume. Individual adaptations were limited to the difficulty, execution speed, number of constraints, and level of support associated with specific exercises. These adaptations were introduced to enable all students to pursue the same instructional objective according to their initial

level of technical competence and did not constitute different training programmes.

Attendance was recorded during each session. Participants who attended fewer than 80% of the scheduled sessions were not included in the final analysis. At the conclusion of the eight-week programme, the quantitative tests and observational rubric were administered again under conditions equivalent to those used at baseline. The semi-structured focus group was subsequently conducted to collect students' perceptions of the intervention.

Intervention Programme

The instructional programme lasted eight consecutive weeks and consisted of two sessions per week. Each session lasted 60 minutes, resulting in 16 instructional sessions and 16 total hours of activity. The programme followed a gradual didactic progression from simple to complex tasks, from controlled individual execution to cooperative and semi-situational activities, and from analytical technical exercises to simplified game-based applications.

The intervention focused primarily on dribbling and shooting. In addition to improving technical performance, the programme was intended to promote movement awareness, active participation, constructive management of errors, peer collaboration, and the ability to recognise and correct relevant aspects of movement execution.

Each 60-minute session was organised into four consecutive phases. The first phase lasted approximately 10 minutes and comprised general and basketball-specific motor activation, including light running, joint mobility, coordination exercises, movement patterns, changes of direction without the ball, and ball-familiarisation activities. The second phase lasted approximately 20 minutes and involved guided technical learning focused on the main skill addressed during the session. The third phase lasted approximately 20 minutes and consisted of applied activities performed through individual challenges, pair exercises, small-group tasks, technical circuits, timed activities, and simplified game situations. The final phase lasted approximately 10 minutes and was dedicated to active recovery, verbalisation, and debriefing. During this phase, students reflected on the difficulties encountered, recurrent technical errors, possible corrective strategies, and bodily sensations perceived during execution.

During weeks 1 and 2, the programme focused on ball familiarisation and basic dribbling control. Activities included static dribbling with the dominant and non-dominant hand, variations in dribbling height, transitions from high to low dribbling, frontal and lateral ball control, alternating dribbles, and simple forward, backward, and lateral movements. Particular attention was given to knee flexion, trunk stability, hand position above the ball, finger opening, controlled ball propulsion, and progressive orientation of the gaze towards the playing environment rather than exclusively towards the ball.

During weeks 3 and 4, the programme progressed to dynamic dribbling and ball control while moving. Activities included slalom courses, changes of direction, starts and stops, rhythm variations, ball protection against a passive defender, and simplified one-against-zero and guided one-against-one situations. Task difficulty was gradually increased by reducing

the distance between cones, increasing execution speed, requiring use of the non-dominant hand in selected sections, and introducing hand changes in response to external signals. Feedback focused on maintaining the ball close to the body, preserving dribbling continuity during directional changes, using the body to protect the ball, and coordinating footwork, trunk movement, and upper-limb action.

During weeks 5 and 6, the instructional focus shifted to shooting. Students initially performed close-range exercises to reduce the influence of shooting distance and direct attention towards movement mechanics. Activities included stationary shooting, shooting after receiving the ball, shooting after one dribble, shooting following one-count and two-count stops, and shooting from different angles. Instruction addressed balanced foot positioning, body orientation towards the basket, lower-limb flexion, coordination between leg drive and arm extension, elbow alignment, ball release, and final wrist follow-through. Students were organised into small groups to increase repetition frequency and reduce waiting time. Brief self-assessment activities were also introduced after shooting series to encourage students to identify successful movement components and elements requiring correction.

During weeks 7 and 8, dribbling and shooting were integrated into more representative basketball situations. Activities included dribble-stop-shoot sequences, change-of-direction followed by shooting, shooting after movement, continuous team shooting drills, and small-sided games incorporating technical constraints. Some activities required at least one hand change before shooting, whereas others required a controlled stop or rewarded correct shooting posture independently of whether the shot was successful. Small-sided games were conducted using reduced team sizes, delimited spaces, and adapted rules to increase ball contacts and promote active participation.

Throughout the intervention, the same instructional principles were applied: gradual progression of task difficulty, high repetition frequency, immediate and non-judgemental feedback, use of error as a learning opportunity, alternation between individual and cooperative activities, attention to safety, and promotion of an inclusive and motivating learning climate. Students experiencing greater difficulty performed simplified versions of the same task or completed the activity at a slower speed. More competent students performed the same technical task with additional constraints, such as the use of two balls, controlled hand changes, or responses to external signals. These adjustments preserved the common instructional objectives and content for the entire group.

Statistical Analysis

Quantitative data were analysed using IBM SPSS Statistics (Version XX; IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated for all quantitative variables and are presented as means and standard deviations (SD). Prior to inferential analyses, the normality of the data distribution was assessed using the Shapiro–Wilk test.

Differences between pre-test and post-test scores were analysed using paired-samples t-tests. For each outcome, the results are reported as mean $\pm$ standard deviation, mean difference, 95% confidence interval (95% CI) of the mean difference, t statistic, degrees of freedom (df),

and corresponding p value. Statistical significance was established at $p < 0.05$.

To evaluate the practical significance of the intervention, effect sizes were calculated using Cohen's d for paired samples and interpreted according to Cohen's conventional thresholds (0.20 = small, 0.50 = medium, and 0.80 = large).

Qualitative data obtained from the technical-motor observational rubric and the semi-structured focus group were analysed using an inductive thematic analysis. Responses were coded and grouped into recurrent themes reflecting common perceptions and experiences related to motor learning, technical awareness, motivation, self-efficacy, error management, and peer collaboration. Representative quotations were selected to illustrate the main themes emerging from the analysis. An exploratory subgroup analysis was also conducted according to age group (15–16 years vs. 17 years). Descriptive statistics were calculated separately for each subgroup, and paired-samples t-tests were performed independently to examine pre-post changes within each age category. Given the limited sample size, subgroup findings were interpreted descriptively and considered exploratory.

Results

Quantitative Results

The quantitative analysis showed an overall improvement in students' performance in the two basketball fundamentals targeted by the intervention, namely dribbling and shooting. Descriptive statistics and inferential analyses are presented in Table 1.

For the Control Dribble Test, the mean completion time decreased from 25.51 ± 2.84 s at baseline to 21.76 ± 2.37 s after the intervention, corresponding to a mean reduction of 3.75 s (95% CI: -4.52 to -2.98 s) and a percentage improvement of 14.7%. The paired-samples t-test revealed a statistically significant difference between the two assessments, $t_{(17)} = -10.28$, $p < .001$, with a very large effect size (Cohen's $d = 2.42$). These findings indicate a substantial improvement in students' ability to control the ball during dynamic movements, negotiate changes of direction, and maintain dribbling continuity throughout the course.

Similarly, performance in the Speed Spot Shooting Test improved significantly following the intervention. The mean number of successful shots increased from 4.78 ± 1.21 at pre-test to 6.56 ± 1.18 at post-test, corresponding to a mean increase of 1.78 successful shots (95% CI: 1.27 to 2.29) and a percentage improvement of 37.2%. Statistical analysis confirmed a significant pre-post difference, $t_{(17)} = 8.00$, $p < .001$, with a large effect size (Cohen's $d = 1.89$). This improvement suggests enhanced shooting accuracy and execution under dynamic conditions involving movement and ball retrieval.

Overall, the quantitative findings demonstrate that the structured basketball workshop produced meaningful improvements in both technical skills. Beyond statistical significance, the large effect sizes observed for both performance measures indicate that the intervention also achieved substantial practical relevance, supporting the educational effectiveness of a progressive, feedback-oriented teaching approach.

Table 1. Quantitative outcomes before and after the intervention (n = 18)

Variable	Pre-test Mean ± SD	Post-test Mean ± SD	Mean Difference	95% CI	t(17)	p	Cohen's d
Control Dribble Test (s)	25.51 ± 2.84	21.76 ± 2.37	-3.75	-4.52 to -2.98	-10.28	<0.001	2.42
Speed Spot Shooting Test (successful shots)	4.78 ± 1.21	6.56 ± 1.18	+1.78	1.27 to 2.29	8.00	<0.001	1.89

Note: Values are presented as mean ± standard deviation (SD). Mean differences are calculated as post-test minus pre-test. Cohen's d values were interpreted according to Cohen's criteria (0.20 = small, 0.50 = medium, 0.80 = large).

Table 2. Exploratory age subgroup analysis according to chronological age.

Variable	Age group	n	Pre-test Mean ± SD	Post-test Mean ± SD	Mean Difference	t	p	Cohen's d
Control Dribble Test (s)	15–16 years	10	25.84 ± 2.71	22.43 ± 2.26	-3.41	-7.14	<0.001	2.01
	17 years	8	25.10 ± 3.08	20.92 ± 2.39	-4.18	-7.89	<0.001	2.37
Speed Spot Shooting Test (successful shots)	15–16 years	10	4.60 ± 1.17	6.20 ± 1.14	+1.60	5.83	<0.001	1.64
	17 years	8	5.00 ± 1.31	7.00 ± 1.20	+2.00	5.98	<0.001	1.82

An exploratory subgroup analysis was conducted to examine whether the effects of the instructional programme differed according to participants' age. Students were divided into two age groups: younger adolescents (15–16 years, n = 10) and older adolescents (17 years, n = 8). Descriptive statistics and within-group comparisons are reported in Table 2.

Both age groups demonstrated significant improvements in the two basketball skills assessed following the eight-week intervention. In the younger subgroup, the mean completion time in the Control Dribble Test decreased from 25.84 ± 2.71 s to 22.43 ± 2.26 s ($p < .001$), while the mean number of successful shots in the Speed Spot Shooting Test increased from 4.60 ± 1.17 to 6.20 ± 1.14 ($p < .001$). Similarly, participants aged 17 years showed significant improvements in dribbling performance, with completion time decreasing from 25.10 ± 3.08 s to 20.92 ± 2.39 s ($p < .001$), and in shooting performance, with successful shots increasing from 5.00 ± 1.31 to 7.00 ± 1.20 ($p < .001$). The magnitude of improvement was comparable between the two age groups, with both younger and older students showing statistically significant pre-post improvements. Given the limited sample size, no formal between-group comparisons were performed, and the subgroup analysis should be interpreted as exploratory (Table 2).

Qualitative Results

The qualitative analysis, conducted through the technical-motor observational rubric and the final semi-structured focus group, made it possible to explore in greater depth the changes observed during the workshop, highlighting not only an improvement in performance, but also a transformation in the quality of motor execution, in students' awareness, and in the way they experienced the sporting activity. The observational rubric revealed significant progress in dribbling control: in the initial phase, several students tended to keep their gaze fixed on the ball, perform the movement with a rigid posture, and frequently

interrupt the continuity of movement during changes of direction; by the end of the intervention, however, greater execution fluency, better ball management while moving, more confident use of the non-dominant hand, and more effective coordination between footwork, trunk, and upper limbs were observed. This change was also confirmed by students' perceptions. One participant stated: "At the beginning, I always looked at the ball and lost control as soon as I had to change direction; after a few lessons, I was able to dribble more confidently and also look ahead." Another student emphasised the improvement in the use of the non-dominant hand, saying: "Before, I almost always used only my strong hand, but with the course exercises I understood that using the other hand also helped me move better."

With regard to shooting, the qualitative indicators also showed positive development. Students progressively improved their foot position, body balance, coordination between lower-limb drive and arm extension, shoulder-elbow-wrist alignment, and final follow-through. In particular, shooting appeared less random and more intentional, as students began to pay attention not only to whether the ball went into the basket, but also to the technical correctness of the execution. This aspect also emerged clearly in the focus group: one female student stated that "before, I only thought about shooting hard, then I understood that foot position, legs, and wrist movement mattered"; another participant pointed out that "even when I did not score, I was able to understand what I had done wrong, for example if I had not bent my legs properly or if my arm was not straight." These statements indicate an important shift from a purely performance-oriented view of shooting, focused only on the outcome, towards greater attention to movement quality and the possibility of self-correction.

Four main thematic areas emerged from the focus group. The first concerns the perception of improvement: many students reported feeling more confident in dribbling and more aware in preparing their shot. The second theme concerns motivation: small-group activities, technical challenges, and mini-games fostered increasing engagement,

Table 3. Main themes emerging from the qualitative analysis.

Theme	Main findings	Representative quotation
Motor awareness	Improved posture, gaze orientation, ball control, coordination, and use of the non-dominant hand	"I was able to dribble more confidently and also look ahead."
Technical execution	Better shooting mechanics, balance, follow-through, and movement control	"I understood that foot position, legs, and wrist movement mattered."
Perceived self-efficacy	Increased confidence in performing basketball skills	"I could see that I was gradually improving."
Error management	Errors perceived as opportunities for learning and self-correction	"Missing a shot was no longer something negative."
Motivation	Greater engagement through challenges and cooperative activities	"Team challenges motivated me more."
Peer collaboration	Reciprocal observation, tutoring, constructive feedback	"My partner noticed mistakes that I didn't realise."

especially among students who initially showed lower confidence in their motor abilities. One participant observed: "Team challenges motivated me more, because it did not feel like just an exercise, but a way to improve while having fun." Another student, who had initially been less involved, stated: "I usually do not feel good at sports, but here I could see that I was gradually improving, so I participated more." The third theme concerns the relationship with error: during the workshop, students progressively interpreted mistakes not as failures, but as useful information for correcting movement and improving subsequent performance. As one student stated, "missing a shot was no longer something negative, because then the teacher helped us understand what to change." The fourth thematic area relates to peer collaboration: reciprocal observation, informal tutoring, and debriefing moments fostered a more cooperative climate, in which students learned to offer suggestions, accept corrections, and recognise their classmates' progress. One female student summarised this aspect by saying: "When we worked in pairs, it helped me to hear my partner's advice, because sometimes they noticed a mistake that I did not realise I was making."

Overall, the qualitative results confirm and enrich the quantitative findings, showing that the workshop produced positive effects not only on the technical fundamentals of dribbling and shooting, but also on motor awareness, perceived self-efficacy, motivation, active participation, and the quality of relationships within the class group. The students' words highlight how the intervention fostered a more reflective form of learning, less focused exclusively on performance, making basketball an educational experience capable of supporting both technical improvement and personal and relational growth (Table 3).

Discussion

The results of the study suggest that a basketball workshop structured according to a gradual didactic progression can contribute significantly to improving the fundamentals of dribbling and shooting in upper secondary school students. The reduction in completion time recorded in the Control Dribble Test and the increase in successful shots in the Speed Spot Shooting Test indicate that the intervention promoted both greater mastery of ball control in dynamic situations and improved shooting effectiveness. These findings are

particularly relevant because the skills analysed are not merely isolated technical gestures, but complex motor competences requiring coordination, balance, postural control, attentional engagement, and adaptation to task demands. From this perspective, the observed improvements should not be interpreted exclusively as gains in performance, but as the outcome of a broader motor learning process through which students progressively developed greater body control, movement awareness, and self-regulation skills.

The improvements observed are likely to result from the interaction of several complementary learning mechanisms rather than from repetitive technical practice alone. The workshop was intentionally organised according to a progressive instructional sequence, beginning with isolated technical exercises and gradually introducing more complex and game-related situations. This progression may have facilitated the gradual integration of perceptual and coordinative processes involved in motor learning, enabling students to refine their movement patterns while adapting them to increasingly variable task demands. Furthermore, repeated practice under progressively challenging conditions may have strengthened motor adaptation and movement consistency, contributing to the more efficient execution of both dribbling and shooting skills.

The quantitative outcomes are consistent with the literature on motor learning in physical education, according to which the quality of teaching, intentional repetition of the movement, progression of task difficulty, and the presence of specific feedback represent key factors in improving technical skills (Zhou et al., 2021; Han et al., 2022). In particular, the improvement observed in dribbling can be interpreted as the result of a combination of analytical exercises, dynamic courses, changes of direction, progressive use of the non-dominant hand, and transfer of skills into simplified game situations. Indeed, the structure of the intervention allowed students to experience dribbling under increasingly complex conditions, moving from static ball control to dynamic movement management, and finally to its application in semi-situational contexts. This progressive transition probably fostered better integration between visual control, footwork coordination, gaze orientation, and spatial management (Farhat et al., 2025).

Similarly, the progress observed in shooting seems to be attributable to the breakdown of the technical gesture, the initial reduction of the distance from the basket, the attention

paid to body balance, and the final follow-through of the movement. These elements enabled students to focus not only on the outcome of the performance, namely scoring a basket, but also on the quality of the execution. This aspect is particularly important in school contexts, where there is often a risk of privileging the immediate result over the learning process. In the present workshop, instead, the gradual nature of the proposed activities and correction-oriented repetition allowed students to understand that effective shooting depends on a set of coordinated components: foot position, balance, lower-limb drive, elbow alignment, ball release, and wrist follow-through.

This approach confirms the value of formative feedback in physical education, especially when it is timely, understandable, task-centered, and oriented towards movement correction rather than the simple evaluation of results (Treschman et al., 2024; Zhou et al., 2021). In the workshop, feedback was not used as a judgment on performance, but as a tool for regulating learning. Students were guided to recognize errors, understand their causes, and identify possible improvement strategies. This approach facilitated the transition from a merely executive logic to a reflective one, in which motor learning does not coincide solely with the repetition of a movement, but also involves observation, interpretation, self-correction, and awareness. From a motor learning perspective, formative feedback may also have facilitated error detection, movement self-monitoring, and the gradual development of more accurate internal representations of the motor task. Rather than simply correcting technical execution, feedback encouraged students to compare intended and executed movements, progressively refining performance through self-regulation and repeated practice. In this sense, feedback took on an educational as well as a technical function, contributing to the construction of a learning climate less centered on performance and more oriented towards personal improvement.

The exploratory subgroup analysis further suggests that the instructional programme was effective across the age range included in the study. Statistically significant improvements were observed in both younger (15–16 years) and older (17 years) students, indicating that the intervention was associated with enhanced basketball-specific technical performance irrespective of age within the sample. Although descriptive data suggested slightly larger improvements among the older students, no formal between-group comparisons were performed and, therefore, these observations should be interpreted with caution. The limited sample size substantially reduced the possibility of detecting true age-related differences. Consequently, it cannot be established whether developmental stage influenced responsiveness to the intervention. Future studies including larger and more heterogeneous samples should investigate whether biological maturation and developmental stage moderate the effectiveness of basketball-based instructional programmes.

The qualitative results further strengthen this interpretation, showing that students developed greater motor awareness, more confidence in execution, and a better ability to recognise and correct errors. The observations carried out through the technical-motor rubric and the statements collected during the focus group indicate that students began to pay greater attention to movement quality, posture, the use of the non-dominant hand, balance, and the overall coordination of the gesture. This finding is particularly relevant when viewed

in light of the concept of physical literacy, which interprets physical education not as simple technical training, but as an integrated process involving motor, cognitive, affective, and motivational dimensions (Graudusius et al., 2024). From this point of view, the workshop promoted not only the acquisition of basketball-specific skills, but also the development of a greater willingness to participate, engage actively, collaborate, and reflect on one's own learning process.

From this perspective, basketball emerges as a didactic context capable of promoting not only specific sports skills, but also active participation, self-regulation, motivation, and peer collaboration. Small-group activities, technical challenges, informal tutoring, and mini-games supported a cooperative learning climate, confirming what has been highlighted by studies on the Sport Education Model, according to which motor experiences organised in a participatory and responsibility-based manner can improve students' attitudes, engagement, and motivation towards physical education (Zhang et al., 2024). The cooperative dimension proved particularly significant because it allowed less confident students to experience accessible and progressive tasks, while more skilled students were valued as a resource for the group. In this way, the workshop fostered more balanced participation, reducing the gap between students with different initial levels of motor ability. Beyond its social value, peer observation and cooperative practice may also have enhanced motor learning by increasing opportunities for observational learning and immediate peer feedback. Observing classmates performing the same tasks likely enabled students to recognise effective movement strategies, identify execution errors, and incorporate corrective adjustments into their own performance, thereby reinforcing the learning process. This mechanism may also explain the improvements in perceived self-efficacy and confidence that emerged from the qualitative findings.

A further relevant aspect concerns the valorization of error as a learning opportunity. The qualitative evidence shows that, during the intervention, students progressively changed the way they interpreted error: from a sign of inability or failure to useful information for correcting the movement and improving subsequent performance. This transition has strong pedagogical value, as it contributes to building a climate of trust in which students can experiment, make mistakes, correct themselves, and try again without experiencing error as a penalising element. This approach is also consistent with the perspective of Quality Physical Education promoted by UNESCO, which emphasises the role of physical education in developing bodily, social, and emotional competences, as well as in promoting well-being, participation, and responsibility (UNESCO, 2021).

Despite the positive outcomes, the study presents some limitations that must be carefully considered. First, the small sample size, consisting of 18 students, does not allow for broad generalization of the results. Moreover, although the participants belonged to the same pre-existing class, the age range of 15–17 years indicates a degree of within-class heterogeneity that may reflect differences in biological maturation, previous motor experience, and individual school trajectories. Because of the small sample size and the class-based design, the possible influence of age and other participant characteristics could not be examined separately. Future studies should include larger samples and multiple classes to allow analyses according to

age, sex, educational trajectory, previous basketball experience, and baseline motor competence. Second, the absence of a control group prevents the improvements observed from being attributed with absolute certainty exclusively to the intervention, since the possible effect of familiarisation with the tests or other contextual factors cannot be entirely excluded (Dewi et al., 2026). Furthermore, the limited duration of the intervention, equal to eight weeks, makes it possible to observe initial improvements, but does not allow for verification of the stability of learning outcomes in the medium to long term. An additional limitation concerns the qualitative rubric, which, although consistent with the objectives of the workshop, was developed ad hoc and does not possess the standardisation features typical of validated instruments (Lesmawan et al., 2025).

In light of these limitations, future research could involve larger samples, quasi-experimental designs with a control group, follow-up assessments, and validated observational tools, in order to verify the stability of learning outcomes and the effectiveness of the workshop in different school contexts. It would also be useful to extend the analysis to other basketball fundamentals, such as passing, defence, off-ball movement, and tactical collaboration, in order to understand whether the proposed workshop structure can also influence more complex and interdependent competences. However, the results indicate that a basketball pathway designed with gradual progression, formative feedback, personalisation, and reflection can represent an effective didactic proposal for promoting technical improvement in dribbling and shooting while also supporting motor awareness, motivation, collaboration, and active participation within the class group.

Conclusions

This pilot study highlighted how a basketball workshop, designed according to a progressive didactic approach and aimed at improving the fundamental skills of dribbling and shooting, can represent an effective proposal within upper secondary school. The quantitative results showed a significant improvement in both the Control Dribble Test and the Speed Spot Shooting Test, indicating growth in students' ability to control the ball while moving and in shooting accuracy. At the same time, the qualitative results made it possible to identify broader transformations related to the quality of motor execution, technical awareness, motivation, perceived self-efficacy, and peer collaboration. From this perspective, the intervention should not be interpreted solely as a technical-sport learning pathway, but as an educational experience capable of integrating bodily, cognitive, emotional, and relational dimensions.

One of the most significant elements emerging from the study concerns the relationship between technical improvement and motor awareness. Students did not simply perform dribbling and shooting more effectively (Candra et al., 2023); rather, they progressively learned to recognise the elements that make the movement more effective: ball control, posture, gaze direction, balance, limb coordination, and final follow-through. This result appears consistent with the perspective of physical literacy, which recognises physical education as a privileged context for promoting motor competences, motivation, and conscious participation in physical activities throughout life (Grauduszus et al., 2024).

The workshop therefore fostered a form of motor learning that was not limited to immediate performance, but was oriented towards understanding movement and building greater confidence in one's own abilities.

The workshop structure, based on gradual progression, formative feedback, task personalisation, peer observation, and moments of reflection, promoted the transition from a logic focused exclusively on performance to one oriented towards improvement, self-correction, and understanding of the movement. This confirms what has been highlighted by recent literature on feedback in physical education, according to which timely, specific, and task-centred instructions can significantly support motor skill learning (Zhou et al., 2021; Han et al., 2022; Treschman et al., 2024). In the context of this study, feedback had not only a corrective function, but also a motivational and reflective one, as it helped students understand that error is not an obstacle, but a natural component of the learning process. This aspect is particularly important in upper secondary school, where the perception of motor incompetence may reduce participation and engagement in physical activities.

Moreover, cooperative activities, technical challenges, and small-sided games strengthened students' engagement, confirming the value of participatory teaching models, such as the Sport Education Model, in promoting positive attitudes, motivation, and responsibility in physical education contexts (Zhang et al., 2024). The workshop showed that basketball can become an inclusive educational environment when activities are designed to enable all students to participate, experience active roles, and perceive personal progress. The presence of differentiated tasks, the valorisation of peer tutoring, and attention to movement quality contributed to building a more collaborative climate, in which individual improvement was also supported by the relationship with the group.

Despite the limitations related to the small sample size, the absence of a control group, and the limited duration of the intervention, the study offers useful indications for didactic planning. In particular, it shows that basketball can be used not only to develop specific technical competences, but also to support processes of motor awareness, inclusion, cooperation, and active participation. From an operational point of view, the results suggest the importance of designing physical education pathways based on clear objectives, progressive task difficulty, formative feedback, cooperative activities, and moments of reflection. These elements can make motor learning more meaningful, as they help students understand the purpose of the movement, monitor their own progress, and experience sport as a formative process, rather than merely as a performance-based activity.

Future research could expand the sample, introduce a control group, include follow-up assessments, and use validated observational tools in order to verify the stability of learning outcomes and the transferability of the workshop model to other school contexts and other basketball fundamentals. It would also be useful to further investigate the relationship between technical improvement, motivation, perceived competence, and participation in physical activities, in order to better understand how structured motor experiences may affect not only sports skills, but also students' disposition towards an active lifestyle. Overall, the experience confirms the educational value of basketball as a meaningful learning

environment, in which technical improvement becomes an opportunity to promote personal growth, educational relationships, and the student's overall development.

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Ethics Approval

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the University of Naples "Parthenope", Department of Medical, Human Movement and Well-Being Sciences (DiSMMeB; Protocol No. 88592/2024).

Informed Consent

Written informed consent was obtained from all participants prior to their participation in the study. For participants under 18 years of age, written informed consent was additionally obtained from their parents or legal guardians.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy restrictions.

AI Transparency Statement

The authors declare that artificial intelligence tools were not used in the design of the study, collection or analysis of data, interpretation of the results, or formulation of the scientific conclusions. Generative artificial intelligence tools were used exclusively for linguistic editing and grammatical improvement of the manuscript. The authors reviewed and approved the final text and take full responsibility for its content.

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Розвиток рухових навичок учнів старших класів у процесі реалізації шкільної програми баскетбольної підготовки

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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. Метою дослідження було визначити вплив восьми тижневої шкільної програми навчання баскетболу на результативність ведення м'яча та кидків в учнів старшої середньої школи, а також дослідити супутні зміни в усвідомленні рухів, сприйнятій самоефективності, мотивації та взаємодії з однолітками.

Матеріали та методи. У пілотному дослідженні з дизайном «претест–посттест» в одній групі взяли участь 18 учнів віком 15–17 років. Інтервенція тривала вісім тижнів і передбачала два 60-хвилинні заняття на тиждень, що включали поступово ускладнювані технічні вправи, роботу в парах і малих групах, спрощені ігрові ситуації, формувальний зворотний зв'язок та рефлексивні завдання. Спеціальну баскетбольну підготовленість оцінювали за допомогою тестів AAHPERD Control Dribble Test і Speed Spot Shooting Test. Якісні дані отримували за допомогою техніко-рухової спостережної рубрики та напівструктурованої фокус-групи. Відмінності між показниками до та після інтервенції аналізували за допомогою парного t-критерію Стюдента, а величину ефекту визначали за d Коена.

Результати. Результат Control Dribble Test покращився з $25,51 \pm 2,84$ с до $21,76 \pm 2,37$ с; середня різниця становила $-3,75$ с (95% ДІ: від $-4,52$ до $-2,98$; $t_{(17)} = -10,28$; $p < 0,001$; $d = 2,42$). У Speed Spot Shooting Test кількість результативних кидків збільшилася з $4,78 \pm 1,21$ до $6,56 \pm 1,18$; середня різниця становила 1,78 кидка (95% ДІ: $1,27$ – $2,29$; $t_{(17)} = 8,00$; $p < 0,001$; $d = 1,89$). Якісний аналіз засвідчив покращення контролю рухів, технічної усвідомленості, сприйманої самоефективності, мотивації, ставлення до помилок та взаємодії з однолітками.

Висновки. Восьмитижнева програма навчання баскетболу була пов'язана зі значним покращенням результатів ведення м'яча та кидків в учнів старшої середньої школи. Також спостерігалися позитивні зміни в усвідомленні учнями виконання рухів та їхній залученості до процесу навчання. З огляду на малий обсяг вибірки та відсутність контрольної групи отримані результати слід розглядати як попередні.

Ключові слова: баскетбол, фізичне виховання, рухове навчання, ведення м'яча, кидок, підлітки.

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Vertical Jump Performance, Arm Swing Benefit, and Body Size in Grades 3–5: A Cross-Sectional Study

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Abstract

Objectives. The study aimed to compare vertical jump performance across Grades 3–5, examine associations with body size, and secondarily evaluate arm swing benefits.

Materials and Methods. This cross-sectional school study included 129 pupils from eastern Slovakia (3rd grade, n = 46; 4th grade, n = 50; 5th grade, n = 33). Data on sex, biological maturation, organized sport participation, and habitual physical activity were unavailable. The best of three valid Chronojump attempts was analyzed for countermovement jump without arm swing (CMJ), countermovement jump with free arm swing (CMJ FA), and squat jump (SJ). One-way ANOVA tested grade differences in these primary outcomes. Absolute and relative arm swing benefits were secondary exploratory outcomes. ANCOVA, joint models including height and mass, correlations, nonparametric sensitivity analyses, and grade × mass interactions were also examined.

Results. Primary outcomes did not differ by grade ($p = 0.19–0.59$; eta squared = $0.008–0.026$). Secondary exploratory analyses identified differences in absolute and relative arm swing benefit (both $p = 0.002$; eta squared is approximately 0.09), with higher values in the 5th grade than in the 3rd and 4th grades; nonparametric analyses supported these contrasts. Mass-adjusted ANCOVA revealed that mass was significant for all tests, and a grade effect emerged for CMJ FA ($p = 0.013$). In joint models, height was positively and mass negatively associated with each primary outcome, whereas grade effects and grade × mass interactions were nonsignificant.

Conclusions. The findings indicate that primary jump outcomes showed no statistically detectable differences across adjacent grades. The larger secondary exploratory arm swing benefit in the 5th grade group does not demonstrate developmental change within pupils and may partly reflect unmeasured sex, maturation, or activity characteristics. Body size interpretation depended on model specification. School testing should emphasize standardized procedures and individual feedback rather than diagnostic labeling or ranking by grade.

Keywords: countermovement jump, squat jump, arm swing, body mass, physical education, children.

Introduction

Primary school physical education provides a structured setting for developing motor competence and fundamental movement skills. Physical education delivered through the curriculum and school interventions can improve these outcomes (Lorås, 2020; Yin et al., 2025). Varied movement opportunities may help offset prolonged sitting, while appropriately supervised strength activities may support motor development (Mikuláková & Andraščíková, 2008; León-Reyes et al., 2025).

Jumping is a fundamental locomotor skill requiring lower limb force, postural control, and coordinated

segmental action. Jump height and movement patterns vary substantially among children (Liu et al., 2022; Koren et al., 2016; Gieysztor et al., 2024), and vertical jump performance has also been examined in pupils with different sport specializations (Leütterová et al., 2019). A school jump score therefore reflects performance under defined test conditions rather than overall motor development.

Vertical jump tests are noninvasive, quick, and suitable for field assessment. Different protocols provide distinct information on explosive power, strength endurance, and stretch-shortening cycle performance (Zemková & Hamar, 2005). Reliability has also been examined in volleyball (Zapletalová, 2018), and diagnostic sensitivity varies by protocol (Hespanhol et al., 2013). Bogataj et al. (2020) reported reliable assessment of SJ, CMJ, and CMJ with free arms in primary school children. Pueo et al. (2020) reported

high concurrent validity and reliability of the Chronojump system in physically active adults.

The SJ, CMJ, and CMJ FA provide related but distinct information. Muscle morphology and the capacity to generate force can influence modeled vertical jump performance (Wong et al., 2016), while empirical work identifies lower limb strength and rate of force development as major determinants, with a smaller contribution from technique (Vanezis & Lees, 2005). Free arm movement can increase jump height by altering force–time characteristics and impulse (Vaverka et al., 2016), including in preschool children despite variable movement efficiency (Petrić et al., 2025). The difference between CMJ FA and CMJ within each pupil may therefore provide a functional index of arm contribution, but it is not a direct measure of coordination.

Body size also matters. Body mass is the load accelerated during takeoff, and it affects interpretation of CMJ kinetics in children (Jones et al., 2020). Associations of body mass status and BMI with running and jumping vary across samples and subgroups (Nikolaidis et al., 2015; Ayan, 2018; Branet et al., 2018). Body mass does not distinguish lean from fat tissue. Stenevi Lundgren et al. (2011) reported DXA measures alongside neuromuscular outcomes, whereas Ljubičić et al. (2025) linked higher adiposity with poorer jumping outcomes.

Evidence specific to adjacent primary school grades is limited. Normative data are available for children aged 10–15 years, whereas some comparisons use sport samples spanning wider age ranges (Taylor et al., 2010; Nikolaidis, 2014). Specific muscular strength characteristics are associated with vertical jump performance in adolescent athletes (Harčarik & Falat Leütterová, 2024). Sex and biological maturation may contribute to variation in jump performance (Ayan, 2018; Hespanhol et al., 2013). Habitual physical activity, organized sport, and training exposure may also influence performance (Rajkovic Vuletic et al., 2024; Wu et al., 2025). These factors complicate interpretation of cross-sectional differences between grades.

The primary aim was to compare CMJ, CMJ FA, and SJ performance among pupils in the 3rd, 4th, and 5th grades and to examine associations between body size and jump outcomes. We expected only modest differences between grades in absolute jump height and a negative association between body mass and performance. A secondary exploratory aim was to compare absolute and relative arm swing benefit across grades; no directional confirmatory hypothesis was specified for this exploratory analysis.

Materials and Methods

Participants

The analytical sample comprised 129 pupils (3rd grade, $n = 46$; 4th grade, $n = 50$; 5th grade, $n = 33$). Body height and body mass increased descriptively across grades (Table 1). Participants received compulsory physical and sports education at least twice weekly. Inclusion required enrolment in a target grade and complete data for body height, body mass, and jump tests. Archived age summaries for each group were 9.10 ± 0.44 years for the 3rd grade, 10.32 ± 0.53 years for the 4th grade, and 11.10 ± 0.59 years for the 5th grade. Sex was not recorded in the archived analytical dataset and therefore could not be included in descriptive or inferential

analyses. Information on organized sport participation and habitual physical activity outside compulsory physical education was unavailable. Biological maturation was not assessed.

Table 1. Participant characteristics by school grade

Grade	n	Age, years M $\pm$ SD	Body mass, kg M $\pm$ SD	Body height, cm M $\pm$ SD
3 rd grade	46	9.10 $\pm$ 0.44	32.40 $\pm$ 7.35	138.59 $\pm$ 6.49
4 th grade	50	10.32 $\pm$ 0.53	37.29 $\pm$ 7.79	145.15 $\pm$ 6.30
5 th grade	33	11.10 $\pm$ 0.59	37.42 $\pm$ 8.22	146.84 $\pm$ 8.84
Total	129	NA	35.58 $\pm$ 8.05	143.24 $\pm$ 7.88

Note. Age values are archived summaries for each group. M = mean; SD = standard deviation.

Study design

This cross-sectional observational study conducted in schools examined vertical jump performance and somatic characteristics among pupils in the 3rd, 4th, and 5th grades. School grade was the grouping variable, and reporting was guided by the STROBE recommendations (von Elm et al., 2007). No intervention was administered; the measurements represented a single assessment point under ordinary school conditions.

School grade was the grouping variable. The primary outcomes were CMJ, CMJ FA, and SJ height. Body height and body mass were prespecified somatic covariates. In the exploratory analysis, absolute arm swing benefit was calculated as CMJ FA – CMJ (cm), and relative benefit as [(CMJ FA – CMJ) / CMJ] $\times$ 100 (%).

Procedures and Instruments

Testing was conducted individually under regular school conditions. Body height (cm) and body mass (kg) were recorded before jump testing and were used for sample description and covariate analyses.

Vertical jump height was measured in centimeters using the Chronojump system (Chronojump Boscossystems, Barcelona, Spain), whose concurrent validity and reliability have been demonstrated in physically active adults (Pueo et al., 2020). After verbal instruction, pupils performed CMJ without arm swing, CMJ FA, and SJ in this fixed order. CMJ involved a rapid countermovement without arm swing; CMJ FA permitted free arm movement; SJ began from a static squat without a preceding countermovement.

Each test included one practice trial followed by three measured attempts. The best valid jump height from the three measured attempts was retained for analysis. An SJ attempt was repeated when a countermovement was observed. At least one minute of rest separated the three jump variations. Values from individual trials were not retained in the analytical file, so reliability within the testing session could not be estimated.

Statistical analysis

Means, standard deviations, 95% confidence intervals (CIs), and minima and maxima were calculated.

Distributional assumptions were assessed with Shapiro–Wilk tests and homogeneity of variance with Levene tests centered on the median. One-way ANOVA was used to compare grades across the three primary outcomes and the two exploratory benefit outcomes. Significant omnibus tests were followed by Tukey comparisons. Eta squared quantified omnibus effects. Cohen's *d* was used to quantify pairwise standardized differences (Cohen, 1988). The 95% confidence intervals were calculated for each Cohen's *d* estimate.

Because arm swing benefit distributions departed from normality in some groups, Kruskal–Wallis tests followed by Mann–Whitney comparisons adjusted using the Holm method were used as sensitivity analyses. Separate ANCOVA models adjusted each primary outcome for body height and body mass; adjusted means with 95% CI, comparisons adjusted using the Bonferroni method, and partial eta squared were reported. Because height and mass were correlated, models including both covariates were included in sensitivity analyses, and variance inflation factors were used to assess collinearity. Interactions between grade and body mass tested whether the slope of the association between body mass and performance differed across grades.

Pearson correlations with 95% CI described associations between body mass and jump outcomes within each grade and in the total sample. These correlations were treated as exploratory; Spearman correlations and the Benjamini–Hochberg adjustment for the false discovery rate were used as sensitivity checks. Statistical significance was set at $p < 0.05$. The available eligible sample determined the study size; no a priori calculation was performed. With $n = 129$ and $\alpha = 0.05$, the design had 80% power to detect approximately Cohen $f = 0.277$ (eta squared = 0.071). Statistical analyses were performed in IBM SPSS Statistics 27 (IBM Corp., Armonk, NY, USA).

Results

Primary Vertical Jump Outcomes

For the three primary outcomes, unadjusted grade effects were not statistically significant for CMJ, $F_{(2,126)} = 0.69$, $p = 0.506$, eta squared = 0.011; CMJ FA, $F_{(2,126)} = 1.69$, $p = 0.189$, eta squared = 0.026; or SJ, $F_{(2,126)} = 0.52$, $p = 0.594$, eta squared = 0.008 (Table 2). Estimated grade effects were small. Mean CMJ FA and SJ values were descriptively highest in the 5th grade, whereas CMJ remained broadly stable; no Tukey comparison was significant.

Secondary exploratory arm swing benefit

In the secondary exploratory analyses, absolute arm swing benefit differed by grade, $F_{(2,126)} = 6.53$, $p = 0.002$, eta squared = 0.094, as did relative benefit, $F_{(2,126)} = 6.44$, $p = 0.002$, eta squared = 0.093 (Table 3). Both outcomes were higher in the 5th grade than in the 3rd and 4th grades, while the two younger grades did not differ. For absolute benefit, standardized differences were $d = 0.90$ (95% CI 0.43 to 1.37) for the 3rd versus 5th grade and $d = 0.63$ (0.18 to 1.08) for the 4th versus 5th grade. Corresponding effects for relative benefit were $d = 0.81$ (0.35 to 1.28) and $d = 0.67$ (0.21 to 1.12). Kruskal–Wallis sensitivity analyses confirmed grade differences for absolute benefit ($H(2) = 13.57$, $p = 0.001$) and relative benefit ($H(2) = 12.16$, $p = 0.002$);

Table 2. Vertical jump performance by grade and one-way ANOVA

Test	3 rd grade (n = 46)	4 th grade (n = 50)	5 th grade (n = 33)	ANOVA result F; p; η^2
CMJ	20.02 ± 4.10 [18.81, 21.24]	20.71 ± 4.35 [19.47, 21.94]	19.68 ± 3.71 [18.37, 21.00]	F = 0.69 p = 0.506 $\eta^2 = 0.011$
CMJ FA	22.76 ± 4.01 [21.57, 23.95]	23.74 ± 5.28 [22.24, 25.24]	24.70 ± 4.55 [23.09, 26.32]	F = 1.69 p = 0.189 $\eta^2 = 0.026$
SJ	19.08 ± 3.99 [17.89, 20.26]	19.82 ± 4.34 [18.58, 21.05]	19.92 ± 4.15 [18.44, 21.39]	F = 0.52 p = 0.594 $\eta^2 = 0.008$

Note. Values are mean ± standard deviation with 95% confidence interval in brackets. CMJ = countermovement jump without arm swing; CMJ FA = countermovement jump with free arm swing; SJ = squat jump; η^2 = eta squared.

pairwise results adjusted using the Holm method confirmed both contrasts involving the 5th grade. Individual distributions are shown in Figure 1.

Table 3. Exploratory absolute and relative arm swing benefit

Outcome	3 rd grade (n = 46)	4 th grade (n = 50)	5 th grade (n = 33)	ANOVA result F; p; η^2
Absolute benefit, cm	2.73 ± 2.55 [1.98, 3.49]	3.03 ± 3.49 [2.04, 4.03]	5.02 ± 2.53 [4.12, 5.92]	F = 6.53 p = 0.002 $\eta^2 = 0.094$
Relative benefit, %	14.98 ± 13.85 [10.86, 19.09]	15.69 ± 17.25 [10.78, 20.59]	26.49 ± 14.52 [21.34, 31.63]	F = 6.44 p = 0.002 $\eta^2 = 0.093$

Note. Values are mean ± standard deviation with 95% confidence interval in brackets. Comparisons adjusted using the Tukey method were significant for the 3rd versus 5th grade (absolute $p = 0.003$; relative $p = 0.004$) and the 4th versus 5th grade (absolute $p = 0.009$; relative $p = 0.006$); the 3rd and 4th grades did not differ. Kruskal–Wallis sensitivity analyses were also significant (absolute $H(2) = 13.57$, $p = 0.001$; relative $H(2) = 12.16$, $p = 0.002$).

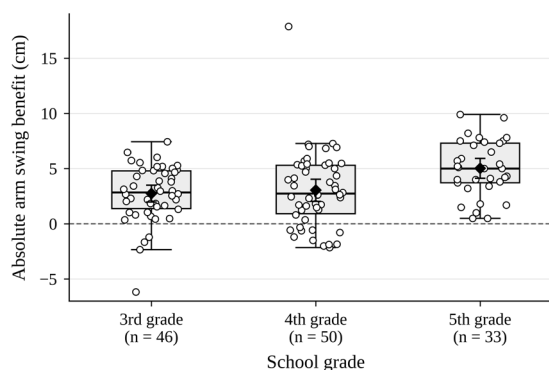


Fig. 1. Distribution of absolute arm swing benefit by grade. Open circles represent pupils; boxes show the interquartile range and median; whiskers extend to $1.5 \times$ IQR; diamonds and error bars show the mean and approximate 95% confidence interval. The dashed line indicates no benefit.

ANCOVA and joint sensitivity models for body size

In ANCOVA containing body height only, neither body height nor grade was significant for any jump outcome (Table 4, Panel A). In models containing body mass only, body mass was significant for CMJ, $F_{(1,125)} = 12.45$, $p < 0.001$; CMJ FA, $F_{(1,125)} = 16.70$, $p < 0.001$; and SJ, $F_{(1,125)} = 11.07$, $p = 0.001$. A grade effect emerged for CMJ FA adjusted for body mass, $F_{(2,125)} = 4.48$, $p = 0.013$, with a difference between the 3rd and 5th grades after adjustment using the Bonferroni method ($p = 0.014$).

Interpretation changed in sensitivity models that simultaneously included height and mass. Variance inflation factors were below 1.8. Body height was positively associated with CMJ ($B = 0.174$ cm per cm, $p = 0.004$), CMJ FA ($B = 0.208$, $p = 0.002$), and SJ ($B = 0.204$, $p < 0.001$), whereas body mass was negatively associated with CMJ ($B = -0.254$ cm per kg), CMJ FA ($B = -0.320$), and SJ ($B = -0.264$; all $p < 0.001$). Grade effects were not significant in these joint models ($p = 0.213$ – 0.713 ; Supplementary Table S2).

Associations between body mass and jump outcomes

Pearson correlations between body mass and the three primary outcomes were negative in the total sample and were numerically strongest in the 3rd grade (Table 5). Neither absolute nor relative arm swing benefit was significantly correlated with body mass. After adjustment for the false discovery rate, the three correlations in the 3rd grade, the CMJ FA correlation in the 4th grade, and all three correlations in the total sample remained significant; however, the CMJ FA association in the 4th grade was not significant in the Spearman sensitivity analysis. Interactions between grade and body mass were not significant for CMJ ($p = 0.302$), CMJ FA ($p = 0.396$), or SJ ($p = 0.345$), providing no statistical evidence that the slope of the association between body mass and performance differed by grade.

Discussion

The primary analyses found no statistically detectable grade differences in CMJ, CMJ FA, or SJ, and estimated

Table 4. ANCOVA of jump performance adjusted separately for body height and body mass

Test	3 rd grade	4 th grade	5 th grade	Grade effect F (p); η^2	Covariate effect F (p); η^2
Panel A. Body height as a covariate					
CMJ	20.06 [18.77, 21.36]	20.69 [19.52, 21.86]	19.65 [18.19, 21.12]	0.67 (0.513) $\eta^2 = 0.011$	0.03 (0.868) $\eta^2 = 0.000$
CMJ FA	22.75 [21.28, 24.23]	23.74 [22.41, 25.07]	24.70 [23.03, 26.37]	1.38 (0.256) $\eta^2 = 0.022$	0.00 (0.997) $\eta^2 = 0.000$
SJ	19.22 [17.91, 20.54]	19.76 [18.57, 20.94]	19.80 [18.31, 21.29]	0.21 (0.814) $\eta^2 = 0.003$	0.37 (0.545) $\eta^2 = 0.003$
Panel B. Body mass as covariate					
CMJ	19.52 [18.33, 20.70]	20.98 [19.87, 22.09]	19.98 [18.61, 21.34]	1.64 (0.198) $\eta^2 = 0.026$	12.45 (<0.001) $\eta^2 = 0.091$
CMJ FA	22.10 [20.77, 23.42]	24.10 [22.85, 25.34]	25.08 [23.56, 26.61]	4.48 (0.013) $\eta^2 = 0.067$	16.70 (<0.001) $\eta^2 = 0.118$
SJ	18.59 [17.38, 19.79]	20.08 [18.94, 21.21]	20.20 [18.81, 21.59]	1.99 (0.140) $\eta^2 = 0.031$	11.07 (0.001) $\eta^2 = 0.081$

Note. Adjusted means are estimated marginal means in centimeters with 95% confidence intervals in brackets. η^2 = partial eta squared. Pairwise comparisons adjusted using the Bonferroni method were not significant except for CMJ FA adjusted for body mass, where the 3rd and 5th grades differed ($p = 0.014$). Joint models including height and mass are reported in Supplementary Table S2.

Table 5. Pearson correlations between body mass and primary jump outcomes

Group	n	Body mass with CMJ r [95% CI]; p	Body mass with CMJ FA r [95% CI]; p	Body mass with SJ r [95% CI]; p
3 rd grade	46	-0.442 [-0.649, -0.174]; p = 0.002	-0.486 [-0.680, -0.228]; p < 0.001	-0.463 [-0.664, -0.199]; p = 0.001
4 th grade	50	-0.280 [-0.518, -0.002]; p = 0.049	-0.351 [-0.573, -0.081]; p = 0.012	-0.199 [-0.452, 0.084]; p = 0.166
5 th grade	33	-0.146 [-0.466, 0.208]; p = 0.417	-0.179 [-0.492, 0.175]; p = 0.319	-0.202 [-0.510, 0.152]; p = 0.260
Total	129	-0.277 [-0.429, -0.109]; p = 0.001	-0.282 [-0.434, -0.114]; p = 0.001	-0.245 [-0.401, -0.075]; p = 0.005

Note. BM = body mass; CMJ = countermovement jump without arm swing; CMJ FA = countermovement jump with free arm swing; SJ = squat jump. Raw p values are shown; adjustment for the false discovery rate and Spearman sensitivity results are provided in Supplementary Table S3.

effects were small. The secondary exploratory analysis identified a larger CMJ FA – CMJ difference in the 5th grade, also supported by nonparametric analyses. Body mass was negatively associated with jump height, while conclusions about height and adjusted grade effects depended on model specification.

Cross-sectional groups combine pupils with different body size, strength, movement experience, and task familiarity. Nonsignificant findings do not establish equivalence; effects below about $\eta^2 = 0.071$ were not detectable with 80% power. Grade should therefore be treated as context, not evidence of change within pupils or motor maturity.

Sex, biological maturation, and physical activity

Sex was not recorded. Sex differences in vertical jump performance have been reported in this age range (Ayan, 2018; Taylor et al., 2010), so unknown group composition may have increased variability or confounded grade comparisons. Biological maturation was also unmeasured. Differences in body proportions, fat-free mass, and neuromuscular function may be relevant particularly to the arm swing contrast in the 5th grade (Hespanhol et al., 2013; Nikolaidis, 2014). Organized sport participation and habitual physical activity were unavailable; variation in training exposure and jump familiarity may therefore have affected performance (Rajkovic Vuletic et al., 2024; Wu et al., 2025). These unmeasured characteristics prevent attribution to grade alone.

Arm swing benefit

The largest grade contrast arose in the secondary exploratory analysis of arm swing benefit. Although CMJ and CMJ FA considered separately did not differ significantly by grade, their difference within each pupil was larger in the 5th grade. This pattern occurred for both indices and in nonparametric analyses. The result is therefore hypothesis-generating rather than confirmatory evidence.

Arm swing can increase jump height by altering impulse and takeoff strategy (Vaverka et al., 2016). The contrast in the 5th grade may reflect group differences in arm use, strength, familiarity, sex, maturation, sport participation, or activity. It cannot indicate developmental improvement or directly measure coordination because the design was cross-sectional and technique was not recorded. The fixed CMJ then CMJ FA order also leaves possible familiarization effects. Prospective studies should randomize order and assess technique and participant characteristics.

Body size and performance

Body size results depended on model specification. In separate ANCOVA models, height was not associated with performance, while mass was significant for all tests. In joint models, height was positively and mass negatively associated with performance, and the grade effect for CMJ FA adjusted for mass was no longer significant. Collinearity was modest. These findings may reflect body proportions and load, but body composition was not measured.

The negative mass associations agree with studies linking body size, higher BMI, or overweight status to poorer

jumping in some child and youth samples (Jones et al., 2020; Nikolaidis et al., 2015; Ayan, 2018; Ljubičić et al., 2025). Because body mass combines muscle and adipose tissue, a plausible mechanical explanation is that force-producing tissue and nonpropulsive load contribute differently. This remains inferential.

Correlations were numerically strongest in the 3rd grade, but interactions between grade and body mass were nonsignificant. The data therefore do not show that older pupils compensate for mass more effectively; weaker estimates in the 5th grade may reflect sampling variation, limited power, or unmeasured group differences.

Practical implications

For school use, CMJ, CMJ FA, and SJ should be administered with consistent equipment, instructions, order, and scoring. Absolute jump height should be interpreted with body size in mind and preferably compared within pupils over time. The CMJ FA – CMJ difference may prompt observation of arm use but is not a diagnostic measure of coordination. The data do not support ranking or performance thresholds based on grade.

Strengths and limitations

Strengths include three complementary tests, electronic measurement, arm swing indices within each pupil, effect size reporting, and sensitivity analyses. Limitations include the regional three-grade sample and unavailable sex, maturation, sport participation, and habitual activity data, leaving potential confounding of grade contrasts. Individual age, body composition, and jump kinematics were also unavailable. The cross-sectional design cannot establish development or causality. Test order was fixed, only one practice trial was given, and values from individual trials were unavailable. Selecting the best of three attempts may increase variability. The arm swing analysis was exploratory, the relative index was sensitive to extreme ratios, multiple correlations increased multiplicity, and small grade effects could not be reliably detected.

Future studies should record these participant characteristics, retain all attempts, randomize test order, and assess technique directly. Longitudinal designs are needed to examine change within pupils, and instructional studies to test whether practice modifies arm swing benefit.

Conclusions

The primary analyses showed no statistically detectable grade differences in CMJ, CMJ FA, or SJ across Grades 3–5, and estimated effects were small. The secondary exploratory analysis observed greater absolute and relative arm swing benefit in the 5th grade than in the 3rd and 4th grades, but this cross-sectional contrast does not demonstrate developmental change within pupils. Body mass was negatively associated with jump height, whereas the independent contributions of body height and the adjusted grade effect depended on model specification. Use in schools should emphasize standardized testing, interpretation that accounts for body size, and feedback for each pupil rather than diagnostic labeling or ranking by grade.

Ethics Approval

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethical Commission of the University of Presov (approval number ECUP 092024PO, 2024).

Informed Consent

Written informed consent was obtained from the parents or legal guardians of all participating pupils before data collection.

Data Availability Statement

The data may be obtained from the corresponding author upon reasonable request, subject to applicable institutional and ethical requirements.

AI Transparency Statement

AI tools were used to assist with language editing, manuscript organization, and independent numerical verification. The authors critically reviewed all analyses, interpretations, and wording and take full responsibility for the final manuscript.

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Conflict of Interest Statement

The authors declare no conflicts of interest.

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Supplementary material

Vertical Jump Performance, Arm Swing Benefit, and Body Size in Grades 3–5: A Cross-Sectional Study

Table S1. Distributional diagnostics and robust analyses of arm swing benefit

Outcome	Grade	n	Median [IQR]	Min to max	Shapiro–Wilk W (p)
Absolute benefit, cm	3rd	46	2.83 [1.38, 4.78]	–6.18 to 7.43	0.947 (0.036)
	4th	50	2.72 [0.92, 5.29]	–2.15 to 17.87	0.890 (<0.001)
	5th	33	5.00 [3.70, 7.30]	0.50 to 9.90	0.969 (0.464)
Relative benefit, %	3rd	46	12.84 [7.66, 23.63]	–21.59 to 42.34	0.978 (0.513)
	4th	50	15.04 [3.76, 24.20]	–10.07 to 83.90	0.920 (0.002)
	5th	33	24.00 [17.70, 38.27]	2.66 to 55.62	0.967 (0.410)

Absolute benefit: Kruskal–Wallis $H(2) = 13.57$, $p = 0.001$. Mann–Whitney p values adjusted using the Holm method: 3rd vs 4th = 0.869, 3rd vs 5th = 0.002, 4th vs 5th = 0.004.

Relative benefit: Kruskal–Wallis $H(2) = 12.16$, $p = 0.002$. Mann–Whitney p values adjusted using the Holm method: 3rd vs 4th = 0.985, 3rd vs 5th = 0.005, 4th vs 5th = 0.005.

Table S2. Joint models including body height and body mass

Outcome	Adjusted mean for 3 rd grade [95% CI]	Adjusted mean for 4 th grade [95% CI]	Adjusted mean for 5 th grade [95% CI]	Grade effect $F(2,124)$, p ; η^2	Height B [95% CI], p	Mass B [95% CI], p	R^2
CMJ	20.02 [18.82, 21.22]	20.81 [19.73, 21.90]	19.53 [18.17, 20.89]	1.19 0.306 0.019	0.174 [0.056, 0.292] 0.004	–0.254 [–0.362, –0.146] <0.001	0.158

Table S2. Continued

Outcome	Adjusted mean for 3 rd grade [95% CI]	Adjusted mean for 4 th grade [95% CI]	Adjusted mean for 5 th grade [95% CI]	Grade effect F(2,124), p; η^2	Height B [95% CI], p	Mass B [95% CI], p	R ²
CMJ FA	22.70 [21.37, 24.04]	23.89 [22.68, 25.10]	24.55 [23.03, 26.06]	1.56 0.213 0.025	0.208[0.076, 0.339] 0.002	−0.320 [−0.440, −0.199] <0.001	0.204
SJ	19.18 [17.97, 20.39]	19.88 [18.78, 20.98]	19.67 [18.30, 21.04]	0.34 0.713 0.005	0.204 [0.084, 0.323] <0.001	−0.264 [−0.373, −0.155] <0.001	0.166

Note. Adjusted means are estimated at the total sample mean body height and body mass. B coefficients represent centimeters of jump height per 1 cm of height or 1 kg of mass difference while holding the other covariate and grade constant. Variance inflation factors were 1.78 for height and 1.70 for mass.

Table S3. Pearson and Spearman sensitivity analyses for body mass correlations

Group	Outcome	n	Pearson r [95% CI]	p values raw / FDR / Holm	Spearman ρ (p)
3 rd	CMJ	46	−0.442 [−0.649, −0.174]	0.002 / 0.008 / 0.034	−0.467 (0.001)
3 rd	CMJ FA	46	−0.486 [−0.680, −0.228]	<0.001 / 0.007 / 0.012	−0.400 (0.006)
3 rd	SJ	46	−0.463 [−0.664, −0.199]	0.001 / 0.007 / 0.023	−0.466 (0.001)
3 rd	Absolute benefit	46	−0.054 [−0.339, 0.240]	0.721 / 0.774 / 1.000	−0.013 (0.931)
3 rd	Relative benefit	46	0.059 [−0.235, 0.344]	0.696 / 0.774 / 1.000	0.072 (0.633)
4 th	CMJ	50	−0.280 [−0.518, −0.002]	0.049 / 0.122 / 0.634	−0.177 (0.219)
4 th	CMJ FA	50	−0.351 [−0.573, −0.081]	0.012 / 0.035 / 0.173	−0.272 (0.056)
4 th	SJ	50	−0.199 [−0.452, 0.084]	0.166 / 0.368 / 1.000	−0.158 (0.272)
4 th	Absolute benefit	50	−0.182 [−0.438, 0.101]	0.206 / 0.412 / 1.000	−0.153 (0.288)
4 th	Relative benefit	50	−0.115 [−0.381, 0.169]	0.427 / 0.610 / 1.000	−0.099 (0.494)
5 th	CMJ	33	−0.146 [−0.466, 0.208]	0.417 / 0.610 / 1.000	−0.321 (0.068)
5 th	CMJ FA	33	−0.179 [−0.492, 0.175]	0.319 / 0.532 / 1.000	−0.275 (0.122)
5 th	SJ	33	−0.202 [−0.510, 0.152]	0.260 / 0.472 / 1.000	−0.341 (0.052)
5 th	Absolute benefit	33	−0.107 [−0.434, 0.246]	0.554 / 0.693 / 1.000	−0.101 (0.576)
5 th	Relative benefit	33	−0.061 [−0.396, 0.288]	0.735 / 0.774 / 1.000	−0.022 (0.903)
Total	CMJ	129	−0.277 [−0.429, −0.109]	0.001 / 0.007 / 0.025	−0.279 (0.001)
Total	CMJ FA	129	−0.282 [−0.434, −0.114]	0.001 / 0.007 / 0.023	−0.264 (0.002)
Total	SJ	129	−0.245 [−0.401, −0.075]	0.005 / 0.017 / 0.078	−0.269 (0.002)
Total	Absolute benefit	129	−0.061 [−0.232, 0.113]	0.489 / 0.652 / 1.000	−0.025 (0.780)
Total	Relative benefit	129	0.003 [−0.170, 0.175]	0.977 / 0.977 / 1.000	0.042 (0.640)

Note. The Benjamini–Hochberg adjustment for the false discovery rate (FDR) and the Holm correction were applied across the 20 Pearson correlation tests. These analyses were exploratory.

Table S4. Interaction tests between grade and body mass and design sensitivity

Outcome	Interaction F(2,123)	p
CMJ	1.21	0.302
CMJ FA	0.93	0.396
SJ	1.07	0.345

At n = 129, alpha = 0.05, and three groups, 80% power corresponded to Cohen f = 0.277 (eta squared = 0.071). Approximate absolute correlations detectable with 80% power were r = 0.47 at n = 33, 0.40 at n = 46, 0.39 at n = 50, and 0.24 at n = 129.

Результативність вертикальних стрибків, ефективність махових рухів руками та розміри тіла учнів 3–5 класів: поперечне дослідження

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

Реферат. Стаття: 9 с., 5 табл., 1 рис., 30 джерел.

Мета дослідження. Дослідження мало на меті порівняти результативність вертикальних стрибків учнів 3–5 класів, вивчити зв'язок із розміром тіла, а також додатково оцінити ефективність махових рухів руками.

Матеріали та методи. У цьому поперечному шкільному дослідженні взяли участь 129 учнів зі Східної Словаччини (3-й клас: $n = 46$; 4-й клас: $n = 50$; 5-й клас: $n = 33$). Дані щодо статі, біологічного дозрівання, участі в організованій спортивній діяльності та звичної фізичної активності були відсутні. Проаналізовано оптимальну з трьох валідних спроб у системі Chronojump для таких тестів: стрибок із контррухом без маху руками (СКР), стрибок із контррухом з вільним махом руками (СКР ВР) та вистрибування з присіду (ВП). Міжкласові відмінності за цими первинними показниками перевіряли за допомогою однофакторного дисперсійного аналізу. Абсолютна та відносна ефективність маху руками виступали як додаткові дослідницькі показники. Також застосовано коваріаційний аналіз, досліджено спільні моделі з урахуванням довжини та маси тіла, кореляції, непараметричний аналіз чутливості та взаємодію факторів «клас $\times$ маса тіла».

Результати. Первинні показники не відрізнялися залежно від класу ($p = 0.19$ – 0.59 ; ета-квадрат = 0.008 – 0.026). Додатковий дослідницький аналіз виявив відмінності в абсолютній та відносній ефективності маху руками (для обох показників $p = 0.002$; ета-квадрат становить приблизно 0.09), причому вищі значення спостерігалися в учнів 5-го класу порівняно з 3-м та 4-м класами; непараметричний аналіз підтвердив ці контрасти. Коваріаційний аналіз із поправкою на масу тіла показав, що маса була значущим фактором для всіх тестів, а для СКР ВР виявлено ефект класу ($p = 0.013$). У спільних моделях довжина тіла мала позитивний, а маса тіла — негативний зв'язок із кожним первинним показником, тоді як ефекти класу та взаємодія «клас $\times$ маса тіла» були незначущими.

Висновки. Отримані результати свідчать про відсутність статистично значущих відмінностей між первинними показниками стрибків у суміжних класах. Вища додаткова дослідницька ефективність маху руками у групі 5-го класу не демонструє внутрішньоіндивідуальні розвиткові зміни в учнів і може частково відображати невраховані характеристики статі, дозрівання або рухової активності. Інтерпретація розмірів тіла залежала від специфікації моделі. Шкільне тестування має акцентувати увагу на стандартизованих процедурах та індивідуальному зворотному зв'язку, уникаючи діагностичного ярликування або ранжування учнів за класами.

Ключові слова: стрибок із контррухом, вистрибування з присіду, мах руками, маса тіла, фізичне виховання, діти.

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Developing an Individual Technical Preparedness Profile for a Highly Qualified Sprint Canoeist Using Biomechanical and Functional Indicators

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Abstract

Background. Technical preparedness in sprint canoeing depends on the coordinated interaction of the athlete, paddle, and boat. Isolated assessment of separate indicators may not reveal the specific factors limiting stroke effectiveness. An individual profile integrating biomechanical and functional data can identify these relationships and support decisions on technique, equipment, and seating configuration.

Objectives. To develop an individual technical preparedness profile of a highly qualified canoeist and substantiate individualized directions for technique, equipment selection, seating calibration, and training.

Materials and Methods. A single-case study involved an international-level canoeist; two additional canoeists provided reference data for selected indicators. Methods included surface electromyography, strain-gauge assessment of stroke parameters with Braca and Erbi paddles, kinematic analysis, 150-m speed testing in Nelo, Vajda, and Plastex boats, analysis of support interactions before and after seating calibration, and strength and functional assessments. The profile was developed through data processing, within-athlete comparison, consistency checking, classification into interpretative levels, and substantiation of coaching decisions.

Results. The algorithm identified strengths in the stability of the paddle attack angle, speed performance in the Plastex and Vajda boats, and support stability after seating calibration. The main reserves concerned force transmission through the “leg–trunk–arm–paddle” chain, trunk stability during the final stroke phase, and shoulder-girdle speed-strength endurance. Compared with Braca, Erbi produced greater work per stroke (73.0 vs 49.3 J), a larger effective stroke portion (45.6 vs 25.8 J), and a higher proportion of effective work (62.3% vs 53.0%). Mean speed was 3.99 m·s⁻¹ in Plastex, 3.95 m·s⁻¹ in Vajda, and 3.80 m·s⁻¹ in Nelo. Seating calibration reduced center-of-pressure displacement in all support zones. No confirmed limiting factors were identified.

Conclusions. Integrating biomechanical and functional indicators into an individual profile provides a scientifically grounded basis for personalizing technical preparation in sprint canoeing.

Keywords: sprint canoeing, technical preparedness, individual profile, biomechanical indicators, electromyography, stroke dynamics, center of pressure, athlete–boat interaction.

Introduction

Technical preparedness in sprint canoeing is one of the key factors of sports performance, because the effectiveness of the stroke cycle determines the athlete's ability to realize strength, functional, and coordination potential in boat velocity over the distance. In the system of canoeist preparation, technical

training should be distinguished as a targeted pedagogical process, whereas technical preparedness reflects the achieved level of the athlete's technical mastery (Altukhov & Shynkaruk, 2026c). In contemporary rowing and paddling biomechanics, technique is considered as an integrated system of interaction between the athlete, paddle, and boat that includes force application to the paddle, the kinematic structure of the stroke, body-position stability, coordinated work of muscle groups, and the ability to maintain an effective movement structure under different intensity modes (Gomes et al., 2015; Michael et al., 2012; Zahálka et al., 2011).

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The use of instrumented paddles, strain-gauge systems, video analysis, surface electromyography, tools for assessing support interactions, and functional monitoring makes it possible to obtain a broad dataset on the canoeist's technique. These methods allow researchers to assess force and work per stroke, the effective part of the stroke cycle, stability of angular characteristics, neuromuscular support of movement, boat velocity, characteristics of body interaction with the boat's support zones, and functional conditions for technique realization (Bonaiuto et al., 2020; Kong et al., 2020; Niu et al., 2019; Trevithick et al., 2007).

At the same time, the availability of a large number of separate biomechanical and functional indicators does not by itself ensure a justified coaching decision. Separate analysis of stroke force, electromyographic activity, kinematic parameters, boat velocity, and support interactions does not provide a complete understanding of which factors limit the technical effectiveness of a specific athlete. Therefore, not only the measurement of individual parameters is relevant, but also the development of a clear algorithm for integrating them into an individual technical preparedness profile.

For C1 sprint canoeing, this issue is especially important because of the asymmetric nature of the motor task caused by one-sided force application from a kneeling position. This specificity creates uneven loading of the body's support structures, trunk-stabilizing muscles, and lower limbs, which requires an individualized analysis of support interactions in the boat. Previous studies show that asymmetric loading in canoeing may be associated both with muscular imbalances and with morphofunctional adaptations of highly qualified athletes to the specific demands of the sport (Štryncl et al., 2021; Álvarez-Yates et al., 2024).

Modern scientific approaches to canoe paddling technique emphasize the need to combine biomechanical, kinematic, dynamic, and functional analyses for an objective assessment of athletes' technical preparedness (Altukhov & Shynkaruk, 2026b). Bibliometric analysis also confirms that current research is mainly focused on separate aspects of stroke biomechanics, kinematics, force dynamics, and sports performance, whereas the issue of forming an individual technical preparedness profile of a canoeist remains insufficiently developed (Altukhov & Shynkaruk, 2026a). Therefore, an approach that makes it possible to integrate heterogeneous indicators into a single interpretive matrix and use it to identify strengths, limiting factors, and priority directions for correction of technique, equipment selection, boat-seat calibration, and training-process planning is scientifically and practically important.

The aim of the study was to form an individual technical preparedness profile of a highly qualified sprint canoeist using biomechanical and functional indicators and to substantiate directions for individual correction of technique, equipment, boat seating position, and the training process.

Materials and Methods

Study Design

The study was conducted as a case-oriented comprehensive biomechanical analysis of the technical preparedness of a qualified sprint canoeist. The methodological basis of the work was the combination of several levels of assessment:

neuromuscular support of the paddling movement, dynamics of force application to the paddle, the kinematic structure of technique, velocity realization of boat movement, support interactions within the "athlete-boat" system, and functional conditions for technique realization.

The individual technical preparedness profile was considered not as a total score, but as a structured interpretive matrix combining indicators of different nature and allowing the identification of the athlete's strengths, technique-limiting factors, and targeted directions for correction. The central position in the profile was occupied by indicators directly related to stroke effectiveness: dynamic parameters of work with Braca and Erbi paddles, kinematic characteristics of the stroke cycle, velocity of Nelo, Vajda, and Plastex boats over the control segment, and stability of support interactions after individual calibration of the athlete's seating position in the boat.

The methodological logic of profile formation included the following sequential stages: primary registration of indicators in each diagnostic block; quality control of primary data; selection of suitable stroke cycles, series, or test attempts; calculation of mean values, variability, and stability; intra-individual comparison of results under different testing conditions; identification of indicators with positive or limiting significance for technique; formation of the final interpretive matrix; and substantiation of coaching decisions regarding paddle selection, boat selection, seating position, technical emphases, and training effects.

Study Participants

The main participant was a highly qualified athlete, Master of Sports of Ukraine of International Class, and a member of the national sprint canoeing team of Ukraine: male, 23 years old, height 186 cm, body mass 88 kg. At the time of assessment, the athlete was at the stage of maximal realization of individual capabilities and had experience in international competitions.

Two qualified athletes of the same specialization and comparable level of mastery were additionally included for reference interpretation of selected strength, speed-strength, and functional indicators. Their data were used only as a basis for individual interpretation of the main athlete's results and were not used for between-group statistical comparison.

Research Organization

The study was organized as a sequential comprehensive assessment of the athlete under laboratory and specific on-water conditions. First, neuromuscular support of the paddling movement was assessed during specialized tasks on paddling ergometers. Then, dynamic stroke parameters were analyzed during work with two paddles: Braca and Erbi. After that, kinematic analysis of technique and assessment of boat velocity characteristics were performed while paddling in Nelo, Vajda, and Plastex boats.

A separate stage was devoted to the analysis of support interactions in the boat before and after individual calibration of the athlete's seating position. Calibration included correction of the support zones and the production of individual pads under the forefoot, a knee pad, and a fixing footrest. After that, changes in the area and direction

of center-of-pressure displacement and the stability of the main support points were assessed.

The final stage included additional assessment of strength and speed-strength capacity, functional state of the respiratory system, body composition, hemodynamic indicators, and heart rate variability. These blocks were used as auxiliary blocks to explain the functional conditions for technique realization, but they did not replace the main biomechanical analysis of the paddle, boat, stroke cycle, and support interactions.

Research Methods

The biomechanical block of the study included electromyographic, strain-gauge, and kinematic analysis of the paddling movement. Primary data were processed according to the type of registration. For each block, a separate data matrix was formed, in which the rows represented test tasks, series, or individual stroke cycles, and the columns represented registered and derived indicators. Further summarization was performed in the specialized software of the corresponding hardware-software systems with additional spreadsheet processing in Microsoft Excel.

Bioelectrical activity of the leading muscle groups was registered by surface electromyography using the “M-TEST” electroneuromyographic system (DX-System, Ukraine). The pectoral muscles, biceps and triceps brachii, deltoid muscles, rectus abdominis, rectus femoris, and teres major muscles of the back were assessed with bilateral electrode placement and real-time visualization of the athlete’s muscle activity. Testing was performed during three specialized tasks: 1-min aerobic work on a paddling ergometer, 30-45 s acceleration on a paddling ergometer, and work in a statodynamic mode on the specialized “Gorka” kayak paddling simulator. For each muscle group, the amplitude of bioelectrical activity, mV, and the percentage contribution to total work were determined. Leading and insufficiently involved muscle groups were determined by the percentage contribution within each test task, and the neuromuscular profile was summarized according to the rank structure of muscle activity across the three tests.

Dynamic stroke parameters were determined during series of 20 consecutive strokes using two paddle models: Braca and Erbi, equipped with strain-gauge sensors for blade load. Registration and primary analysis of the strain-gauge signal were performed in the specialized software of the corresponding hardware-software system. For each stroke, paddle-blade load, work per stroke, the effective part of the stroke, and the percentage of the effective part of the stroke relative to total work were determined. The effective part of the stroke was calculated as the part of the work performed in the segment of the stroke cycle where blade load exceeded 70% of the maximum value in that stroke. The percentage of the effective part of the stroke characterized the athlete’s ability to maintain productive effort in the propulsive part of the stroke cycle. Braca and Erbi paddles were compared by mean values, variability, and stability of dynamic indicators, which allowed assessment of the efficiency of force transfer from the athlete to the boat (Gomes et al., 2015; Kong et al., 2020; Michael et al., 2012).

Kinematic analysis of technique was performed using video recordings followed by frame-by-frame goniometric analysis of stroke-cycle phases with the Contemphas mobile

biomechanical system and Contemphas movement-analysis software. The analysis was conducted during paddling in Nelo, Vajda, and Plastex boats in combination with Braca and Erbi paddles. Six to eight technically complete stroke cycles in each series were included in the processing when the phases of blade entry into the water, the propulsive part of the stroke, and stroke completion with transition to paddle recovery were clearly identifiable. For each cycle, paddle attack angle, trunk inclination, knee-joint angle of the swing leg, and knee-joint angle of the support leg were determined. Analysis of these indicators in three phases of the stroke cycle made it possible to evaluate not only the magnitude of angular parameters but also the reproducibility of the movement structure under different stroke conditions (Tilden et al., 2024; Zahálka et al., 2011).

For strain-gauge and kinematic indicators, the mean value, standard deviation, coefficient of variation, and coefficient of stability were calculated. The coefficient of variation was defined as the ratio of the standard deviation to the mean value, expressed as a percentage. The coefficient of stability was calculated as the difference between 100% and the coefficient of variation and was used to assess the repeatability of stroke cycles for the corresponding parameter. Higher coefficient-of-stability values were interpreted as better reproducibility of the corresponding element of the movement structure.

Boat velocity characteristics were determined while the athlete covered a 150 m control segment with a task emphasizing speed and power of distance completion (Contemphas mobile biomechanical system with video-analytical registration of spatiotemporal movement characteristics; additional spreadsheet data processing in Microsoft Excel). Nelo, Vajda, and Plastex boats were compared by maximum velocity in the propulsive part of the stroke cycle, minimum velocity during paddle recovery, and mean velocity over the control segment. This block was used to determine the individual suitability of the boat for the specific athlete, considering velocity realization of the paddling movement.

Support interactions between the athlete’s body and the boat were assessed in three support zones: swing-leg foot, support-leg knee, and support-leg foot on the footrest (strain-gauge system for pressure-distribution and center-of-pressure displacement analysis; Tekscan I-Scan pressure mapping system, Tekscan, USA). The area of center-of-pressure displacement, anteroposterior and mediolateral center-of-pressure oscillations, displacement-vector direction, and pressure force in each support zone were determined. The assessment was performed before and after individual calibration of the athlete’s seating position in the boat. This block was used to evaluate the stability of the “athlete-boat” system, asymmetry of support interactions, and effectiveness of force transfer under the specific posture of a canoeist (Štryncl et al., 2021; Álvarez-Yates et al., 2024).

Strength and speed-strength capacity were assessed using tests that characterize the functional capabilities of the lower limbs and shoulder girdle: “barbell squats for 30 s,” “20 vertical jumps,” “bench pull to the chest,” and “standing pull to the chest.” For jump tests, the OptoJump optoelectronic system (OptoJump, Microgate, Italy; OptoJump Next software) was used; it enables determination of jump height, duration of support and flight phases, rhythm,

tempo, and power in jump tests. For barbell exercises, a linear displacement sensor / movement-power analyzer was used. The number of repetitions, mean, maximum, and peak power, relative power, peak force, movement-speed characteristics, and fatigue resistance were recorded.

The functional state of the respiratory system was assessed by spirometry with registration of a series of forced inspirations using hardware-software tools for assessing external respiratory function and respiratory-muscle strength (POWERbreathe K5 mobile ergospirometry system with Breathe-Link software). Mean and maximum inspiratory power, mean and maximum inspiratory velocity, and mean and maximum inspiratory volume were analyzed. These indicators were used to determine the functional reserve of the respiratory system and the feasibility of including individualized breathing exercises in the athlete's preparation.

Body composition was determined by bioimpedance analysis (Tanita MC-780MA body composition analyzer, Tanita Corporation, Japan; Tanita / GMON software). Body mass index, fat and fat-free mass, active cell mass, body-water compartments, basal metabolic rate, phase angle, and skeletal muscle mass were assessed. Hemodynamic indicators were considered an auxiliary functional block of the individual profile and were used to characterize the conditions of technique realization, not as an independent criterion of technical preparedness.

Heart rate variability (CardioPlus diagnostic system, Metekol, Ukraine) was analyzed using a short-term 5-min electrocardiographic recording (lead I, sensitivity 10 mm/mV) at rest in a sitting position, according to standard requirements for short-term registration (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Before calculating the indicators, the quality of the primary RR series was controlled by checking the correctness of registration and the presence of extrasystolic intervals. Records with pronounced rhythm disturbances or incorrect registration were not included in further analysis. Heart rate, SDNN, coefficient of variation of heart rhythm, stress index (SI), centralization index (CI), activity index of regulatory systems (PARS), power of HF, LF, and VLF waves, and total spectral power (TP) were calculated according to the method of mathematical analysis of heart rhythm by R. M. Baevisky (Baevisky & Chernikova, 2017), which includes construction of a cardiointervalogram, histogram of RR-interval distribution, and scattergram (Poincare plot) for qualitative control of recording homogeneity. Model ranges of HRV indicators were formed based on the database of assessments of qualified sprint canoeists at the Research Institute of the National University of Ukraine on Physical Education and Sport and were used as an indicative range for qualitative interpretation. Cardiorhythmographic indicators were used as an auxiliary functional block of the individual profile and were interpreted considering the case-oriented design, the stage of the training process, and the need to control training load and recovery (Plews et al., 2013).

Algorithm for Developing an Individual Profile of Technical Preparedness

The individual profile of technical preparedness was developed as a structured interpretative matrix integrating

biomechanical and functional indicators of different types. The profile was not treated as a composite integral score because the indicators under investigation had different units of measurement, differed in biomechanical significance, and varied in the degree of their direct association with stroke effectiveness.

No weighting coefficients were applied. In the practical interpretation, priority was given to indicators that directly characterized force transmission to the paddle, stability of the stroke cycle, boat speed performance, and support interactions within the "athlete – boat" system.

At the first stage, data preparation, recording, and primary processing were performed. Testing conditions, the athlete's functional state before assessment, the sequence of tests, measurement-equipment settings, and equipment parameters were standardized. Following primary data recording, the completeness and correctness of the signals were verified, technical noise and distortions were identified, invalid recording fragments were excluded, and technically complete movement cycles were selected. Mean values, variability and stability indices, work per stroke, the effective portion of the stroke, and speed and support characteristics were then calculated.

The obtained indicators were grouped according to the main profile components: neuromuscular support of the stroke, dynamics of force application to the paddle, kinematic structure of the stroke cycle, boat speed performance, support interactions in the boat, and the athlete's functional state. Key informative indicators were identified for each component: the amplitude and relative contribution of muscle groups, work per stroke, the effective portion of the stroke, the proportion of effective work, paddle attack angle, trunk inclination, angular characteristics of the lower limbs, mean and maximum boat speed, the area and direction of center-of-pressure displacement, as well as strength, respiratory, hemodynamic, and cardiorhythmographic indicators.

At the second stage, within-athlete comparisons were performed across test tasks, paddle and boat models, and before and after seating calibration. The consistency of findings across the different diagnostic domains was then examined. An individual indicator was considered practically meaningful when its changes were reproducible across repeated trials, supported by findings obtained using other methods, or associated with changes in work per stroke, technique stability, or boat speed.

At the third stage, the results were operationally classified into four interpretative levels: "strength," "acceptable level," "reserve for correction," and "limiting factor." Classification was not performed by mathematically combining the indicators into a single score but by comparing them with model values, reference data, within-athlete results obtained under different testing conditions, and qualitative biomechanical interpretation.

Strengths included indicators that corresponded to model or reference values, demonstrated high reproducibility, and were associated with greater stroke effectiveness or better boat speed performance. Indicators were classified as acceptable when they met the functional requirements of stroke execution, showed no pronounced unfavorable deviations, and did not limit technical performance.

Reserves for correction included indicators characterized by lower stability, less effective force transmission, reduced

boat speed performance, a lower relative contribution of individual muscle groups, or moderate asymmetry of support interactions, whose influence on performance required further confirmation. Limiting factors included recurrent unfavorable characteristics supported by findings from several interrelated diagnostic domains or directly associated with a reduction in the effective portion of the stroke, impaired stability of the stroke cycle, or lower boat speed.

At the same stage, the results were integrated into a structured individual profile in which the current status, practical interpretation, and correction priority were determined for each component.

At the fourth stage, the individual profile was used to substantiate coaching decisions concerning paddle and boat selection, maintenance of the calibrated seating configuration, correction of trunk position during the final phase of the stroke, improvement of force transmission through the “leg-trunk-arm-paddle” chain, development of speed-strength endurance of the shoulder girdle, optimization of inspiratory mechanics, and monitoring of the balance between training load and recovery.

Following the implementation of corrective interventions, repeated standardized testing and updating of the individual profile were planned. Positive changes in the target indicators, together with improvements in work per stroke, technique stability, or boat speed, were regarded as confirmation of the validity of the initial interpretation and the coaching decision adopted.

The classification of profile components is operational rather than normative and is intended for within-athlete analysis. Classification of an indicator as a limiting factor cannot be based on a single isolated value or solely on its deviation from a model range. The determining criteria are the reproducibility of the result, its consistency with findings from other diagnostic domains, and its association with indicators of stroke effectiveness or boat speed (Fig. 1).

Justification of Model Values

The model values used to interpret selected indicators of the individual profile were formed based on a long-term database of comprehensive assessments of athletes of the Ukrainian national kayaking and canoeing team conducted at the Research Institute of the National University of Ukraine on Physical Education and Sport (2010-2025; $n = 750$ person-assessments for each method of assessing the functional state of athletes).

Model ranges were formed by summarizing repeated assessments of national-team athletes, taking into account specialization, level of sports qualification, stage of preparation, and correspondence of indicators to the competitive demands of sprint canoeing. Model values were not considered universal norms for the entire population of athletes; they were used as internal reference ranges for interpreting the individual indicators of a highly qualified canoeist.

When forming the individual profile, model values were used only as an auxiliary criterion for assessing the correspondence of selected functional and biomechanical indicators to the level of national-team athletes. The main principle of interpretation remained intra-individual comparison of the athlete's results under different testing conditions: between Braca and Erbi paddles, between Nelo, Vajda, and Plastex boats, and before and after individual calibration of the seating position in the boat. This approach made it possible to avoid incorrect generalization and to use model indicators as a tool for individualizing technical preparation.

Statistical Analysis

Statistical processing was performed using descriptive statistics in Microsoft Excel. For quantitative indicators, the arithmetic mean, standard deviation, coefficient of variation, coefficient of stability, and absolute and relative differences between testing conditions were calculated.

The coefficient of variation was defined as the ratio of the standard deviation to the mean value, expressed as a percentage. Values below 30% were considered a sign of relative homogeneity of the measurement series, and values below 10% were interpreted as low dispersion. The coefficient of stability was defined as the difference between 100% and the coefficient of variation. Values above 90% were interpreted as high stability, 85-90% as above average, 75-85% as average, 70-75% as below average, and below 70% as low stability.

For electromyographic indicators, muscle groups were ranked by their percentage contribution to total work in each task, followed by calculation of the sum of ranks across the three tests. The effectiveness of paddles, boats, and changes in seating position was compared using absolute and relative differences in mean values, coefficients of variation and stability, and qualitative biomechanical interpretation of the observed changes.

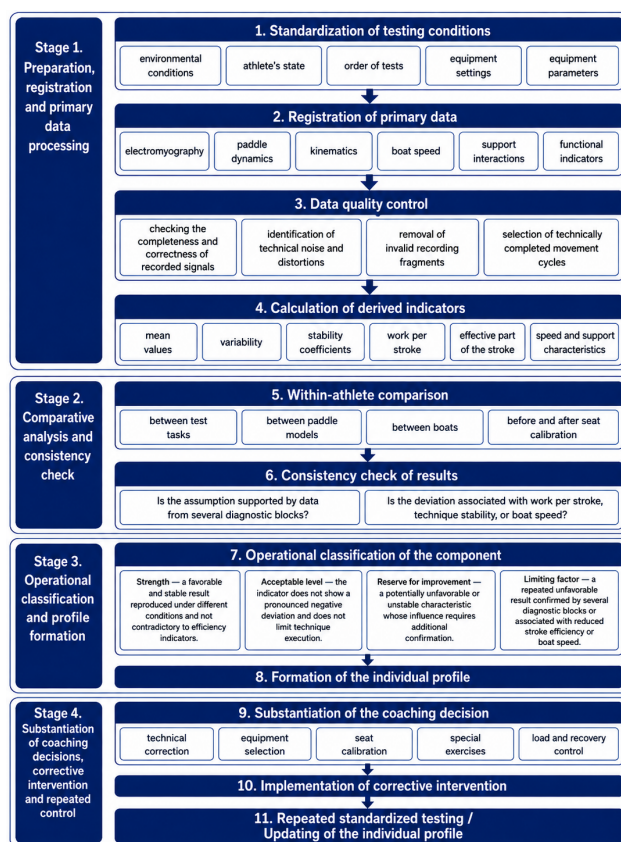


Fig. 1. Algorithm for developing an individual profile of a canoeist's technical preparedness and substantiating coaching decisions

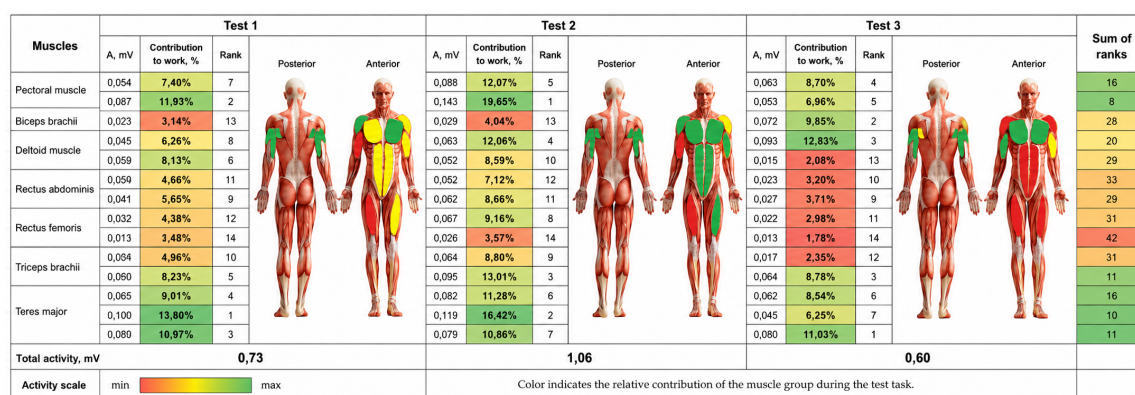


Fig. 2. Bioelectrical activity of leading muscle groups of the canoeist during three specialized test tasks (n = 1, Master of Sports of Ukraine of International Class)

Considering the case-oriented design of the study, the main analysis was aimed not at testing group statistical hypotheses, but at intra-individual comparison of the athlete's indicators under different testing conditions. Individual stroke cycles, movement series, and test attempts were used to assess repeatability, stability, and variability of indicators, but were not considered independent observations for between-group statistical analysis. Therefore, methods of statistical hypothesis testing were not applied.

Limits of Generalization

The results of the study characterize the individual profile of a specific highly qualified canoeist and cannot be directly extrapolated to a broader population of athletes without further experimental verification, because the purpose of the study was not to establish universal norms but to demonstrate an algorithm for integrating heterogeneous indicators for individualizing technical preparation.

Results

The results of the comprehensive assessment sequentially characterized individual components of the technical preparedness of the qualified sprint canoeist: neuromuscular support of the paddling movement, effectiveness of force

application to the paddle, kinematic stability of the stroke cycle, boat velocity characteristics, support interactions within the "athlete-boat" system, strength capacity, and functional state. Each block was interpreted in terms of its contribution to the formation of the athlete's individual technical preparedness profile and the identification of technique-limiting factors.

Analysis of bioelectrical activity of the leading muscle groups showed that the structure of muscle involvement changed depending on the nature of the test task. Total activation of the neuromuscular system was 0.73 mV during aerobic work on the paddling ergometer, increased to 1.06 mV during acceleration, and decreased to 0.60 mV in the statodynamic mode on the specialized "Gorka" kayak paddling simulator (Table 1).

Table 1 shows that as work intensity increased, the structure of muscle activation changed: in the acceleration test, total activity was highest, whereas during statodynamic work a more localized redistribution of activity occurred toward the shoulder-girdle muscles, pectoral muscles, and back muscles. For the individual profile, this indicates the need to improve coordinated force transfer from the support links through the trunk to the paddle.

In the first test task, the greatest contribution to total work was made by the teres major muscles of the back, the left pectoral muscle, and the triceps brachii. Minimal

Table 1. Neuromuscular profile of the paddling movement according to electromyography (n = 1, Master of Sports of Ukraine of International Class)

Test task	Total activity, mV	Leading muscle groups	Muscles with minimal contribution	Relevance to profile formation
Aerobic work, 1 min	0.73	Teres major muscles of the back; left pectoral muscle; triceps brachii	Right biceps brachii; right rectus femoris	Basic structure of muscular support of the stroke movement under moderate intensity was identified
Acceleration, 30–45 s	1.06	Pectoral muscles; rectus abdominis; left biceps brachii; left rectus femoris	Right biceps brachii; right rectus femoris	Maximum neuromuscular mobilization and muscle groups more actively involved during intensive work were revealed
Statodynamic work	0.60	Pectoral muscles; right biceps brachii; triceps brachii; right teres major muscle of the back	Selected lower-limb muscles	Redistribution of muscle activity in the propulsive part of the stroke cycle and reserves for coordination of the trunk, shoulder girdle, and support links were identified

activity was demonstrated by the right biceps brachii and the right rectus femoris. In the second test, which modeled acceleration, the contribution of the pectoral muscles, rectus abdominis, left rectus femoris, and left biceps brachii increased (Fig. 2).

In the third test, which modeled the statodynamic mode of specialized work, the greatest activity was concentrated in the pectoral muscles, right biceps brachii, triceps brachii, and right teres major muscle of the back. This indicates the leading participation of these muscle groups in force application during the propulsive phase of the stroke. Leading muscle groups were identified according to the largest percentage contribution to total bioelectrical activity during each test task. Muscles with minimal contribution were considered potential reserves for improving the coordination of the support links, trunk, and shoulder girdle in the paddling movement.

Thus, the electromyographic block showed that the neuromuscular component of the athlete's individual profile is characterized by the leading participation of the back muscles, pectoral muscles, and shoulder-girdle muscles in supporting the paddling movement. The lower contribution of selected lower-limb muscles indicates a reserve for improving sequential force transfer in the biomechanical chain "leg - trunk - arm - paddle."

Comparative analysis of dynamic stroke parameters showed differences in the nature of effort realization when using Braca and Erbi paddles. With the Braca paddle, the athlete demonstrated a higher mean blade load of 20.5 kg with a high coefficient of stability of 93.5%. At the same time, mean work per stroke was 49.3 J, the effective part of the stroke was 25.8 J, and the share of effective work in total work was 53.0% (Fig. 3).

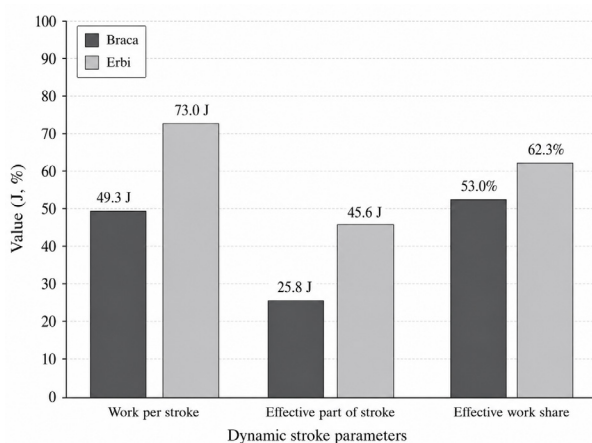


Fig. 3. Comparison of Braca and Erbi paddle effectiveness according to key dynamic stroke indicators (n = 1, Master of Sports of Ukraine of International Class)

When using the Erbi paddle, mean blade load was lower at 18.5 kg; however, work per stroke increased to 73.0 J, the effective part of the stroke increased to 45.6 J, and the share of effective work increased to 62.3%. For three of the four main parameters, the coefficient of stability was higher when using the Erbi paddle.

Thus, the dynamic block showed that the Braca paddle provided a higher mean blade load, whereas the Erbi paddle facilitated more effective effort realization according to work

per stroke, the effective part of the stroke, and the share of effective work. For the individual profile, this means that the limiting factor was not the athlete's ability to generate force, but the efficiency of its transfer throughout the stroke cycle. Therefore, stroke-dynamics indicators provided the basis for recommending gradual adaptation of the athlete to the Erbi paddle.

Goniometric analysis of stroke technique in boats from different manufacturers showed an overall high level of stability in key angular parameters. The coefficient of stability of the paddle attack angle was 96.6-98.3%, indicating high reproducibility of paddle position during entry and force application. Stability of trunk inclination in the first phase of the stroke was 94.5-98.2%, and stability of the angular indicators of the swing-leg knee joint in the first phase was 96.8-98.5%.

Mean values of the paddle attack angle ranged from 59.3° to 63.0°. Trunk inclination decreased from the first to the third phase of the stroke, from 41.5-57.1° to 30.2-47.5°. At the same time, the angle in the swing-leg knee joint increased from 84.0-91.0° in the first phase to 135.0-150.0° in the third phase, whereas the angle in the support-leg knee joint decreased from 118.0-134.0° to 77.0-88.0°. The lowest stability was recorded for trunk inclination in the third phase of the stroke - 85.2-93.8% - which makes it possible to identify the final phase of the stroke cycle as a zone of technical reserve.

Over the 150 m control segment, the highest velocity indicators were recorded when paddling in the Plastex boat. Maximum boat velocity in the support phase of the stroke was 5.15 m/s in the Nelo boat, 5.24 m/s in the Vajda boat, and 5.30 m/s in the Plastex boat. Minimum velocity in the non-support phase was also highest in the Plastex boat at 2.68 m/s, whereas it was 2.65 m/s in the Vajda boat and 2.24 m/s in the Nelo boat. Mean velocity over the control segment was 3.80 m/s in Nelo, 3.95 m/s in Vajda, and 3.99 m/s in Plastex (Table 2).

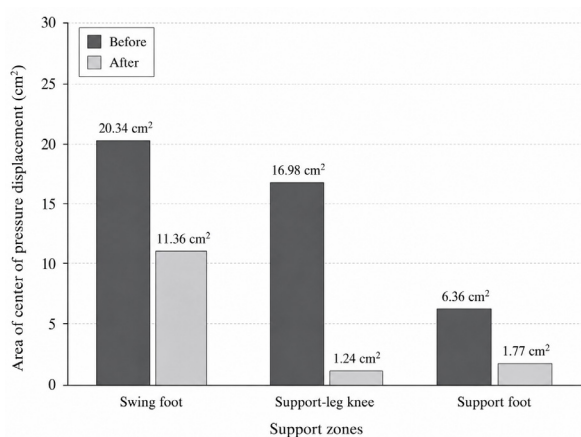
The kinematic component of the profile demonstrated a high level of stability of the paddle attack angle and lower-limb positions in most phases of the stroke cycle. The least stable indicator was trunk inclination in the third phase of the stroke, which allows the final phase to be identified as a zone of technical reserve. The velocity block showed that the Vajda and Plastex boats better matched the athlete's individual technical characteristics, whereas in the Nelo boat a greater decrease in velocity was observed during the non-support phase. For profile formation, this had practical significance because it linked technical efficiency not only with the athlete's movements but also with the individual suitability of sports equipment.

Three-zone analysis of support interactions showed that before individual seat calibration the athlete demonstrated asynchronous effort application within the "athlete-boat" system. This was manifested by increased pressure on the support-leg knee, displacement of the pressure vector of the swing foot toward the outer edge of the foot, and insufficiently effective pressure of the support foot on the footrest (Fig. 4).

After individual seat calibration, substantial improvement in the stability of support interactions was registered. The area of center-of-pressure displacement in the swing-foot zone decreased from 20.34 to 11.36 cm²; in the support-leg knee zone, from 16.98 to 1.24 cm²; and

Table 2. Key biomechanical indicators of equipment and the stroke cycle (n = 1, Master of Sports of Ukraine of International Class)

Assessment block	Indicator	Main result	Relevance to profile formation
Stroke dynamics with Braca paddle	Blade load	20.5 kg; Cst = 93.5%	High force load with lower work effectiveness
Stroke dynamics with Erbi paddle	Work per stroke; effective part of the stroke	73.0 J; 45.6 J	Better realization of effort throughout the stroke
Paddle attack angle	Coefficient of stability	96.6–98.3%	High reproducibility of a basic technical element
Trunk inclination in the third phase	Coefficient of stability	85.2–93.8%	Zone of technical reserve
Nelo boat	Mean velocity	3.80 m/s	Lower individual suitability according to velocity characteristics
Vajda boat	Mean velocity	3.95 m/s	Suitable equipment option for the athlete
Plastex boat	Mean / maximum velocity	3.99 m/s; 5.30 m/s	Best velocity characteristics for the athlete

**Fig. 4.** Changes in center-of-pressure displacement area in support zones before and after individual seat calibration (n = 1, Master of Sports of Ukraine of International Class)

in the support-foot zone, from 6.36 to 1.77 cm². The most pronounced reduction in the area of center-of-pressure displacement was observed in the support-leg knee zone, where the indicator decreased by 13.7 times (Fig. 5).

Anteroposterior center-of-pressure oscillations also decreased in all support zones: in the swing-foot zone from 15.20 to 10.63 cm, in the support-leg knee zone from 11.85 to 3.20 cm, and in the support-foot zone from 3.07 to 1.40 cm. Mediolateral oscillations decreased from 4.37 to 2.11 cm, from 2.90 to 0.95 cm, and from 5.16 to 2.81 cm, respectively.

The obtained results showed that individual seat calibration substantially increased the stability of support interactions within the “athlete-boat” system.

For the formation of the individual profile, this means that the seating position in the boat is not an auxiliary organizational factor but an independent biomechanical reserve for improving technical efficiency. Therefore, center-of-pressure displacement indicators were included in the profile as criteria of support-interaction stability and force-transfer effectiveness.

Results of strength and speed-strength tests showed a sufficient level of preparedness of the lower limbs and

shoulder girdle for realization of an effective paddling movement: in the “barbell squats for 30 s” test, the athlete completed 34 repetitions with a mean power of 356.9 W, peak power of 654.4 W, and relative power of 4.1 W/kg; in the “20 vertical jumps” test, mean power was 1266.1 W, peak force was 1886.7 N, and relative power was 14.4 W/kg; in the “bench pull to the chest” and “standing pull to the chest” tests, 56 and 40 repetitions were recorded, respectively, with mean power values of 369.6 and 472.8 W and peak power values of 870.2 and 916.8 W. Spirometric testing showed high values of respiratory potential indicators: mean and maximum inspiratory power were 178.06 and 203.13 cm H₂O, inspiratory velocity was 9.47 and 10.63 L/s, and inspiratory volume was 4.81 and 5.52 L, respectively. This indicates a sufficient functional reserve of the respiratory system but points to the feasibility of further optimization of inspiratory mechanics.

According to bioimpedance analysis, the athlete’s body mass index was 22.45 kg/m², fat mass was 26%, active cell mass was 51%, and phase angle was 10.68°. Hemodynamic and cardiorythmographic indicators supplemented the characterization of the athlete’s current functional state: heart rate was 66 beats/min, cardiac output was 5.32 L/min, reserve coefficient was 81.9%, coefficient of variation of heart rhythm was 21.2%, stress index was 9 conventional units, and total spectral power was 6974 ms². The HRV spectral structure was characterized by predominance of the HF component (50.2%) over LF (44.4%) and VLF (5.3%); the centralization index was 1.0, and the activity index of regulatory systems was 6 conventional units. This combination of indicators points to tension of adaptive mechanisms and possible functional overstrain, which should be considered when planning loads, recovery, and further dynamic monitoring.

The functional block showed that strength, speed-strength, and respiratory potential generally created sufficient conditions for realization of paddling technique. At the same time, the remaining reserves were development of speed-strength endurance of the shoulder girdle, optimization of inspiratory mechanics, and control of the balance between load and recovery using cardiorythmographic indicators. These data were included in the individual

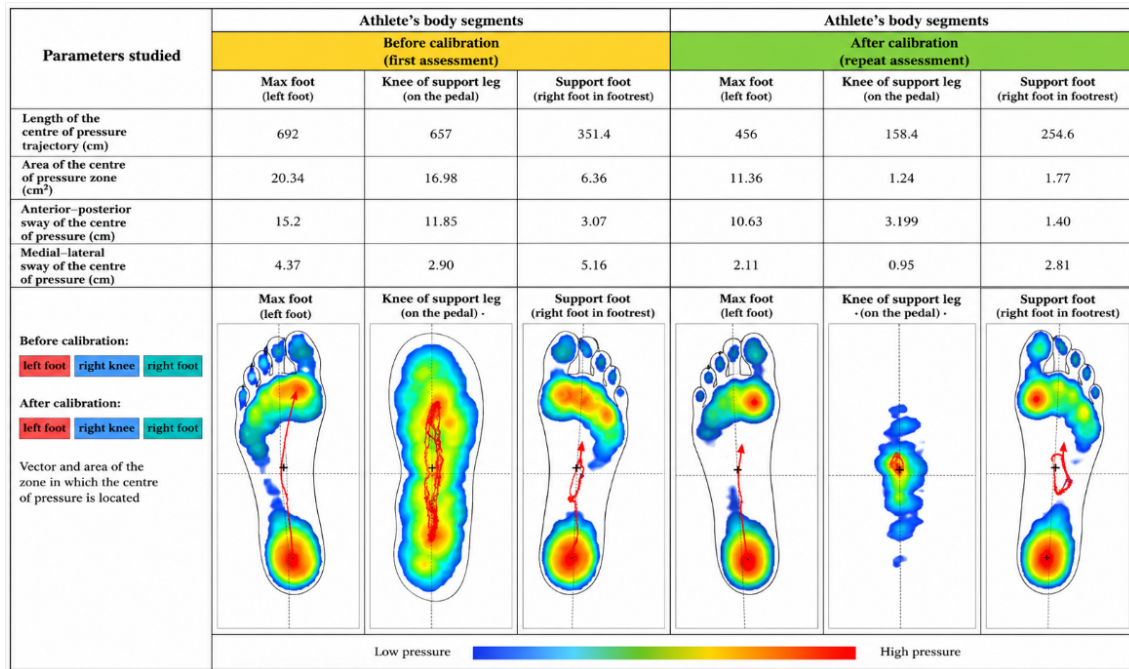


Fig. 5. Support-interaction indicators between the athlete's body and the boat before and after individual seat calibration (n = 1, Master of Sports of Ukraine of International Class)

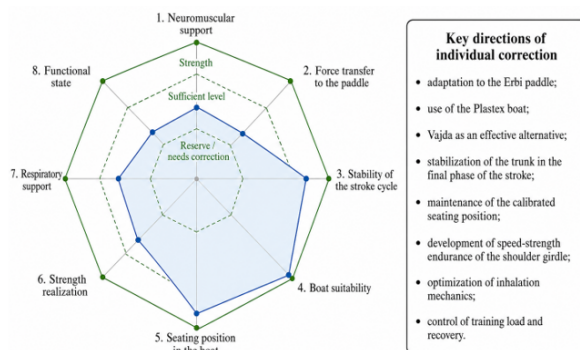


Fig. 6. Individual technical preparedness profile of the highly qualified canoeist based on the results of the comprehensive assessment

profile as a functional context that clarifies the conditions for realizing technical mastery but does not replace the main biomechanical analysis of the stroke, equipment, and support interactions.

Generalization of the results of all diagnostic blocks made it possible to form an individual technical preparedness profile of the canoeist, combining neuromuscular, dynamic, kinematic, velocity-related, support-related, strength, and functional characteristics. The profile is not reduced to a single indicator or an integral score; rather, it reflects the relationship between strengths, limiting factors, and practical reserves for improving technique (Fig. 6).

The formed individual profile showed that the athlete's strengths were high stability of basic elements of the stroke cycle, sufficient strength capacity, improved stability of support interactions after individual seat calibration, and high velocity realization of technique in the Plastex and

Vajda boats. The main reserves were improving force-transfer efficiency in the "leg - trunk - arm - paddle" chain, stabilizing trunk position in the final stroke phase, further adaptation to the Erbi paddle, development of speed-strength endurance of the shoulder girdle, optimization of inspiratory mechanics, and control of recovery dynamics during the training process (Table 3).

Discussion

An individual profile of a canoeist's technical preparedness should be developed not by summing separate test indicators, but by interpreting their functional interrelationships. Stroke effectiveness depends on the coordination of neuromuscular activation, force application to the paddle, kinematic stability, support interactions, and the translation of these factors into boat speed. Accordingly, the diagnostic value of an indicator increases when its deviation is confirmed by several methods and is associated with changes in work per stroke, technical stability, or boat speed. This principle corresponds to the current understanding of technical preparedness as a multicomponent system and makes it possible to distinguish the strengths, reserves for correction, and potential limiting factors of an individual athlete (Altukhov & Shynkaruk, 2026b; Shynkaruk & Altukhov, 2026).

The electromyographic data confirmed the leading role of the back, pectoral, and shoulder-girdle muscles, which is consistent with the findings of Trevithick et al. (2007). From a biomechanical perspective, this can be explained by the fact that the propulsive effort during the stroke is generated not through the isolated action of the upper limb, but through the sequential transmission of mechanical impulse from the support segments through the pelvis and trunk to the shoulder girdle, arm, and paddle. The contribution of the lower limbs to paddle force and boat

Table 3. Individual Profile of Technical Preparedness of the Examined Canoeist

Component of technical preparedness	Main informative indicators	Interpretation	Practical recommendations
Neuromuscular organization of the paddling movement	Ranking structure of electromyographic activity in three sport-specific tests; predominant activity of the back, pectoral, and shoulder-girdle muscles; lower relative contribution of individual lower-limb muscles	The predominant involvement of the trunk and shoulder-girdle muscles represents a well-developed component. The lower contribution of individual lower-limb muscles is considered a preliminary reserve for improving coordination rather than a confirmed local strength deficit.	Improve the coordination of force transmission through the “support segments–pelvis–trunk–shoulder girdle–paddle” chain. Confirm this interpretation using synchronized on-water electromyographic, kinematic, and force measurements.
Dynamic structure of the stroke	Braca: blade load, 20.5 kg; work, 49.3 J; effective portion of the stroke, 25.8 J; proportion of effective work, 53.0%. Erbi: 18.5 kg, 73.0 J, 45.6 J, and 62.3%, respectively	The ability to generate force was classified as an adequate level. The greater work and effective portion of the stroke obtained with the Erbi paddle represent a promising reserve for improving effectiveness that requires repeated verification.	Conduct a standardized period of adaptation to the Erbi paddle. Reassess work per stroke, stroke rate, kinematics, stability across stroke series, and boat speed. Peak or mean blade load should not be used as the sole criterion for paddle selection.
Kinematic stability	Stability of the paddle attack angle, 96.6–98.3%; stability of trunk inclination during the third phase, 85.2–93.8%	Reproducibility of the paddle attack angle is a strength. Variability of trunk position during the final phase represents a reserve for improvement, whose significance should be verified in relation to stroke dynamics and speed loss.	Use synchronized video and strain-gauge feedback. Correct only the component of trunk variability that is accompanied by reduced effective work or increased speed loss.
Individual boat suitability	Mean speed over 150 m: Nelo, 3.80 m·s ⁻¹ ; Vajda, 3.95 m·s ⁻¹ ; Plastex, 3.99 m·s ⁻¹ . Maximum speed: 5.15, 5.24, and 5.30 m·s ⁻¹ , respectively	Under the testing conditions, Plastex and Vajda were favorable individual options. Nelo represents a potential reserve for optimizing equipment suitability, but not a confirmed limiting factor.	Repeat the comparison with randomized trial order, identical stroke-rate instructions, and control of environmental conditions. Make the final selection after a series of repeated trials.
Support interactions and seating configuration	Reduction in the center-of-pressure displacement area: swing-leg foot, from 20.34 to 11.36 cm ² ; support-leg knee, from 16.98 to 1.24 cm ² ; support foot, from 6.36 to 1.77 cm ²	The response to seating calibration is a strength of the proposed individualized configuration. However, a direct increase in propulsive effectiveness was not separately demonstrated.	Maintain the individualized seating configuration provided that no discomfort occurs. In subsequent assessments, monitor the center of pressure, paddle force, kinematics, and boat speed synchronously.
Strength and speed-strength capacity	Power in squat and jump tests; indicators of pulling exercises performed in lying and standing positions; ability to reproduce sport-specific force repeatedly	General strength capacity was classified as an adequate level. The ability to maintain effective shoulder-girdle performance over time represents a reserve for improvement.	Develop sport-specific speed-strength endurance while monitoring the preservation of technical structure and the effective portion of the stroke under fatigue.
Respiratory support	Inspiratory power, flow rate, and volume; pattern of respiratory-maneuver execution	Respiratory capacity was classified as an adequate level and was not identified as a leading limiting factor. The forceful inspiratory pattern represents a complementary reserve for improving movement economy.	Improve the coordination of breathing with the structure of the stroke cycle. Respiratory indicators should not be interpreted separately from sport-specific performance and technical stability.
Functional state and recovery	Heart rate, hemodynamic indicators, time- and frequency-domain HRV characteristics, stress index, and index of regulatory systems activity	Single measurements characterize the current functional context but do not allow functional strain to be diagnosed or technical skill to be assessed directly.	Perform serial measurements under standardized conditions and compare them with training load, sleep, subjective well-being, sport-specific performance, and technical stability.

Table 3. Continued

Component of technical preparedness	Main informative indicators	Interpretation	Practical recommendations
Integrated “athlete–paddle–boat” interaction	Consistency among dynamic, kinematic, speed, neuromuscular, and support characteristics	The principal reserve is associated not with a single isolated indicator but with optimization of coordination and force transmission within the integrated biomechanical system.	Combine correction of trunk technique, verification of the Erbi paddle, use of the Plastex or Vajda boats, maintenance of the calibrated seating configuration, and development of sport-specific endurance. Confirm the effectiveness of the recommendations through repeated comprehensive testing.

Note. The profile categories are operational and intended for within-athlete interpretation. A “strength” denotes a favorable and stable indicator confirmed under different conditions or consistent with performance-related characteristics. An “adequate level” indicates the absence of evidence of a substantial limitation to technical execution. A “reserve for improvement” reflects a potentially unfavorable or unstable characteristic whose influence requires verification. The category “limiting factor” may be applied only when an unfavorable result is reproducible and confirmed by several diagnostic domains or is directly associated with reduced stroke effectiveness or boat speed

speed has been demonstrated in biomechanical models of paddling (Begon et al., 2010; Nilsson & Rosdahl, 2016). At the same time, the lower relative contribution of individual lower-limb muscles should not be interpreted unequivocally as a local strength deficit. It may reflect the athlete’s coordination strategy, the specific characteristics of the test task, or temporal inconsistency in muscle activation. This finding should therefore be considered a reserve for improving intersegmental force transmission, which requires confirmation through synchronized recording of electromyographic, kinematic, and dynamic indicators under on-water conditions.

The comparison of the Braca and Erbi paddles showed that a greater load on the blade does not necessarily result in greater mechanical effectiveness. The advantage of the Erbi paddle in terms of work and the effective portion of the stroke may be attributable to a more favorable temporal distribution of force, longer maintenance of effective force application, and a better match between blade geometry and the athlete’s individual movement pattern. This is consistent with evidence indicating that stroke performance depends not only on peak force but also on its temporal organization within the propulsive phase (Gomes et al., 2015; Michael et al., 2012). Instrumented paddles increase the objectivity of such analysis because they allow the amount and pattern of force application to be assessed directly during the sport-specific movement (Kong et al., 2020; Niu et al., 2019). Nevertheless, the observed differences may have been partly influenced by the athlete’s familiarity with each paddle model, the order of testing, stroke rate, and accumulated fatigue. The Erbi paddle should therefore be considered a promising individualized option whose effectiveness should be verified after a standardized adaptation period.

The high reproducibility of the paddle attack angle and most angular characteristics of the lower limbs indicates that the basic spatiotemporal structure of the movement was well established. The lower stability of trunk inclination during the final phase may be associated with the need to complete force application, maintain boat balance, and initiate the recovery phase simultaneously. Disturbance of the temporal coordination of these actions may alter the direction of the resultant force, increase rotational oscillations within the athlete–boat system, and intensify speed loss between

strokes. The importance of phase-related and angular characteristics for boat speed has been demonstrated in international studies of paddling kinematics (McDonnell et al., 2013; Zahálka et al., 2011). However, variability is not necessarily unfavorable, as a certain degree of movement variability may facilitate adaptation to boat instability and changing external conditions. Therefore, correction should target not trunk variability itself, but only the component that is consistently associated with reduced effective work or lower boat speed.

The better speed characteristics observed in the Plastex and Vajda boats indicate that, under the testing conditions, these models were more closely matched to the athlete’s individual anthropometric and coordinative characteristics. This compatibility may be determined by hull geometry, the positioning of support areas, system stiffness, and the boat’s response to the asymmetrical movements of a canoeist. However, the observed differences do not demonstrate the universal superiority of any particular model, as they may have been influenced by familiarity with the equipment, trial order, fatigue, and environmental conditions. The results therefore support prioritized further testing of the Plastex and Vajda boats, whereas the final selection should be based on repeated standardized trials.

Seat calibration reduced center-of-pressure displacement in all support zones, indicating increased mechanical stability of the athlete’s interaction with the boat. A more stable support base creates the prerequisites for more effective impulse transmission from the lower limbs through the pelvis and trunk to the paddle and reduces non-productive compensatory movements. The relationship between support forces, paddle dynamics, and boat speed has been demonstrated in recent biomechanical studies (Bonito et al., 2022; Klitgaard et al., 2021; Nilsson & Rosdahl, 2016). However, a reduction in the center-of-pressure displacement area does not provide direct evidence of increased propulsive effectiveness, because the relevant indicators were not recorded simultaneously before and after calibration. In addition, excessive stabilization may restrict the functionally necessary mobility of the pelvis and trunk. An optimal seating configuration should therefore increase support stability without reducing the amplitude of effective movements or causing localized discomfort.

The findings on support interactions are consistent with studies of morphofunctional adaptations to asymmetrical loading in canoeing (Štryncl et al., 2021; Álvarez-Yates et al., 2024). The specific canoeing position produces uneven loading of the support and non-support legs, pelvis, and trunk-stabilizing muscles. Such asymmetry may represent either a functional adaptation to the sporting technique or a source of excessive compensatory movements. In the present study, its assessment had direct practical relevance because the findings were used not merely to identify differences between support zones, but to individualize the athlete's seating configuration.

The functional indicators clarified the conditions under which technique was expressed but did not replace biomechanical analysis. The athlete's adequate strength and speed-strength capacity of the lower limbs indicates that the identified technical reserves were not attributable to a pronounced limitation in overall strength. At the same time, the reserve in speed-strength endurance of the shoulder girdle may limit the ability to maintain a stable force-application pattern under fatigue. This supports the view that paddling performance is determined not by the maximal strength of an isolated muscle group, but by the athlete's capacity to repeatedly express strength within a sport-specific coordination pattern (Michael et al., 2012; Nilsson & Rosdahl, 2016).

The respiratory indicators did not suggest that respiratory function was a major limiting factor. However, the forceful pattern of inspiration may increase the energetic cost of accessory respiratory-muscle activity and contribute to greater trunk tension. Optimization of inspiratory mechanics should therefore be regarded as a complementary intervention aimed at preserving movement economy and technical stability during high-intensity work rather than as the primary means of correcting paddling technique.

Cardiorhythmographic indicators characterize the current state of autonomic regulation but cannot be used as an independent criterion of technical preparedness or as evidence of functional strain. Their values depend on previous training load, sleep quality, psycho-emotional state, body position, and the athlete's individual baseline. Therefore, the dynamics of these indicators are more informative than a single measurement and should be interpreted together with the stress index, centralization index, spectral structure, training load, subjective well-being, and sport-specific performance. This approach is consistent with standards for the interpretation of short-term heart rate recordings and recommendations for monitoring athletes' adaptation (Task Force, 1996; Baevsky & Chernikova, 2017; Plews et al., 2013).

The scientific significance of the proposed approach lies in the transition from isolated assessment of separate indicators to their integrated within-athlete interpretation. The profile is neither a composite score nor a universal normative scale; rather, it functions as an algorithm for supporting coaching decisions. Classification of a component as a strength, acceptable level, reserve for correction, or limiting factor is based on the reproducibility of the indicator, its consistency with other diagnostic domains, and its association with stroke effectiveness or boat speed. This reduces the risk of misinterpreting isolated deviations and allows testable hypotheses to be formulated regarding the causes of technical limitations.

The practical value of profiling lies in the direct transition from test results to targeted decisions: adaptation to the Erbi paddle, further comparative testing of the Plastex and Vajda boats, maintenance of the calibrated seating configuration, correction of trunk position during the final phase, improvement of force transmission through the "leg-trunk-arm-paddle" chain, development of speed-strength endurance of the shoulder girdle, optimization of inspiratory mechanics, and monitoring of the balance between training load and recovery. The validity of these decisions should be confirmed through repeated standardized testing, because only targeted changes in the relevant biomechanical indicators, together with improvements in work per stroke and boat speed, can confirm the accuracy of the initial interpretation.

Future Research

Future research should test the proposed algorithm for forming an individual profile in a larger sample of canoeists of different qualification levels, sex, anthropometric characteristics, and dominant paddling side. This would make it possible to verify the reproducibility of the approach, clarify the informativeness of key biomechanical indicators, and determine its possible use for individualizing technical preparation in C1 sprint canoeing.

Limitations

The study was conducted as a case-oriented analysis of one qualified sprint canoeist; therefore, the obtained results characterize the individual profile of a specific athlete and cannot be directly extrapolated to the entire population of canoeists. The two additionally included athletes were used only as a reference context for interpreting selected strength and functional indicators, not for between-group statistical comparison.

A long-term pedagogical experiment was not conducted, which would have allowed assessment of the effect of the proposed technical and training recommendations on sports performance over time. The obtained data reflected the athlete's state during a specific period of preparation.

Despite this, the case-oriented design made it possible to analyze in detail the relationship between biomechanical indicators and the athlete's functional state and to substantiate their practical significance for individualizing technical preparation.

Conclusions

The developed individual profile showed that the principal reserve in the technical preparedness of the examined canoeist was associated not with a deficit in any single physical quality, but with the coordination of force transmission within the "athlete-paddle-boat" system. Work per stroke, the effective portion of the stroke, the stability of the kinematic movement structure, boat speed, and the characteristics of support interactions were the most practically informative indicators.

The neuromuscular support of the stroke was characterized by the predominant involvement of the back, pectoral, and shoulder-girdle muscles. The lower relative contribution of individual lower-limb muscles does not

provide sufficient evidence of a local strength deficit but indicates a potential reserve for improving intersegmental coordination and force transmission through the “leg–trunk–arm–paddle” chain.

Under the testing conditions, the Erbi paddle provided greater work per stroke, a larger effective portion of the stroke, and a higher proportion of effective work despite a lower mean blade load compared with the Braca paddle. This indicates that, for this athlete, stroke effectiveness depended more on the temporal organization and duration of effective force application than on maximum blade load. The Erbi paddle should therefore be considered a promising individualized option whose effectiveness should be confirmed after a standardized adaptation period and repeated testing.

The stability of the paddle attack angle and most angular characteristics of the lower limbs was identified as a strength of the athlete’s technique. The lower stability of trunk inclination during the final phase of the stroke cycle represents a specific reserve for correction. The appropriateness of such intervention should be evaluated according to whether changes in trunk position are accompanied by improved work per stroke, reduced speed loss, and greater movement stability.

Under the testing conditions, the Plastex and Vajda boats provided better speed performance than the Nelo boat. This finding indicates a better individual match between these boats and the examined athlete but does not demonstrate the universal superiority of either model. Final boat selection should be based on repeated trials with standardized trial order, stroke rate, fatigue level, and environmental conditions.

Individual seating calibration reduced center-of-pressure displacement in the support zones, confirming increased mechanical stability of the athlete’s interaction with the boat. However, the findings do not demonstrate a direct increase in propulsive efficiency because paddle force and boat speed were not recorded synchronously before and after calibration. The calibrated seating configuration should therefore be maintained provided that it does not cause discomfort or restrict the functionally necessary mobility of the pelvis and trunk.

The functional assessment provided no basis for attributing the identified technical reserves to pronounced limitations in strength, respiratory, or hemodynamic support. At the same time, the findings supported the development of shoulder-girdle speed-strength endurance, optimization of inspiratory mechanics, and systematic monitoring of the balance between training load and recovery. Cardiorhythmographic indicators should be interpreted longitudinally together with data on training load, recovery, and sport-specific performance rather than used as an independent criterion of functional strain.

The proposed algorithm enabled the identification of individualized priorities for technical correction through the integrated analysis of biomechanical and functional indicators. Its further validation requires repeated testing and assessment in a larger sample of athletes. Given the single-case study design, the developed profile should be regarded as an algorithm for supporting coaching decisions rather than as a universal normative model. The validity of the proposed recommendations should be confirmed through

repeated standardized testing after the implementation of corrective interventions.

Ethical Considerations

The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and accepted requirements for research involving human participants. The participants were informed about the aim, content, and procedures of the assessment. All athletes provided informed consent to participate in the study and to use anonymized results for scientific purposes. Personal data were anonymized, and confidentiality was ensured at all stages of the study.

Data Availability Statement

The study data are part of a comprehensive individual assessment of the athlete and contain personalized information on technical preparedness and functional state. Due to confidentiality, the full primary dataset is not publicly available. The summarized results necessary for interpretation of the study are presented in the text, tables, and figures.

Artificial Intelligence Transparency Statement

The authors state that artificial intelligence was not used for the collection, analysis, or interpretation of primary research data. AI-based auxiliary software was used only for language and stylistic editing of the manuscript. The study design, methodological decisions, interpretation, conclusions, and final responsibility for the manuscript content belong to the authors.

Conflict of Interest

The authors declare no conflict of interest.

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Формування індивідуального профілю технічної підготовленості висококваліфікованого каноїста за біомеханічними і функціональними показниками

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

Реферат. Стаття: 15 с., 3 табл., 6 рис., 22 джерела.

Актуальність. Технічна підготовленість у веслуванні на каное залежить від узгодженої взаємодії спортсмена, весла й човна. Ізолюване оцінювання показників не дозволяє визначити, які саме порушення обмежують ефективність гребка. Комплексне формування індивідуального профілю дає змогу виявити ці взаємозв'язки та обґрунтувати напрями корекції техніки, інвентарю й посадки в човні.

Мета. Сформувати індивідуальний профіль технічної підготовленості висококваліфікованого каноїста на основі комплексного аналізу біомеханічних і функціональних показників та обґрунтувати напрями індивідуалізації техніки, вибору інвентарю, калібрування посадки й тренувального процесу.

Матеріали і методи. Дослідження виконано за дизайном індивідуального випадку за участю каноїста міжнародного рівня. Для референтної інтерпретації окремих показників додатково обстежено двох каноїстів. Застосовано поверхневу електроміографію, тензометричну реєстрацію гребка з веслами Braca та Erbi, кінематичний аналіз, оцінювання швидкості човнів Nelo, Vajda і Plastex на 150 м, аналіз опорних взаємодій до і після калібрування посадки, методи оцінки сили, функціональні методи. Профіль формували через первинне опрацювання даних, внутрішньоіндивідуальне порівняння, перевірку узгодженості, розподіл результатів за рівнями та обґрунтування тренерських рішень.

Результати. Застосування алгоритму дозволило сформувати індивідуальний профіль технічної підготовленості каноїста. До сильних сторін віднесено стабільність кута атаки весла, швидкісну реалізацію техніки на човнах Plastex і Vajda та підвищення стабільності опорних взаємодій після калібрування посадки. Основними резервами визначено міжланкове передавання зусилля в системі «нога – тулуб – рука – весло», стабільність нахилу тулуба у завершальній фазі гребка та швидкісно-силову витривалість плечового поясу. Erbi порівняно з Braca забезпечувало більшу роботу за гребок – 73,0 проти 49,3 Дж, більшу ефективну частину гребка – 45,6 проти 25,8 Дж і вищу частку ефективної роботи – 62,3 проти 53,0 %. Середня швидкість становила 3,99 м·с⁻¹ на Plastex, 3,95 м·с⁻¹ на Vajda і 3,80 м·с⁻¹ на Nelo. Калібрування посадки зменшило площу переміщення центра тиску в усіх опорних зонах. Підтверджених лімітуючих факторів за результатами комплексного аналізу не встановлено.

Висновки. Інтеграція біомеханічних і функціональних показників в індивідуальний профіль створює науково обґрунтовану основу для персоналізації технічної підготовки каноїста.

Ключові слова: веслування на каное, технічна підготовленість, індивідуальний профіль, біомеханічні показники, електроміографія, динаміка гребка, центр тиску, взаємодія «спортсмен – човен».

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Physiological Responses to CrossFit Training: Evaluation of Aerobic Endurance through Cardiopulmonary Exercise Testing

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Abstract

Background. CrossFit is a high-intensity training method involving varied functional movements that is potentially effective for improving aerobic endurance.

Objectives. This study used a mixed-methods approach to evaluate the effects of a structured CrossFit programme on cardiorespiratory fitness, combining objective measurements with the athletes' subjective perceptions.

Materials and Methods. A total of 80 regular exercisers (aged 20–35) were divided into an experimental group (CrossFit) and a control group (weight training). A quantitative assessment was conducted using cardiopulmonary exercise testing (CPET) at two time points (T0 and T1, after 12 weeks), analysing VO₂ max, ventilatory threshold and heart rate response to submaximal loads. In parallel, semi-structured interviews were conducted at the end of the intervention and analysed using thematic analysis.

Results. The results showed greater improvements in the CrossFit group than in the control group, with an average increase in VO₂ max of +8.2% vs. +1.9%, an increase in ventilatory threshold of +6.4% vs. +1.1%, and a reduction in heart rate at the same load of –3.7% vs. –0.9%, respectively.

Conclusions. The interviews confirmed better fatigue management, more efficient breathing, and the transfer of benefits to daily activities. Therefore, the findings indicate that a 12-week CrossFit programme appears to promote significant cardiorespiratory adaptations, consistent with the athletes' perceptions.

Keywords: CrossFit, aerobic endurance, VO₂max, cardiopulmonary exercise testing, high-intensity training.

Introduction

CrossFit is a sport that originated in the early 2000s. It aims to develop various motor skills simultaneously, including strength, power, agility, coordination and cardiovascular endurance (Dawson, 2017). It is a training method based on constantly varied functional movements performed at high intensity. The discipline's fundamental principles include variety of stimuli, the importance of intensity in adaptation, and the functionality of movements, which are often inspired by everyday gestures (Glassman, 2003; Claudino et al., 2018). This combination makes

CrossFit a comprehensive workout that engages multiple physiological systems in a coordinated manner, making it suitable for individuals with varying degrees of physical fitness (Meyer et al., 2017).

In recent years, there has been a significant increase in scientific attention regarding CrossFit, particularly with regard to its impact on cardiorespiratory capacity (Feito, et al., 2018). Aerobic endurance plays a central role among the physical abilities that can be trained through this discipline, as many workouts involve prolonged or repeated efforts over time characterised by high metabolic demand. Aerobic endurance is the body's capacity to sustain moderate or high-intensity physical activity over an extended period, thanks to the efficient utilisation of oxygen by the muscular, respiratory, and cardiovascular systems (Bassett & Howley, 2000).

A widely used benchmark for assessing aerobic endurance is maximum oxygen consumption ($\text{VO}_2 \text{ max}$), which is an indicator of the body's maximum capacity to transport and use oxygen during exercise. Measuring $\text{VO}_2 \text{ max}$ provides accurate information on cardiorespiratory efficiency and training-induced adaptations. In this context, cardiopulmonary exercise testing (CPET) is the most reliable and detailed tool for objectively assessing aerobic performance (Balady et al., 2010).

CPET (Cardio-Pulmonary Exercise Testing) is a functional assessment that simultaneously analyses the responses of the cardiovascular, respiratory and metabolic systems during incremental physical exercise. The test can be performed on a treadmill or cycle ergometer according to standardised protocols involving a progressive increase in workload until voluntary exhaustion is reached. Throughout the test, physiological parameters such as oxygen consumption (VO_2), carbon dioxide production (VCO_2), pulmonary ventilation, heart rate and blood pressure response are continuously monitored. This allows an integrated assessment of the body's ability to adapt to exertion to be made (Wasserman et al., 1987). As well as determining $\text{VO}_2 \text{ max}$, CPET enables significant physiological thresholds to be identified, such as the ventilatory or anaerobic threshold. This provides valuable information on tolerance to exertion and exercise duration over time (Beaver et al., 1986). This information is particularly useful in high-intensity disciplines such as CrossFit, where alternation between aerobic and anaerobic phases requires high metabolic adaptability.

Therefore, the application of cardiopulmonary testing in a CrossFit training context allows for the objective quantification of physiological adaptations induced by a structured intervention, while also providing insight into the subjective experience of athletes. Integrating quantitative and qualitative data enables us to understand not only whether measurable improvements exist, but also how athletes perceive and apply these changes to their daily activities (Plano Clark & Creswell, 2008).

Materials and Methods

Description of the Study

The study was conducted using a mixed-methods approach, which integrated quantitative and qualitative analysis tools in order to obtain a comprehensive assessment of the effects of CrossFit training on aerobic endurance. The integration of objective and subjective data made it possible to examine not only the physiological changes caused by training, but also the athletes' personal perceptions of the changes they experienced during sports activities and in their daily lives, in accordance with the principles of mixed research in motor sciences (Plano Clark & Creswell, 2008).

The quantitative assessment of aerobic endurance was performed using the cardiopulmonary exercise test (CPET), considered the gold standard for the combined analysis of cardiovascular, respiratory, and metabolic responses during physical activity (Beaver et al., 1986). The test was administered at two different times, at time T0, before the start of the CrossFit training program, and at time T1, at the end of the intervention, according to a pre-post repeated measures design. During the test, participants were continuously

monitored using a breath-by-breath respiratory gas analysis system, which allowed the detection of key physiological parameters, including oxygen consumption (VO_2), carbon dioxide production (VCO_2), pulmonary ventilation (VE), and respiratory quotient (RER). At the same time, heart rate and blood pressure response were recorded in accordance with international guidelines for CPET (Forman et al., 2010).

The main parameter taken into consideration to assess aerobic endurance was maximum oxygen consumption ($\text{VO}_2 \text{ max}$), alongside other indicators obtained from the test, such as ventilatory thresholds, which help to describe exercise tolerance and aerobic metabolism efficiency (Beaver et al., 1986). The comparison of the values obtained at T0 and T1 allowed for the analysis of any cardiorespiratory adaptations induced by the training intervention.

The qualitative analysis was conducted through semi-structured interviews with participants at the end of the training program. The choice of this tool is justified by the need to examine in depth the athletes' subjective perceptions of the effects of CrossFit on their aerobic endurance and bodily experiences during training, as indicated by the qualitative approaches used in motor sciences (Sparkes & Smith, 2013). The interviews were conducted using a predefined set of open-ended questions, which ensured a certain degree of uniformity in data collection while leaving room for personal experiences and individual meanings to emerge. The main themes explored included the perception of fatigue during training, the ability to sustain prolonged effort, perceived changes in breathing and intensity management, and the possible transfer of improvements to everyday life (e.g., during activities such as brisk walking or climbing stairs). The interviews were audio-recorded, transcribed in their entirety, and analyzed using a thematic analysis method, widely used for the interpretation of qualitative data in the context of sports and motor activities (Braun & Clarke, 2006). The integration of qualitative results with quantitative data allowed for a more complete and contextualized reading of the effects of CrossFit on aerobic endurance.

Participants

The study was conducted at a sports association offering CrossFit and traditional resistance-training programmes in Naples, Italy. The final sample consisted of 80 participants, divided into an experimental CrossFit group ($n = 40$) and a traditional resistance-training control group ($n = 40$), consistent with previous studies comparing high-intensity functional training and conventional strength-training modalities (Feito et al., 2018; Claudino et al., 2018). All participants completed both the baseline cardiopulmonary exercise test at T0 and the post-intervention assessment at T1 and were therefore included in the final analysis.

The total sample included 34 women (42.5%) and 46 men (57.5%), with a mean age of 27.5 ± 4.0 years and an age range of 20–35 years. The CrossFit group included 18 women (45.0%) and 22 men (55.0%), with a mean age of 27.2 ± 4.0 years. The control group included 16 women (40.0%) and 24 men (60.0%), with a mean age of 27.8 ± 4.1 years. No statistically significant differences were observed between the groups in age ($p = .510$) or sex distribution ($p = .651$), indicating demographic comparability at baseline. The selected age range is commonly considered appropriate for

investigations of cardiorespiratory performance in trained adult populations (Bassett & Howley, 2000).

Participants were not randomly assigned to the study groups. Group allocation was based on the training modality habitually practised during the study period. Participants in the experimental group followed a structured CrossFit programme, whereas participants in the control group followed a traditional resistance-training programme focused primarily on weightlifting and without structured metabolic-conditioning or continuous aerobic-training components. Consequently, the study adopted a quasi-experimental, non-randomised pre-post design, consistent with the methodological approach used in previous research comparing high-intensity functional and resistance-training programmes (Feito et al., 2018; Claudino et al., 2018).

The inclusion criteria were: (a) age between 20 and 35 years; (b) regular participation in the respective training modality; (c) at least four years of continuous experience in CrossFit or traditional resistance training; (d) possession of a valid medical certificate confirming eligibility for competitive or non-competitive sport; and (e) absence of cardiovascular, respiratory or musculoskeletal conditions contraindicating high-intensity exercise. Requiring at least four years of previous training experience was intended to ensure adequate familiarity with the intensity and technical structure of the exercises and to reduce the potential influence of motor-learning effects on test performance (Lopez, 2026). Medical eligibility and health screening were established in accordance with international recommendations for exercise testing and participation in high-intensity physical activity (American College of Sports Medicine [ACSM], 2018).

The mean training experience was 5.9 ± 1.1 years in the CrossFit group and 5.7 ± 1.0 years in the control group, with no statistically significant between-group difference ($p = .397$). This finding indicated that the two groups were also comparable in terms of previous exposure to structured physical training.

Participants were excluded if they reported an injury during the six months preceding enrolment, a health condition that could interfere with cardiopulmonary exercise testing, use of medications capable of substantially altering cardiovascular responses to exercise, or participation in other structured endurance-training programmes during the intervention period. The exclusion of participants with current or recent musculoskeletal injuries was consistent with recommendations aimed at reducing health risks and potential measurement bias in high-intensity exercise research (Weisenthal et al., 2014). Participants attending fewer than 50% of the scheduled sessions or failing to complete either the T0 or T1 assessment were also excluded from the final analysis. The minimum attendance criterion was established to ensure sufficient exposure to the intervention and adequate reliability in the interpretation of training-related adaptations (Feito et al., 2018).

During the 12-week intervention, both groups completed a maximum of 24 scheduled sessions. Participants in the CrossFit group completed an average of 22.1 ± 1.3 sessions, corresponding to an attendance rate of $92.1 \pm 5.5\%$, whereas participants in the control group completed 21.8 ± 1.5 sessions, corresponding to an attendance rate of $90.8 \pm 6.2\%$. Attendance did not differ significantly between the groups ($p = .324$), suggesting that differences in the

physiological outcomes were unlikely to be attributable to unequal exposure to the training programmes.

An age subgroup analysis was not conducted because the study was designed to examine the overall differences between the two training groups rather than group-by-age interactions. Dividing the sample into narrower age categories would have substantially reduced the number of participants in each subgroup, resulting in insufficient statistical power and potentially unstable estimates. Moreover, the 20–35-year inclusion range represented a relatively homogeneous young-adult population from a physiological perspective. Age was therefore analysed as a continuous baseline variable and considered when interpreting the generalisability of the findings.

All participants received detailed written and verbal information regarding the objectives, procedures, potential risks and expected benefits of the study. Written informed consent was obtained before data collection. The study was conducted in accordance with the ethical principles for research involving human participants and with the Declaration of Helsinki (World Medical Association, 2013).

Activities

Two supervised training programmes were implemented: a high-intensity functional training programme for the experimental CrossFit group and a traditional resistance-training programme for the control group. Both interventions were conducted at the same sports association in Naples, Italy, over a period of 12 weeks. Each group completed two 60-minute sessions per week, corresponding to a maximum of 24 training sessions. Sessions were scheduled on non-consecutive days, with an interval of at least 48 hours between consecutive sessions, to allow adequate recovery.

To facilitate supervision and maintain an appropriate instructor-to-participant ratio, the participants in each group were organised into four subgroups of 10 individuals. Each session was supervised by two qualified instructors holding a degree in exercise and sport sciences and possessing at least five years of professional experience in CrossFit or resistance training. The same instructors supervised each subgroup throughout the intervention to reduce variability in programme delivery.

Before the intervention, the instructors received a standardised programme manual describing the exercise sequence, session duration, prescribed intensity, loading ranges, recovery intervals, progression criteria and permitted exercise adaptations. Attendance, completed exercises, training loads, individual modifications and any adverse symptoms were recorded in an individual training log at the end of each session.

CrossFit training programme

The experimental group followed a structured CrossFit programme based on constantly varied functional movements performed at moderate-to-high intensity. The programme combined resistance and weightlifting exercises, body-weight gymnastic movements and metabolic-conditioning activities, in accordance with the principles of CrossFit and high-intensity functional training (Glassman, 2003; Feito et al., 2018).

Each 60-minute session consisted of:

1. a 10-minute general warm-up;
2. 15 minutes of technical preparation and specific activation;
3. a 12–15-minute Workout of the Day;
4. 10 minutes of cool-down and stretching.

The remaining 10–13 minutes were used for exercise explanation, equipment preparation, transitions between activities, hydration and individual adjustment of exercise loads.

General warm-up

The general warm-up was designed to progressively increase body temperature, activate the cardiovascular system and prepare the joints and muscle groups involved in the main workout. It included dynamic mobility exercises for the ankles, knees, hips, thoracic spine and shoulders, combined with low- to moderate-intensity activities such as jumping jacks, running on the spot, high knees, body-weight squats, dynamic lunges and arm rotations.

The activities were organised as two circuits of five exercises. Each exercise was performed for 30–40 seconds, with approximately 15 seconds allowed for transition between exercises. Warm-up intensity corresponded to approximately 3–4 on the 0–10 rating of perceived exertion scale. This phase promoted neuromuscular activation and progressive cardiovascular preparation before high-intensity exercise (Fradkin et al., 2010). The gradual organisation of the session was also intended to promote safe participation, engagement and social interaction among participants (Di Palma et al., 2025).

Technical preparation and specific activation

The technical phase focused on the movements included in the subsequent WOD. Participants performed core-activation exercises, scapular-stability exercises and dynamic lower-limb activation, followed by technical progressions of the principal weightlifting and gymnastic movements.

Squats, deadlifts, cleans and thrusters were initially rehearsed using body weight, a PVC pipe or an empty barbell. Participants subsequently performed two or three sets of six to eight repetitions with approximately 30–40% of their estimated one-repetition maximum. Pull-ups, push-ups and other gymnastic movements were practised using standard or scaled variations according to individual ability.

Exercise scaling included the use of resistance bands for pull-ups, elevated supports for push-ups, reduced ranges of motion and lighter external loads. Loads were increased only when participants demonstrated adequate postural alignment, movement control and the ability to complete all prescribed repetitions without substantial technical deterioration. This progression was intended to support movement quality and reduce the risk associated with complex exercises performed at high intensity (Behm et al., 2016).

Workout of the Day

The WOD represented the main conditioning component of the session and lasted between 12 and 15 minutes. Each

workout included three to five exercises selected from the following categories:

- resistance and weightlifting exercises, including deadlifts, squats, cleans and thrusters;
- gymnastic and body-weight exercises, including pull-ups, push-ups and burpees;
- metabolic-conditioning activities, including running, rowing and jumping rope.

The workouts were organised using AMRAP, EMOM and For Time formats. AMRAP workouts required participants to complete as many technically correct rounds or repetitions as possible within a predetermined time. During EMOM workouts, participants completed a prescribed number of repetitions at the beginning of each minute and used the remaining time for recovery. For Time workouts required participants to complete a predetermined volume of work in the shortest possible time while maintaining appropriate movement technique.

Each WOD generally included 6–15 repetitions per resistance or gymnastic exercise, running or rowing distances of 200–400 metres and sets of 30–60 jump-rope repetitions. Resistance exercises were performed using loads corresponding to approximately 40–65% of the participant's estimated 1RM. Maximum or near-maximum loads were not used during the WOD.

Recovery depended on the workout format. During EMOM sessions, the time remaining within each minute served as recovery. During AMRAP and For Time sessions, participants were allowed brief self-selected pauses of approximately 10–30 seconds when they could no longer maintain the prescribed technique or exercise intensity.

Training intensity was monitored using the 0–10 rating of perceived exertion scale. Participants were asked to maintain an RPE between 7 and 9 during the main workout. Session RPE was recorded approximately 15 minutes after the end of each session. The instructors reduced the load, number of repetitions or movement complexity when the participant's technique deteriorated or the perceived exertion exceeded the intended level.

The combination of functional resistance exercises, gymnastic movements and metabolic-conditioning activities was intended to stimulate cardiovascular and metabolic adaptations through repeated alternation between high-intensity work and incomplete recovery (Claudino et al., 2018). High-intensity exercise may also influence metabolic regulation and physiological processes involved in energy balance (Di Maio et al., 2026).

Progression of the CrossFit programme

The programme followed a progressive structure across the 12 weeks. Since the participants already had at least four years of CrossFit experience, the first phase was used for technical standardisation rather than initial familiarisation.

During weeks 1–4, emphasis was placed on movement standards, pacing and technical control. During weeks 5–8, total repetitions, external loads or WOD duration were progressively increased by approximately 5–10%, depending on individual tolerance. During weeks 9–12, progression was primarily achieved by increasing work density, reducing self-selected recovery periods and using more complex combinations of exercises.

Table 1. Summary of the Training Protocol for the Experimental Group

Intervention phase	Weeks	WOD duration	Resistance load	Target RPE	Principal objective
Technical standardisation	1–4	10–12 min	40–50% 1RM	7–8	Standardisation of movement technique and moderate work density
Progressive overload	5–8	12–14 min	45–60% 1RM	7–8	Increased training volume, repetitions and exercise density
Higher-density conditioning	9–12	12–15 min	50–65% 1RM	8–9	Maintenance of technique under greater metabolic demand

Only one principal training variable—load, volume, duration or recovery—was increased within the same session. When participants were unable to maintain correct technique, the external load was reduced by approximately 10–20%, the repetitions were decreased or a scaled exercise variation was used.

CrossFit cool-down

The session concluded with approximately three minutes of low-intensity walking or cycling and controlled breathing, followed by seven minutes of static and dynamic stretching. Stretching exercises targeted the quadriceps, hamstrings, gluteal muscles, calf muscles, pectoral muscles, shoulders and lower back.

Each static stretch was maintained for approximately 20–30 seconds and repeated twice without reaching a painful range of motion. The cool-down was intended to promote a gradual reduction in cardiovascular demand and relieve muscular tension accumulated during the workout (Herbert & Gabriel, 2002).

Traditional resistance-training programme

The control group completed a traditional resistance-training programme with the same intervention duration, weekly frequency and session duration as the CrossFit group. Participants attended two supervised 60-minute sessions per week for 12 weeks, corresponding to a maximum of 24 sessions.

The programme focused on muscular strength and hypertrophy and did not include metabolic-conditioning circuits, continuous aerobic exercise or high-intensity interval training. This distinction was maintained throughout the study to preserve the methodological contrast between traditional resistance training and high-intensity functional training (Feito et al., 2018).

Each session consisted of:

- a 10-minute general warm-up;
- 40–45 minutes of traditional resistance training;
- 5–10 minutes of cool-down and stretching.

General warm-up

The warm-up included dynamic joint mobility and low-intensity muscle-activation exercises targeting the muscle groups involved in the subsequent resistance-training session. Participants performed body-weight squats, dynamic lunges, shoulder rotations and trunk-stability exercises.

Before each principal multi-joint exercise, participants completed two preparatory sets: the first set at approximately

40% of the working load for 10 repetitions and the second set at approximately 60% of the working load for six repetitions. These preparatory sets were not included in the prescribed training volume.

Resistance-training component

The programme included the squat, leg press, bench press, seated or bent-over rowing and shoulder press. Supplementary exercises for the elbow flexors, elbow extensors, hamstrings, calf muscles and abdominal muscles were included when time permitted.

The two weekly sessions followed a full-body structure. The exercises involving the largest muscle groups and the most technically demanding multi-joint movements were performed at the beginning of each session.

Participants completed three sets of 8–12 repetitions for each principal exercise. Initial loads corresponded to approximately 65% of estimated 1RM and were progressively increased to approximately 75% of 1RM during the final four weeks. Recovery intervals were two minutes for squats, leg presses, bench presses and rowing exercises and approximately 90 seconds for shoulder presses and supplementary exercises.

Repetitions were performed using a controlled tempo consisting of approximately two seconds during the eccentric phase and one to two seconds during the concentric phase. Participants were instructed to complete the prescribed range of motion without using momentum or substantially altering their posture.

The estimated 1RM was determined during the week preceding the intervention using a submaximal five-repetition maximum assessment. The load was adjusted on the basis of the heaviest load that could be completed for five technically correct repetitions.

The resistance-training progression was organised as follows:

Table 2. Summary of the Training Protocol for the Control Group

Intervention phase	Weeks	Sets × repetitions	Approximate load	Recovery
Initial phase	1–4	3 × 12	65% 1RM	90–120 s
Intermediate phase	5–8	3 × 10	70% 1RM	90–150 s
Final phase	9–12	3 × 8	75% 1RM	120–180 s

When a participant completed the maximum number of prescribed repetitions in all three sets with correct technique during two consecutive sessions, the external load was increased by approximately 2.5% for upper-body

exercises and 5% for lower-body exercises. When the participant could not complete the minimum number of prescribed repetitions, the load was maintained or reduced by approximately 5% in the subsequent session.

Unlike the CrossFit programme, exercises were performed in conventional sets and were not organised as circuits. Resistance exercises were not alternated with running, rowing, jumping rope or other activities intended to maintain elevated cardiorespiratory demand.

Resistance-training cool-down

The control-group sessions concluded with approximately two minutes of low-intensity walking and five to eight minutes of static stretching targeting the muscle groups involved in the resistance exercises. Each stretch was maintained for 20–30 seconds and repeated once or twice. No cardiovascular-conditioning or metabolic-training activity was included during the cool-down.

Cardiopulmonary exercise testing (CPET)

The cardiopulmonary exercise test (CPET) was used to assess the participants' aerobic capacity and was administered at two distinct points in time: at T0 before the training intervention began and at T1 after the 12-week programme had finished. The test was performed under standardised conditions to ensure the reliability and comparability of the measurements taken before and after the intervention, in accordance with international recommendations for conducting CPET (Balady et al., 2010).

During the CPET, participants were instructed to maintain a consistent speed or cadence throughout the test and to refrain from using self-regulation strategies to adjust the intensity, following the operator's guidance. In the case of the treadmill test, the protocol involved gradually and progressively increasing the speed and/or incline at regular intervals to induce a continuous and increasing workload. Participants had to maintain the pace set by the protocol until they could no longer sustain the required effort, as in classic incremental protocols for assessing aerobic capacity (Wasserman et al., 1987).

For the cycle ergometer test, participants were asked to maintain a constant pedalling cadence of between 60 and 80 revolutions per minute while the workload increased progressively in increments of power expressed in watts at set intervals.

In accordance with the guidelines for performing incremental tests on a cycle ergometer (Balady et al., 2010; Forman et al., 2010), the athletes were encouraged to maintain the prescribed cadence for as long as possible until they reached voluntary exhaustion.

Throughout the test, participants received standardised verbal instructions to encourage them to continue exercising and to ensure they made maximum effort. However, they were not given any feedback on the physiological values recorded. Participants were asked to report any symptoms of excessive fatigue, severe breathlessness, dizziness or pain, as these would have led to the test being terminated immediately for safety reasons, in accordance with the safety guidelines for exercise testing.

Gradually increasing the intensity while maintaining a set speed, incline or cadence allowed for a precise examination

of the cardiorespiratory response to the increased workload, enabling the accurate identification of maximum aerobic capacity and personal physiological thresholds (Beaver et al., 1986).

Results

Quantitative Data Analysis

A quantitative analysis was conducted to examine changes in the principal cardiopulmonary outcomes from baseline (T0) to post-intervention (T1) and to compare the effects of the CrossFit and traditional resistance-training programmes. Descriptive data are reported as means and standard deviations. The normality of the distributions was assessed using the Shapiro–Wilk test and through the visual inspection of histograms and Q–Q plots, while the homogeneity of variances was examined using Levene's test. No substantial violations of the assumptions required for parametric analyses were identified.

Baseline comparability was assessed using independent-samples t-tests for continuous variables. Changes in each physiological outcome were analysed using a two-way mixed-design analysis of variance, with time (T0 vs T1) as the within-subject factor and training group (CrossFit vs traditional resistance training) as the between-subject factor. The group-by-time interaction represented the principal test of intervention effectiveness.

When a statistically significant interaction was identified, Bonferroni-adjusted paired-samples t-tests were performed to examine within-group changes. Individual change scores were also compared between groups using independent-samples t-tests. Partial eta squared (η^2p) was reported as the effect-size measure for group-by-time interactions. Cohen's d_z was calculated for within-group changes, whereas Cohen's d , based on the pooled standard deviation of the change scores, was calculated for between-group differences. Effect sizes were interpreted as small, moderate or large using conventional thresholds. Statistical significance was set at $p < .05$, and 95% confidence intervals were reported where appropriate.

The individual percentage change was calculated using the following formula:

$$\Delta\% = [(T1 - T0) / T0] \times 100.$$

All 80 participants completed both the baseline and post-intervention assessments. Therefore, no missing outcome data were recorded, and all participants were included in the quantitative analysis.

Baseline comparability

At baseline, no statistically significant differences were observed between the CrossFit and traditional resistance-training groups in any of the principal physiological outcomes. Mean $\text{VO}_{2\text{max}}$ was $43.9 \pm 5.4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ in the CrossFit group and $44.1 \pm 5.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ in the control group, with a mean difference of $-0.20 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (95% CI $[-2.56, 2.16]$, $p = .866$, $d = -0.04$).

Ventilatory threshold was $68.8 \pm 4.9\%$ of $\text{VO}_{2\text{max}}$ in the CrossFit group and $69.1 \pm 5.0\%$ in the control group. The mean difference was -0.30 percentage points (95% CI $[-2.50, 1.90]$, $p = .787$, $d = -0.06$).

Table 3. Baseline comparability of the principal physiological outcomes

Outcome	CrossFit group, T0 (n = 40)	Control group, T0 (n = 40)	Mean difference (95% CI)	p	Cohen's d
VO ₂ max, mL·kg ⁻¹ ·min ⁻¹	43.9 ± 5.4	44.1 ± 5.2	-0.20 (-2.56 to 2.16)	.866	-0.04
Ventilatory threshold, % VO ₂ max	68.8 ± 4.9	69.1 ± 5.0	-0.30 (-2.50 to 1.90)	.787	-0.06
Heart rate at the same submaximal workload, beats·min ⁻¹	151.4 ± 9.5	150.8 ± 9.7	0.60 (-3.67 to 4.87)	.781	0.06

Heart rate at the same standardised submaximal workload was 151.4 ± 9.5 beats·min⁻¹ in the CrossFit group and 150.8 ± 9.7 beats·min⁻¹ in the control group. The mean difference was 0.60 beats·min⁻¹ (95% CI [-3.67, 4.87], $p = .781$, $d = 0.06$). These results demonstrated adequate baseline comparability between the two groups.

Changes in maximal oxygen uptake

Following the 12-week intervention, VO₂max in the CrossFit group increased from 43.9 ± 5.4 to 47.5 ± 5.6 mL·kg⁻¹·min⁻¹. The mean increase was 3.60 mL·kg⁻¹·min⁻¹ (95% CI [2.96, 4.24]), corresponding to an improvement of 8.2%. The within-group change was statistically significant and associated with a large effect size ($p < .001$, $dz = 1.80$).

The traditional resistance-training group showed a smaller increase in VO₂max, from 44.1 ± 5.2 to 44.9 ± 5.3 mL·kg⁻¹·min⁻¹. The mean change was 0.84 mL·kg⁻¹·min⁻¹ (95% CI [0.33, 1.35]), corresponding to an improvement of 1.9%. The change remained statistically significant following Bonferroni correction, although the effect size was moderate ($p = .004$, $dz = 0.53$).

Changes in ventilatory threshold

Ventilatory threshold in the CrossFit group increased from 68.8 ± 4.9% to 73.2 ± 4.8% of VO₂max. The mean increase was 4.40 percentage points (95% CI [3.47, 5.33]), corresponding to a relative improvement of 6.4%. The change was statistically significant and associated with a large within-group effect ($p < .001$, $dz = 1.52$).

In the control group, ventilatory threshold increased from 69.1 ± 5.0% to 69.9 ± 5.0% of VO₂max. The mean increase was 0.76 percentage points (95% CI [-0.14, 1.66]), corresponding to a relative improvement of 1.1%. This change was not statistically significant after Bonferroni correction and was associated with a small effect size ($p = .188$, $dz = 0.27$).

Changes in submaximal heart rate

Heart rate at the same standardised submaximal workload decreased in the CrossFit group from 151.4 ± 9.5 to 145.8 ± 9.2 beats·min⁻¹. The mean reduction was 5.60 beats·min⁻¹ (95% CI [-6.88, -4.32]), corresponding to a decrease of 3.7%. The reduction was statistically significant and associated with a large within-group effect ($p < .001$, $dz = -1.40$).

In the control group, heart rate decreased from 150.8 ± 9.7 to 149.4 ± 9.6 beats·min⁻¹. The mean reduction was 1.36 beats·min⁻¹ (95% CI [-2.90, 0.18]), corresponding to a decrease of 0.9%. This change was not statistically significant and was associated with a small effect size ($p = .162$, $dz = -0.28$).

Group-by-time interactions

The mixed-design analyses of variance identified statistically significant group-by-time interactions for all three principal physiological outcomes, indicating that the magnitude of change differed significantly between the two training conditions.

Table 4. Baseline, post-intervention and within-group changes in the principal physiological outcomes

Outcome and group	T0, mean ± SD	T1, mean ± SD	Mean change (95% CI)	Change, %	Adjusted p	Cohen's dz
VO ₂ max, mL·kg ⁻¹ ·min ⁻¹						
CrossFit	43.9 ± 5.4	47.5 ± 5.6	3.60 (2.96 to 4.24)	+8.2	< .001	1.80
Control	44.1 ± 5.2	44.9 ± 5.3	0.84 (0.33 to 1.35)	+1.9	.004	0.53
Ventilatory threshold, % VO ₂ max						
CrossFit	68.8 ± 4.9	73.2 ± 4.8	4.40 (3.47 to 5.33)	+6.4	< .001	1.52
Control	69.1 ± 5.0	69.9 ± 5.0	0.76 (-0.14 to 1.66)	+1.1	.188	0.27
Heart rate at the same submaximal workload, beats·min ⁻¹						
CrossFit	151.4 ± 9.5	145.8 ± 9.2	-5.60 (-6.88 to -4.32)	-3.7	< .001	-1.40
Control	150.8 ± 9.7	149.4 ± 9.6	-1.36 (-2.90 to 0.18)	-0.9	.162	-0.28

Note. Data are presented as mean ± standard deviation. T0 = baseline assessment; T1 = assessment after the 12-week intervention; CI = confidence interval; SD = standard deviation; VO₂max = maximal oxygen uptake. Within-group comparisons were performed using paired-samples t-tests. Reported p-values were adjusted using the Bonferroni procedure. A negative change in heart rate indicates improved cardiovascular efficiency at the same external workload.

Table 5. Group-by-time interactions and between-group differences in change

Outcome	CrossFit change, mean $\pm$ SD	Control change, mean $\pm$ SD	Difference in change (95% CI)	$F_{(1,78)}$	p	η^2p	Cohen's d
VO ₂ max, mL·kg ⁻¹ ·min ⁻¹	3.60 $\pm$ 2.00	0.84 $\pm$ 1.60	2.76 (1.95 to 3.57)	46.45	< .001	.373	1.52
Ventilatory threshold, % VO ₂ max	4.40 $\pm$ 2.90	0.76 $\pm$ 2.80	3.64 (2.37 to 4.91)	32.61	< .001	.295	1.28
Heart rate at the same submaximal workload, beats·min ⁻¹	-5.60 $\pm$ 4.00	-1.36 $\pm$ 4.80	-4.24 (-6.21 to -2.27)	18.42	< .001	.191	-0.96

For VO₂max, the group-by-time interaction was statistically significant, $F_{(1,78)} = 46.45$, $p < .001$, $\eta^2p = .373$. The mean improvement in the CrossFit group was 2.76 mL·kg⁻¹·min⁻¹ greater than that observed in the control group (95% CI [1.95, 3.57]). The between-group effect size was large ($d = 1.52$).

A statistically significant interaction was also identified for ventilatory threshold, $F_{(1,78)} = 32.61$, $p < .001$, $\eta^2p = .295$. The improvement in the CrossFit group exceeded that observed in the control group by 3.64 percentage points (95% CI [2.37, 4.91]), with a large between-group effect size ($d = 1.28$).

For heart rate at the same standardised submaximal workload, the group-by-time interaction was statistically significant, $F_{(1,78)} = 18.42$, $p < .001$, $\eta^2p = .191$. The reduction in heart rate was 4.24 beats·min⁻¹ greater in the CrossFit group than in the control group (95% CI [-6.21, -2.27]), with a large between-group effect size ($d = -0.96$).

Overall, the statistically significant group-by-time interactions indicated that the CrossFit and traditional resistance-training groups followed different physiological trajectories during the 12-week intervention. The CrossFit programme produced greater improvements in maximal aerobic capacity, ventilatory threshold and cardiovascular efficiency during submaximal exercise. Although the control group demonstrated a small-to-moderate improvement in VO₂max, only the CrossFit group achieved statistically significant and large improvements across all three principal physiological outcomes. These findings support the interpretation that the repeated combination of functional resistance exercises, gymnastic movements and metabolic-conditioning activities elicited cardiorespiratory adaptations that were not reproduced to the same extent by traditional resistance training alone.

Qualitative data analysis

The qualitative analysis of the semi-structured interviews allowed us to explore the athletes' individual experiences regarding the effects of training on aerobic endurance, perception of effort, and overall bodily experience during physical activity. Thematic analysis of the transcripts revealed recurring interpretative categories, reflecting perceived changes not only on a physiological level, but also on a cognitive, emotional, and functional level, outlining a detailed picture of the athletes' experience over the 12 weeks of the intervention.

In the experimental group (CrossFit), most participants reported a clear sense of progress in managing fatigue, describing a perception of greater 'control' over effort during training. The athletes reported perceiving fatigue as less sudden and less limiting than in the pre-intervention phase,

emphasizing a greater ability to distribute energy throughout the workout. In particular, many pointed out that during WODs characterized by high work density or prolonged duration, it was possible to maintain a more constant pace, reducing the need for frequent or prolonged breaks.

A frequently reported aspect concerned the improvement in respiratory perception. Several athletes described their breathing as more "controlled" and "efficient," associated with less breathlessness in the middle and final stages of training. This change was interpreted by the participants themselves as a greater ability to adapt to the required intensity, with a reduction in anxiety related to breathing difficulties and greater confidence in sustaining high levels of effort.

A second central theme concerned tolerance to submaximal effort, with many athletes reporting a perceived shift in the threshold beyond which fatigue became excessive. In particular, metabolic conditioning exercises (such as running, rowing, or combined workouts) were described as more "manageable," both in terms of continuity of execution and in terms of recovery between the various phases of the workout. Athletes often reported being able to resume activity more quickly after short breaks, suggesting a perceived improvement in recovery capacity during exercise.

Another element that emerged concerned the transfer of improvements to everyday life, an aspect that played a significant role in the narratives of the CrossFit group participants. Many athletes reported greater ease in performing daily activities that require moderate physical effort, such as walking at a brisk pace, climbing several flights of stairs without stopping, or carrying loads for prolonged periods. These changes were often associated with a general feeling of greater physical efficiency, reduced fatigue, and improved overall physical well-being.

In the control group (weight training), the athletes' opinions highlighted a different experience. Although many participants reported perceived improvements in muscle strength, joint stability, and confidence in performing movements with overload, perceptions of aerobic endurance were more limited. In particular, most athletes did not report significant changes in fatigue management during prolonged or high cardiovascular demand activities, nor did they report a noticeable improvement in their ability to sustain continuous effort.

Some participants in the control group also pointed out that, although they felt stronger, the feeling of breathlessness or fatigue during aerobic activities or in daily life remained substantially unchanged compared to the pre-intervention period, suggesting a perception of predominantly muscular rather than cardiorespiratory adaptations.

Overall, the integration of qualitative results with quantitative data showed a strong convergence between

objectively measured improvements and subjectively perceived changes, particularly in the CrossFit group. This convergence reinforces the interpretation of the results, suggesting that the cardiorespiratory adaptations detected through CPET are clearly reflected in the athletes' experience, contributing to a more complete, ecological, and contextualized understanding of the effects of training on aerobic endurance.

Discussion

The results obtained indicate that CrossFit's integrated, high-intensity approach could promote more significant cardiorespiratory adaptations than a program focused solely on weight lifting. In particular, the joint improvement of indicators related to aerobic performance and sustainability of effort appears consistent with the principle of specific training, according to which physiological adaptations are strongly influenced by the characteristics of the training stimulus. Repeated exposure to tasks that alternate between moments of high metabolic demand and partial recovery seems, in fact, to be able to stimulate various energy systems simultaneously (Jacob et al., 2020), promoting both "central" adaptations, such as increased cardiovascular system efficiency, and "peripheral" adaptations, linked to better oxygen utilization at the muscular level, such as increased mitochondrial density and oxidative capacity (Bassett & Howley, 2000; MacInnis & Gibala, 2017). These adaptations are reflected in a greater ability to sustain prolonged or repeated workloads, even at submaximal intensities, which is particularly relevant in disciplines characterized by intermittent and variable efforts such as CrossFit (Claudino et al., 2018).

From this perspective, CrossFit seems to act not only on maximal aerobic capacity but also on the quality of performance during prolonged exercise, improving exercise tolerance and intensity management over time. This result coincides with findings from previous research on high-intensity functional training, which reported improvements not only in $\text{VO}_{2\text{max}}$ but also in the ability to manage high workloads with less perceived fatigue (Feito et al., 2018; Heinrich et al., 2014). This aspect takes on significant functional value, as the ability to maintain high intensity without a rapid decline in performance is a key factor in both athletic performance and efficiency in daily activities that require continuous or repeated effort.

Another element of particular interest that emerged from the study concerns the convergence between objective measures and subjective perceptions. The consistency observed between the changes detected through CPET and the experiences reported by the athletes reinforces the ecological interpretation of the results, suggesting that physiological adaptations are not confined to the laboratory setting but translate into perceptible and functionally significant changes during training and in daily life (Wasserman et al., 1987).

The consistency observed between the changes detected through CPET and the experiences reported by the athletes highlights the broader impact of structured sport interventions, suggesting that physiological adaptations may extend beyond performance outcomes and contribute to meaningful changes in participation, well-being, and daily

life experiences (Di Palma et al., 2025). The perception of improved fatigue management, more effective respiratory control, and greater continuity of action is a central element of the athletes' experience and can be considered an indirect indicator of the effectiveness of the intervention, in line with approaches that integrate physiological outcomes and subjective experience in the evaluation of training (Creswell & Plano Clark, 2010).

This alignment of quantitative and qualitative data is particularly relevant from motivational and behavioural perspectives. Perceiving greater control over effort and reduced fatigue can positively influence adherence to the training programme, the willingness to sustain high loads and the quality of commitment during sessions. All of these factors are considered crucial for maintaining the long-term benefits of physical exercise (Gipson et al., 2021). In this sense, the benefits of physical exercise could extend beyond immediate physiological improvements, fostering inclusive participation and contributing to the stimulation of cognitive capacities, particularly attentional processes (Tafari et al., 2025), in line with recent mixed-methods research showing that structured sport interventions produce not only measurable performance improvements but also significant motivational, relational and reflective benefits perceived by participants, while supporting the maintenance of a physically active lifestyle and a greater awareness of one's physical abilities over time. From this perspective, physical activity can also be effectively integrated into the school context as a pedagogical tool aimed at promoting inclusion, well-being, and students' cognitive development (Latino, et al., 2025).

Conclusion

When interpreting the results, it is important to consider certain methodological aspects that may have influenced the magnitude of the observed effects and how generalisable they are. Firstly, assigning participants to groups based on their usual training type (CrossFit vs. weightlifting) creates a quasi-experimental design, which reduces the ability to attribute differences exclusively to the intervention with causal certainty. This is because pre-existing factors, such as motivation, lifestyle, individual preferences and initial fitness level, may have contributed to the changes. Furthermore, although CPET is a highly reliable method, using two different ergometers (treadmill or cycle ergometer) may introduce variability related to movement specificity and familiarity with the testing procedure. To reduce this effect, future studies should standardise the ergometer for all participants or stratify the analysis by test type. Another limitation is the difficulty of controlling external factors such as diet, sleep quality, extra-protocol physical activity and recovery management, which are not always fully monitorable in 'real' contexts such as a sports association and which may affect both physiological adaptation and subjective perceptions. From a qualitative point of view, collecting interviews at the end of the intervention may have favoured a retrospective reading influenced by social desirability or expectations of improvement. In future, integrating weekly diaries or short longitudinal check-ins would provide a more accurate understanding of how experiences evolve over time.

In light of these considerations, future prospects could involve more controlled experimental designs (e.g.

randomised) and the systematic monitoring of internal and external load (e.g. heart rate, RPE, total volume and work density), in order to more accurately describe the actual training 'dose' received. Expanding the outcomes beyond cardiorespiratory markers to include recovery and adaptation variables (e.g. body composition, neuromuscular markers, performance in specific tests and stress/fatigue indicators) would also be useful, as would conducting more refined threshold analyses (determination methods and reliability). Finally, multicentre studies involving more heterogeneous samples in terms of gender, level of experience and age groups could clarify whether the observed effectiveness is comparable in different populations, and which training components (metcon, intervals, density and choice of movements) are most decisive in producing improvements (VanBuskirk, 2026). This would help to build more targeted and transferable protocols in sports and health promotion contexts.

Ethics Approval

The study was approved by the Ethics Committee of the University of Naples Parthenope (DiSMMeB, Prot. No. 16761/2026). Written informed consent was obtained from all participants and/or their legal guardians prior to participation in the study.

Data Availability Statement

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

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The authors declare no conflicts of interest.

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Фізіологічні реакції на тренування з кросфіту: оцінка аеробної витривалості за допомогою кардіопульмонального навантажувального тестування

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

Реферат. Стаття: 12 с., 5 табл., 30 джерел.

Обґрунтування. Кросфіт — це метод високоінтенсивного тренування, що включає різноманітні функціональні рухи та є потенційно ефективним для покращення аеробної витривалості.

Мета дослідження. У цьому дослідженні застосовано підхід змішаних методів для оцінки впливу структурованої програми з кросфіту на кардіореспіраторну підготовленість шляхом поєднання об'єктивних вимірювань із суб'єктивним сприйняттям спортсменів.

Матеріали та методи. Загалом 80 осіб, які регулярно тренуються (віком 20–35 років), були розділені на експериментальну групу (кросфіт) та контрольну групу (силові тренування). Кількісну оцінку проводили за допомогою кардіопульмонального навантажувального тестування (КПНТ) у двох часових точках (T0 та T1 — через 12 тижнів), аналізуючи максимальне споживання кисню (VO₂ max), вентиляційний поріг та реакцію частоти серцевих скорочень на субмаксимальні

навантаження. Паралельно наприкінці інтервенції було проведено напівструктуровані інтерв'ю, дані яких проаналізували за допомогою тематичного аналізу.

Результати. Результати продемонстрували вищі показники покращення в групі занять з кросфіту порівняно з контрольною групою: середнє збільшення $\text{VO}_2 \text{ max}$ становило +8.2% проти +1.9%, підвищення вентиляційного порогу — +6.4% проти +1.1%, а зниження частоти серцевих скорочень за однакового навантаження становило –3.7% проти –0.9% відповідно.

Висновки. Результати інтерв'ю підтвердили поліпшення контролю втоми, вищу ефективність дихання та перенесення позитивних ефектів тренувань на повсякденну діяльність. Таким чином, отримані дані свідчать про те, що 12-тижнева програма з кросфіту стимулює значні кардіореспіраторні адаптації, що узгоджуються із суб'єктивним сприйняттям спортсменів.

Ключові слова: кросфіт, aerobic витривалість, $\text{VO}_2 \text{ max}$, кардіопульмональне навантажувальне тестування, високоінтенсивне тренування.

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The Effects of Combined TRX Suspension and Functional Circuit Training on Biomotor and Physiological Adaptations in Adolescent Basketball 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

Objectives. This study aimed to compare the effects of an 8-week intervention combining TRX suspension and functional circuit training, as well as functional circuit training alone, and regular basketball practice on biomotor abilities and physiological adaptations in adolescent basketball players.

Materials and Methods. A total of 60 adolescent male basketball players were randomly divided into three groups: combined TRX suspension and functional circuit training group (TRXG, $n = 20$); functional circuit training group (FCG, $n = 20$); and control group (CG, $n = 20$). The training lasted 8 weeks, with sessions performed three times per week. Sprint speed, agility, countermovement jump (CMJ) performance, body fat percentage, skeletal muscle mass, resting heart rate, and systolic and diastolic blood pressure were measured before and after the intervention. A mixed design ANOVA with Bonferroni comparisons was used for data analysis.

Results. All biomotor and physiological variables showed significant Group $\times$ Time interactions (all $p < .001$; partial $\eta^2 = 0.64\text{--}0.82$). The TRXG exhibited a greater improvement across all outcomes compared to both the FCG and CG. Notably, there were large interaction effects for sprint performance ($F_{(2,57)} = 75.32$, $p < .001$, $\eta^2 = 0.73$), agility ($\eta^2 = 0.82$), countermovement jump ($\eta^2 = 0.78$), body composition, resting heart rate, and blood pressure.

Conclusions. The findings suggest that functional circuit training enhances biomotor and physiological parameters. Furthermore, incorporating TRX suspension exercises yields greater improvements than functional circuit training alone and may provide additional benefits when integrated into a progressively structured and supervised conditioning programme.

Keywords: adolescent basketball players, TRX suspension training, functional circuit training, biomotor abilities, physiological adaptations, conditioning.

Introduction

Basketball is a high-intensity, intermittent sport with frequent changes in direction, jumping, landing, and multidirectional movements with different competitive demands. To perform successfully requires the development of the biomotor skills, especially speed, agility, and the lower body's power, as well as physiological elements that enable repetition of high-intensity efforts (Scanlan et al., 2019; Stojanović et al., 2017). In the adolescent period, conditioning programmes should improve these performance-related qualities, but must also consider the continued developmental processes of the neuromuscular

system and physiology of young athletes (Lesinski et al., 2020). Therefore, finding training techniques that will enhance more than one aspect of physical fitness is a primary goal in youth basketball conditioning.

Although considerable research has been conducted on youth strength and conditioning, one scientific issue remains unresolved. Current evidence supports the effectiveness of suspension-based resistance training and functional training for improving selected components of athletic performance; however, these training approaches have been investigated predominantly as independent interventions rather than in combination (Cao et al., 2024; Zhang et al., 2024). Consequently, it remains unclear whether incorporating TRX suspension exercises into functional circuit training provides greater benefits than functional circuit training alone. This uncertainty extends beyond

a simple gap in the literature, as it limits evidence-based coaching and physical education decisions regarding the use of specialised suspension-training equipment, technical supervision, and implementation costs. Direct comparative evidence is therefore needed to determine whether these additional demands are justified by superior performance and physiological adaptations (Beato et al., 2024).

Studies have demonstrated that resistance training can improve muscular strength, power, and movement performance in adolescent athletes. When appropriately supervised, resistance training is considered safe and effective for enhancing athletic performance and reducing injury risk in youth (Zhang et al., 2024). Likewise, functional circuit training has been shown to improve speed, agility, muscular endurance, and explosive power by incorporating multi-joint, sport-specific movement patterns that closely reflect the physical demands of basketball. Collectively, the available evidence indicates that functional training is an effective approach for developing multiple components of physical fitness simultaneously (Cao et al., 2024). However, most previous studies have evaluated functional circuit training as a standalone intervention, with limited investigation of its combined application with other training modalities.

TRX suspension training has gained popularity over the years since it adds instability during the exercise, which means that the trunk and stabilizing muscles are constantly engaged while performing functional movements during the exercises. Electromyographic tests have shown that core muscles are more engaged when performing suspension exercises than similar exercises performed on stable surfaces (Aguilera-Castells et al., 2018; Oliva-Lozano & Muyor, 2020). Improved neuromuscular activation may contribute to better lumbopelvic stability, postural control, force transfer, and movement efficiency, which are crucial for basketball-specific movements like sprinting, cutting, jumping, landing, and quick changes of direction. While these theoretical mechanisms offer the potential for improved transfer to sport performance, the limited available evidence has not been consistent, and the majority of TRX studies have included healthy adults, recreational participants, or rehabilitation populations, and not competitive adolescent basketball players. In addition, few studies have investigated whether there are any added adaptations to a functional conditioning programme when using suspension-based instability training (Bao et al., 2025).

A second limitation of the existing literature concerns the outcome measures used to evaluate training effectiveness. Previous studies have primarily focused on isolated aspects of performance, such as muscular strength or jump height, whereas basketball performance depends on the simultaneous development of multiple biomotor and physiological characteristics (Cao et al., 2024; Lesinski et al., 2020). Physiological adaptations, including favourable changes in body composition, resting heart rate, and blood pressure, may also contribute to training tolerance, recovery, and long-term athlete development. Resistance and functional training have been associated with improvements in these health-related outcomes (Guillem et al., 2020; Liu et al., 2024). However, the extent to which these parameters change following combined TRX suspension and functional circuit training in adolescent basketball players remains unclear.

The effectiveness of combined training programmes is also uncertain because of methodological limitations. Some prior research has assessed only passive controls or not included a randomly allocated control group with active basketball practice. This is because such designs are hard to differentiate intervention-specific effects from those that may be due to normal basketball participation, growth, maturation, and/or repeated testing (Liu & Li, 2025; Maggioni et al., 2018). Therefore, well-designed RCTs with active comparison groups should be used to establish whether combined suspension and functional circuit training results in adaptations not observed in regular basketball practice or functional circuit training alone.

Thus, there is a clear and unaddressed scientific need in the current literature. Although TRX suspension training and functional circuit training have each demonstrated positive effects when applied independently, limited experimental evidence has examined whether combining these training modalities produces greater improvements in biomotor performance and physiological adaptations in adolescent basketball players (Bao et al., 2025; Delextrat et al., 2018). Addressing this question is important for developing evidence-based conditioning programmes that maximize performance while making efficient use of time, equipment, and coaching resources in youth basketball. Thus, this study aimed to evaluate the effects of an 8-week TRX suspension plus functional circuit training (TRX+FCT) programme, a functional circuit training (FCT) programme, and regular basketball training on selected biomotor abilities (speed, agility, and explosive power) and physiological adaptations (body composition, resting heart rate, and blood pressure) in adolescent basketball players.

The hypotheses were: (1) that both intervention groups would show significant improvements in the biomotor and physiological variables compared to the control group; (2) that the combined TRX suspension and functional circuit training group would show significantly greater improvements than the functional circuit training only group, suggesting an additive effect of suspension-based instability training; and (3) that the functional circuit training only group would show significant improvements compared to the control group.

Materials and Methods

Study Participants

In this randomized controlled trial, 60 male adolescent basketball players (mean age: 17.4 ± 0.8 years; height: 180.0 ± 5.5 cm; body mass: 72.5 ± 5.5 kg; years of basketball training: 4.1 ± 0.8) from regional basketball clubs and collegiate teams in Chennai, India, participated. Subjects included people aged 16-18 who had at least 3 years of organized basketball training, who attended team practice and played regularly in team competition, and were physically capable of vigorous exercise. Exclusion criteria were an injury or illness of the musculoskeletal system at the time of study, structured resistance training, suspension training, functional circuit training in the last 6 months, cardiovascular, metabolic, or neurological disease that precluded exercise, use of performance-enhancing substances, or failure to complete the intervention. Written informed consent was obtained

from all participants, with parental/legal guardian consent also obtained for participants under the age of 18. The study protocol was approved by the Institutional Ethics Committee of Hindustan Institute of Technology and Science, Chennai, India (Approval ID: HITS/CRC/004/22703049). All procedures were carried out following the guidelines of the Declaration of Helsinki.

Study Organization

The design was a three-arm randomized controlled pre-test–post-test. After eligibility screening and familiarization, all participants took part in baseline assessments followed by random assignment (1:1:1) to the TRX suspension combined with functional circuit training group (TRXG, $n = 20$), functional circuit training group (FCG, $n = 20$), and control group (CG, $n = 20$). The number of participants is presented in Figure 1. Randomization was done using a computer-generated sequence prepared by an independent researcher, and the allocation was hidden in sequentially numbered, opaque, sealed envelopes. Baseline assessments were taken two days before the intervention, while post-intervention assessments were performed two days following the eight-week training programme under standardised conditions by the same trained assessors at around the same time of day. The reporting of this randomized controlled trial followed the CONSORT 2010 statement (Moher et al., 2010).

Outcome Measures

The effects of the study were measured at baseline and post-8 weeks. Biomotor abilities (speed, agility, explosive power, body fat percentage, and skeletal muscle mass) and physiological variables (resting heart rate, systolic and diastolic blood pressure) were the primary outcomes. Assessment procedures are detailed for each of the following subsections. All the measurements were taken by trained staff under standardized conditions, using established and

validated protocols with established reliability in adolescent athletes (American College of Sports Medicine, 2021; Zhao et al., 2019).

Biomotor Abilities

The 8-week intervention was evaluated for biomotor abilities before and after the intervention, under standardized testing conditions. The 50 m sprint test, Illinois Agility Test, and the Countermovement Jump test (CMJ) were used to assess speed, agility, and explosive power, respectively. Each performance test was performed three times using passive recovery for 3 minutes between each trial, and the best performance was kept for statistical analysis. Body composition variables were evaluated by a multi-frequency bioelectrical impedance analyzer (BIA) after an overnight fast of at least 8 hours and 24 hours of abstinence from strenuous exercise before testing, body fat percentage (%), and skeletal muscle mass (kg). Assessments were performed in line with standardized procedures described in previous studies (American College of Sports Medicine, 2021; Reijnen & Soeters, 2020).

Physiological Adaptations

Physiological adaptation was measured before and after the 8-week intervention, under standard resting conditions. Participants sat quietly for 10 minutes before measurement. HR was recorded for 5 minutes, and the lowest stable one-minute average HR was taken in beats per minute (bpm). Blood pressure was measured by an automated digital sphygmomanometer with a cuff that was the correct size for the arm, using the arm at heart level. Three readings were taken every minute, and the average of the second and third readings was recorded in millimetres of mercury (mmHg). These procedures were in line with the recommended guidelines for resting cardiovascular assessment and standardized blood pressure measurement (American College of Sports Medicine, 2021; Muntner et al., 2019).

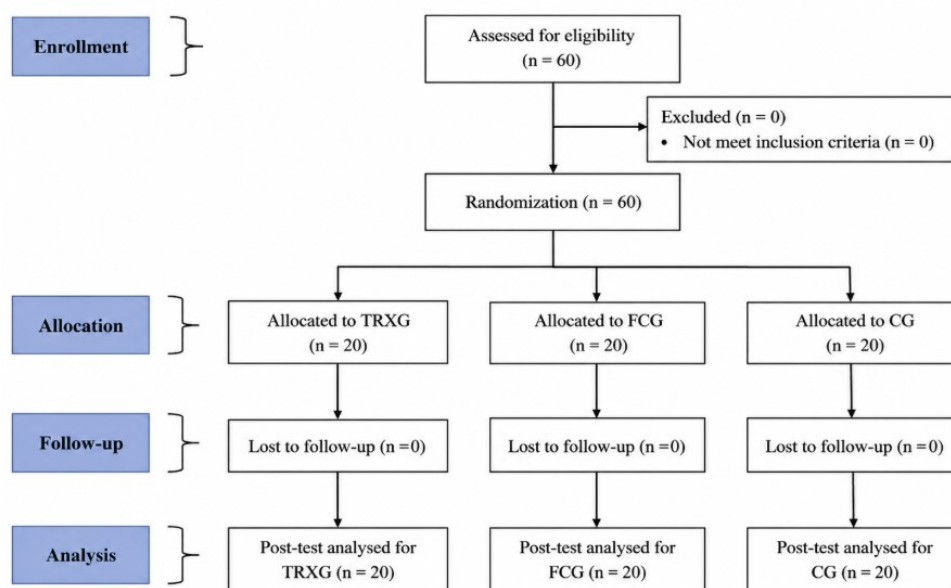


Fig. 1. Schematic representation of the research study

Training Intervention Procedure

The intervention took place for 8 weeks, with three sessions per week (non-consecutive days) (24 sessions). Each session was 50-60 minutes long with a 10-minute warm-up, 35-40 minutes of main training, and a 5-10-minute cool down. The Borg Category Ratio-10 scale was used to track training intensity from 5-6 in Weeks 1-2, up to 8-9 in Weeks 7-8. Each phase of the intervention involved increased exercise volume, complexity, and speed of movement. The TRX suspension combined with functional circuit training group (TRXG) performed TRX suspension exercises that were combined with functional circuit training exercises, while the functional circuit training group (FCG) performed bodyweight and free-weight exercises of the same movement patterns. The training frequency, duration, progression, recovery intervals (2 min between sets; 30-40 s between exercises), and training volume were identical for both groups, as detailed in Tables 1 and 2. Progressions were made by adding exercises, reps, complexity of movement, unilateral loading, resistance, and velocity. The control group (CG) completed the same amount of basketball practice as the experimental group, but without the structured suspension or functional circuit training. The control group performed the same number of sessions of basketball practice as the experimental group (three sessions per week, 60-90 minutes per session), which included technical drills, tactical activities, small-sided games, and scrimmages. All sessions were attended and the participants had to attend at least 85% of the planned sessions (20/24). There were no adverse events reported related to the intervention.

Statistical Analysis

IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA) was used for data analysis.

Table 1. TRX suspension combined with a functional circuit training programme

Training period	Exercises per session	Volume (sets × reps)	Rest between sets	Rest between exercises
Weeks 1-2	5	3 × 6-8 repetitions	2 min	30-40 s
Weeks 3-4	6	3 × 8 repetitions	2 min	30-40 s
Weeks 5-6	7	3 × 8-10 repetitions	2 min	30-40 s
Weeks 7-8	8	3 × 6-10 repetitions	2 min	30-40 s

Exercises: TRX squat, TRX row, TRX chest press, TRX mountain climber, TRX lunge, TRX inverted row, TRX push-up, TRX jump squat, TRX chest fly, box jump, lateral bound, medicine-ball throw, agility run, burpee, and TRX power pull.

Table 2. Functional circuit training programme

Training period	Exercises per session	Volume (sets × reps)	Rest between sets	Rest between exercises
Weeks 1-2	5	3 × 6-8 repetitions	2 min	30-40 s
Weeks 3-4	6	3 × 8 repetitions	2 min	30-40 s
Weeks 5-6	7	3 × 8-10 repetitions	2 min	30-40 s
Weeks 7-8	8	3 × 6-10 repetitions	2 min	30-40 s

Exercises: goblet squat, inverted row, push-up, lunge, plank hold, glute bridge, Bulgarian split squat, box jump, lateral bound, medicine-ball throw, burpee, skater jump, and agility run.

Data are reported as the mean ± SD. The normality and homogeneity of variance were checked by the Shapiro-Wilk and Levene's tests, respectively. One-way analysis of variance (ANOVA) was used to determine differences between groups at baseline. A 3x2 repeated measures ANOVA was used to analyse the effects of intervention with Group (TRXG, FCG, and CG) as the between-participants factor and Time (pre-test and post-test) as the within-participants factor. If there were significant interactions between groups and time, Bonferroni corrections were used to make post hoc comparisons. With only two measurement occasions, the assumption of sphericity was assumed. The effect size for ANOVA effects was reported as partial eta squared (η^2) and for pairwise comparisons, Cohen's d. When appropriate, 95% confidence intervals (95% CI) and exact p-values were presented, when $p < .001$. $P < .05$ was used as the cut-off for statistical significance. Analysis was conducted per protocol, meaning only those who finished both assessments and had at least 90% attendance were included.

Results

All 60 participants took both the baseline and post-intervention assessments, and were analyzed. There were 20 participants in each group. All numerical values reported in previous versions of the manuscript have been replaced by the recalculated results presented here, which have been drawn from the participant-level data.

Biomotor Variables

The pre-test and post-test results for sprint speed, agility, and explosive power are shown in Table 3. All three biomotor variables showed significant Group × Time interactions. For the 50-m sprint, the interaction effect was significant and large, $F_{(2, 57)} = 75.32$, $p < 0.001$, $\eta^2 = 0.73$. All three groups had a significant reduction in sprint time, but the TRXG had the largest improvement. The reduction in sprint time was 0.17 s greater in the TRXG than in the FCG (95% CI: 0.11-0.23, Bonferroni-adjusted $p < 0.001$, $d = 1.85$) and 0.29 s greater than in the CG (95% CI: 0.24-0.34, $p < 0.001$, $d = 3.59$). The FCG also improved more than the CG by 0.12 s (95% CI: 0.09-0.15, $p < 0.001$, $d = 2.67$).

A significant and large interaction was also found for the Illinois Agility Test, $F_{(2, 57)} = 129.56$, $p < 0.001$, $\eta^2 = 0.82$. The TRXG achieved a 0.48 s greater improvement than the FCG (95% CI: 0.36-0.61, $p < 0.001$, $d = 2.46$) and a 0.82 s greater improvement than the CG (95% CI: 0.72-0.93, $p < 0.001$, $d = 5.03$). The improvement in the FCG exceeded that in the CG by 0.34 s (95% CI: 0.27-0.42, $p < 0.001$, $d = 2.86$). The countermovement-jump performance was similar, with a significant Group × Time interaction, $F_{(2, 57)} = 98.37$, $p < 0.001$, $\eta^2 = 0.78$. The increase in jump height was 1.48 cm greater in the TRXG than in the FCG (95% CI: 0.96-1.99, $p < 0.001$, $d = 1.84$) and 2.94 cm greater than in the CG (95% CI: 2.51-3.36, $p < 0.001$, $d = 4.43$). The FCG also improved more than the CG by 1.46 cm (95% CI: 1.15-1.77, $p < 0.001$, $d = 3.01$).

Physiological Variables

Significant Group × Time interaction effects were observed for all five physiological variables shown in Table 4.

Table 3. Comparisons of changes in biomotor variables among the TRX suspension combined with functional circuit training, functional circuit training, and control groups

Variables	Group	Mean $\pm$ SD Baseline	Mean $\pm$ SD After	Paired t-test p-value	MD (95% CI)	Main effect Group p (η^2)	Main effect Time p (η^2)	Interaction Group $\times$ Time p (η^2)
Speed (seconds)	TRXG	7.38 $\pm$ 0.26	7.05 $\pm$ 0.25	<0.001	0.33 (0.27 to 0.38)			
	FCG	7.68 $\pm$ 0.41	7.52 $\pm$ 0.39	<0.001	0.16 (0.13 to 0.19)	0.004 (0.18)	<0.001 (0.85)	<0.001 (0.73)
	CG	7.46 $\pm$ 0.39	7.43 $\pm$ 0.38	<0.001	0.04 (0.03 to 0.04)			
Agility (seconds)	TRXG	16.94 $\pm$ 0.74	16.01 $\pm$ 0.79	<0.001	0.93 (0.83 to 1.04)			
	FCG	16.69 $\pm$ 0.76	16.24 $\pm$ 0.73	<0.001	0.45 (0.37 to 0.52)	0.176 (0.06)	<0.001 (0.91)	<0.001 (0.82)
	CG	16.90 $\pm$ 0.71	16.80 $\pm$ 0.71	<0.001	0.11 (0.08 to 0.13)			
Explosive power (centimetres)	TRXG	35.27 $\pm$ 1.80	38.64 $\pm$ 1.77	<0.001	-3.37 (-3.80 to -2.94)			
	FCG	33.95 $\pm$ 2.67	35.84 $\pm$ 3.06	<0.001	-1.90 (-2.20 to -1.59)	<0.001 (0.26)	<0.001 (0.90)	<0.001 (0.78)
	CG	33.58 $\pm$ 2.11	34.02 $\pm$ 2.05	<0.001	-0.44 (-0.52 to -0.35)			

Note. TRXG = TRX suspension combined with functional circuit training group; FCG = functional circuit training group; CG = control group; MD = mean pre-test minus post-test difference; CI = confidence interval; η^2 = partial eta squared. Positive mean differences for speed and agility indicate reduced completion time and improved performance. Negative mean differences for explosive power indicate increased jump height.

Body-fat percentage demonstrated a large interaction effect, $F(2, 57) = 86.99$, $p < 0.001$, $\eta^2 = 0.75$. The reduction was 0.71 percentage points greater in the TRXG than in the FCG (95% CI: 0.51–0.90, $p < 0.001$, $d = 2.29$) and 1.04 points greater than in the CG (95% CI: 0.86–1.21, $p < 0.001$, $d = 3.70$). The FCG also showed a greater reduction than the CG (mean difference = 0.33 points, 95% CI: 0.24–0.42, $p < 0.001$, $d = 2.35$). The Group $\times$ Time interaction for skeletal muscle mass was significant and large, $F(2, 57) = 71.23$, $p < 0.001$, $\eta^2 = 0.71$. The increase was 0.51 kg greater in the TRXG than in the FCG (95% CI: 0.28–0.73, $p < 0.001$, $d = 1.47$) and 1.09 kg greater than in the CG (95% CI: 0.88–1.29, $p < 0.001$, $d = 3.31$). The FCG increased skeletal muscle mass by 0.58 kg more than the CG (95% CI: 0.48–0.68, $p < 0.001$, $d = 3.87$).

Resting heart rate also showed a significant interaction, $F(2, 57) = 50.62$, $p < 0.001$, $\eta^2 = 0.64$. The reduction was greater in the TRXG than in the FCG by 1.95 bpm (95% CI: 1.15–2.75, $p < 0.001$, $d = 1.57$) and greater than in the CG by 3.35 bpm (95% CI: 2.60–4.10, $p < 0.001$, $d = 2.87$). The FCG also demonstrated a greater reduction than the CG (mean difference = 1.40 bpm, 95% CI: 0.97–1.83, $p < 0.001$, $d = 2.11$). Large interaction effects were found for systolic blood pressure, $F(2, 57) = 117.35$, $p < 0.001$, $\eta^2 = 0.80$, and diastolic blood pressure, $F(2, 57) = 75.56$, $p < 0.001$, $\eta^2 = 0.73$. The ordering of improvement was also consistent for both outcomes, as confirmed by pairwise comparisons: TRXG > FCG > CG. After the Bonferroni correction ($p < 0.001$), all comparisons between groups were statistically significant. Pairwise comparisons demonstrated statistically significant differences among the groups after Bonferroni adjustment (all $p < .001$). The percentage changes in biomotor and physiological outcome measures across the three groups are presented in Figure 2.

Discussion

This study was based on two related hypotheses. First, it would be important to see that structured conditioning programmes would bring about more changes in biomotor

abilities and physiology than regular basketball training. Second, adding TRX suspension exercises to functional circuit training would elicit greater adaptations than functional circuit training alone. The present results are in favour of both hypotheses. The following significant Group $\times$ Time interactions were found: sprint speed, agility, countermovement-jump performance, body fat percentage, skeletal muscle mass, resting heart rate, and blood pressure. The magnitude of improvement was consistently in the following order: TRXG > FCG > CG, with the combined TRX suspension and functional circuit training programme being the most effective.

The enhanced sprint speed, agility, and explosive power of the intervention groups are in line with the physical demands of basketball as described in the introduction. During offensive and defensive movements in basketball, repeated acceleration, deceleration, multidirectional movements, and jumping are required (Scanlan et al., 2019; Stojanović et al., 2017). Functional circuit training can meet these demands by using multi-joint repetition, very quick transitions, using only one side of the body, jumping, and change of direction exercises. The superior results of the FCG compared with the control group are consistent with the previous findings that structured resistance and functional training can enhance speed, power, and movement performance in young athletes and basketball players (Cao et al., 2024; Lesinski et al., 2020).

The greater improvements observed in the TRXG may be associated with the additional postural and stabilization demands imposed by suspension-based exercises. During TRX movements, participants generated force while continuously controlling body position and balance. This training condition may increase the activation and coordination demands placed on the trunk and stabilizing muscles compared with similar exercises performed on stable surfaces (Aguilera-Castells et al., 2018; Bao et al., 2025). Greater stabilization demands could contribute to improved proximal control and coordinated force transmission during sprinting, jumping, and rapid changes of direction (Oliva-Lozano & Muyor, 2020). However, electromyographic

Table 4. Comparisons of changes in physiological variables among the TRX suspension combined with functional circuit training, functional circuit training, and control groups

Variables	Group	Mean $\pm$ SD Baseline	Mean $\pm$ SD After	Paired t-test p-value	MD (95% CI)	Main effect Group p (η^2)	Main effect Time p (η^2)	Interaction Group $\times$ Time p (η^2)
Body fat (%)	TRXG	13.46 $\pm$ 1.33	12.34 $\pm$ 1.34	<0.001	1.12 (0.94 to 1.30)	0.630 (0.02)	<0.001 (0.83)	<0.001 (0.75)
	FCG	13.06 $\pm$ 1.62	12.65 $\pm$ 1.57	<0.001	0.42 (0.33 to 0.50)			
	CG	12.54 $\pm$ 1.43	12.45 $\pm$ 1.41	<0.001	0.09 (0.06 to 0.11)			
Skeletal muscle mass (kg)	TRXG	32.82 $\pm$ 2.84	34.05 $\pm$ 2.99	<0.001	-1.24 (-1.45 to -1.02)	0.019 (0.13)	<0.001 (0.86)	<0.001 (0.71)
	FCG	31.09 $\pm$ 1.86	31.82 $\pm$ 1.89	<0.001	-0.73 (-0.82 to -0.64)			
	CG	33.36 $\pm$ 2.56	33.51 $\pm$ 2.59	<0.001	-0.15 (-0.20 to -0.10)			
Resting heart rate (bpm)	TRXG	64.35 $\pm$ 3.92	60.40 $\pm$ 3.50	<0.001	3.95 (3.21 to 4.69)	0.073 (0.09)	<0.001 (0.82)	<0.001 (0.64)
	FCG	65.70 $\pm$ 3.36	63.70 $\pm$ 3.29	<0.001	2.00 (1.63 to 2.37)			
	CG	63.15 $\pm$ 3.03	62.55 $\pm$ 2.98	<0.001	0.60 (0.36 to 0.84)			
Systolic blood pressure (mmHg)	TRXG	116.35 $\pm$ 3.69	111.15 $\pm$ 3.79	<0.001	5.20 (4.58 to 5.82)	0.189 (0.06)	<0.001 (0.89)	<0.001 (0.80)
	FCG	117.20 $\pm$ 5.55	114.75 $\pm$ 5.64	<0.001	2.45 (2.03 to 2.87)			
	CG	116.10 $\pm$ 3.14	115.55 $\pm$ 3.03	<0.001	0.55 (0.31 to 0.79)			
Diastolic blood pressure (mmHg)	TRXG	74.45 $\pm$ 3.30	70.60 $\pm$ 3.30	<0.001	3.85 (3.30 to 4.40)	0.873 (0.01)	<0.001 (0.85)	<0.001 (0.73)
	FCG	73.95 $\pm$ 3.89	72.05 $\pm$ 3.85	<0.001	1.90 (1.50 to 2.30)			
	CG	73.25 $\pm$ 3.49	72.85 $\pm$ 3.39	0.002	0.40 (0.16 to 0.64)			

Note. TRXG = TRX suspension combined with functional circuit training group; FCG = functional circuit training group; CG = control group; MD = mean pre-test minus post-test difference; CI = confidence interval; η^2 = partial eta squared; bpm = beats per minute. Positive mean differences for body fat, resting heart rate, and blood pressure indicate reductions. Negative mean differences for skeletal muscle mass indicate increases

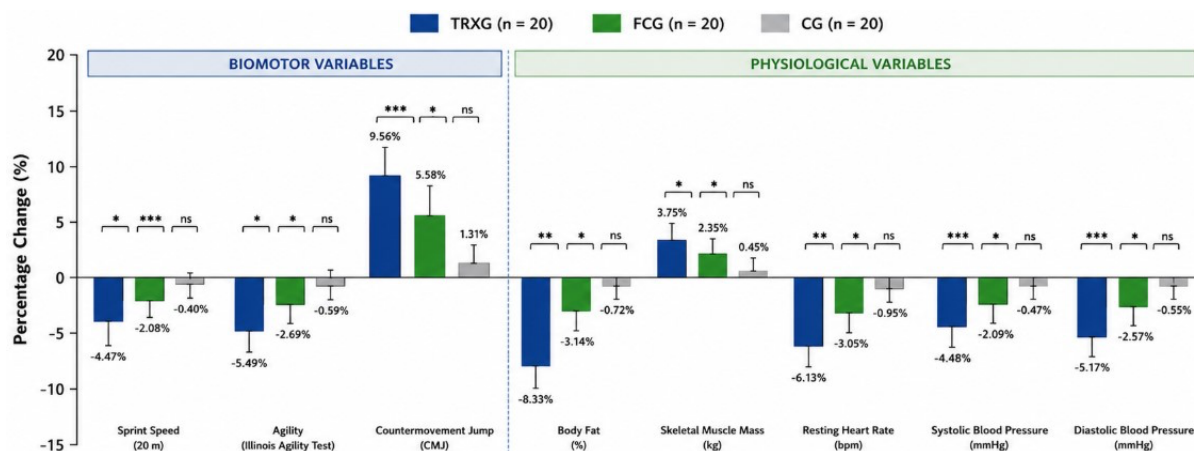


Fig. 2. Pre- and post-intervention percentage changes in biomotor and physiological outcome measures following the eight-week intervention

activity, postural control, muscle coordination, and force-transfer characteristics were not measured in the present study. These mechanisms should therefore be regarded as plausible explanations for the observed differences rather than effects demonstrated directly by the study.

Countermovement jump performance also improved most in the TRXG, followed by the FCG and the CG. Exercises such as squats, lunges, box jumps, and lateral bounds involve rapid hip, knee, and ankle extension and are directly associated with lower-body power development. These findings are consistent with previous evidence showing that appropriately prescribed resistance and functional training

can improve muscular power and jump performance in young athletes (Hind et al., 2020; Lesinski et al., 2020). The modest improvement observed in the control group may be attributable to regular basketball practice, normal growth and maturation, or increased familiarity with the jump test. The greater improvements observed in the intervention groups are consistent with an additional effect of structured conditioning beyond regular technical and tactical training.

The physiological findings further support the effectiveness of the interventions. The greater reduction in body fat percentage and the increase in skeletal muscle mass observed in the training groups are consistent with previous

evidence showing that resistance and functional training can improve body composition in children and adolescents (Lesinski et al., 2020; Liu et al., 2024). The multi-joint, stabilizing, and circuit-based components of the combined programme may have provided a greater training stimulus. However, these findings should be interpreted with caution because body composition was assessed using bioelectrical impedance analysis, which may be influenced by hydration status and other testing conditions despite standardized assessment procedures (Mao et al., 2023).

Resting heart rate and blood pressure also showed greater improvements in the intervention groups than in the control group. These adaptations are consistent with evidence that structured exercise may positively influence resting cardiovascular health and health-related fitness in youth (Guillem et al., 2020). The repeated muscular activity and limited recovery periods during the circuit sessions may have increased the cardiovascular demands of training. However, oxygen consumption, autonomic function, and vascular responses were not assessed; therefore, the physiological mechanisms underlying these adaptations remain unclear.

The agility findings are particularly relevant to the scientific problem identified in the Introduction. Most previous studies have investigated resistance training, functional training, or suspension training as independent interventions rather than evaluating their combined effects (Aguilera-Castells et al., 2018; Cao et al., 2024). Consequently, it remained unclear whether suspension-based exercises provided additional benefits when incorporated into an existing functional training programme. In the present study, the TRXG demonstrated greater improvements than the FCG despite identical training frequency, duration, progression, and perceived exercise intensity. These findings suggest that the unstable training environment and increased postural demands of the combined programme may induce adaptations beyond those achieved with functional exercises performed on stable surfaces (Zuo et al., 2022). Although the randomized controlled design supports causal inference for the intervention effects on the measured outcomes, the physiological and neuromuscular mechanisms responsible for these adaptations were not directly evaluated and therefore require confirmation in future mechanistic studies.

The active control design strengthened the interpretation of the findings. Compared with passive control groups, an active control better distinguishes intervention-specific effects from those attributable to normal basketball participation, growth, maturation, and repeated testing (Schulz et al., 2010). Participants in the control group continued their regular basketball training and showed only modest improvements over the 8-week intervention. These findings are consistent with an additional effect of structured functional conditioning beyond regular basketball practice (Lesinski et al., 2020).

The present study has several limitations. First, a formal a priori sample-size calculation was not performed, which may have reduced the precision of the estimated effects. Second, the findings are limited to male adolescent basketball players who completed an 8-week intervention, which may restrict the generalizability of the results. Third, body composition was assessed using bioelectrical impedance analysis, and physiological adaptations were evaluated using

resting cardiovascular measures only. Future studies should incorporate criterion body-composition techniques, direct physiological measurements, larger samples, longer follow-up periods, female athletes, and mechanistic assessments to strengthen the evidence and improve generalizability.

The findings suggest that functional circuit training is a practical conditioning approach for adolescent male basketball players. When TRX suspension equipment and qualified supervision are available, incorporating suspension exercises into a progressively structured functional circuit programme may provide additional improvements in sprint speed, agility, countermovement-jump performance, body composition, and resting cardiovascular measures over an 8-week training period. These recommendations are limited to the population, intervention duration, and outcomes evaluated in the present study. Coaches should emphasize correct movement technique before progressing to unilateral, unstable, or explosive exercises.

The main scientific contribution of this study was the direct comparison of combined TRX suspension and functional circuit training with functional circuit training alone and regular basketball practice. The consistent graded response observed across all measured outcomes suggests that incorporating suspension exercises into a structured functional training programme may provide additional benefits beyond functional circuit training alone. However, the physiological and neuromuscular mechanisms underlying these adaptations were not directly assessed and therefore require confirmation in future mechanistic studies. Future research should examine longer intervention periods, follow-up retention, maturation status, female athletes, and basketball-specific performance outcomes (e.g., repeated sprint ability and match performance). In addition, studies incorporating electromyography, force-time analysis, and direct physiological monitoring are needed to further elucidate the mechanisms underlying the observed adaptations.

Conclusion

The present study demonstrated that structured conditioning programmes produced greater improvements in biomotor abilities and physiological adaptations than regular basketball practice in adolescent male basketball players. The combined TRX suspension and functional circuit training programme resulted in the greatest improvements in sprint speed, agility, countermovement-jump performance, body fat percentage, skeletal muscle mass, resting heart rate, and blood pressure, whereas functional circuit training alone produced intermediate improvements. These findings suggest that functional circuit training is an effective conditioning approach for adolescent male basketball players and that incorporating TRX suspension exercises into a progressively structured and supervised programme may provide additional benefits. The conclusions are limited to the 8-week intervention, the male adolescent sample, and the outcomes measured in the present study.

Ethics Approval

The study protocol received approval from the Institutional Ethics Committee of Hindustan Institute of

Technology & Science, Chennai, India (Approval ID: HITS/CRC/004/22703049). All the procedures were carried out in adherence with the principles of the Declaration of Helsinki. All parents/legal guardians gave informed consent before participation in the study.

Data Availability Statement

All datasets have been analyzed during the present study and can be obtained from the corresponding author on reasonable request.

Conflicts of Interest

The authors have no conflicts of interest.

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AI Transparency Statement

The authors used AI-assisted tools for language editing and improving the clarity of the manuscript. The authors accept full responsibility for the accuracy, interpretation, and integrity of all scientific content in this manuscript.

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Вплив комбінованого тренування з використанням підвісних петель та функціонального колового тренування на біомоторні й фізіологічні адаптації баскетболістів підліткового віку

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

Реферат. Стаття: 10 с., 4 табл., 2 рис., 24 джерела.

Мета дослідження. Це дослідження мало на меті порівняти вплив 8-тижневої тренувальної інтервенції комбінованого тренування з використанням підвісних петель (TRX-тренування) та функціонального колового тренування, а також застосування виключно функціонального колового тренування та регулярної тренувальної практики з баскетболу, щодо біомоторних здібностей та фізіологічних адаптацій у баскетболістів підліткового віку.

Матеріали та методи. Загалом 60 баскетболістів підліткового віку чоловічої статі були розподілені за методом рандомізації на три групи: групу комбінованого тренування з використанням підвісних петель та функціонального колового тренування (TRXГ, n = 20), групу функціонального колового тренування (ФКГ, n = 20) та контрольну групу (КГ, n = 20). Тренування тривали 8 тижнів із періодичністю занять тричі на тиждень. На перед- та постінтервенційному етапах дослідження проведено вимірювання показників швидкості спринту, спритності, результативності стрибка з контрпрухом (КРС), відсотка жирової маси в організмі, скелетно-м'язової маси, частоти серцевих скорочень у стані спокою, а також систолічного і діастолічного артеріального тиску. Для статистичного аналізу даних використовувався метод змішаного дисперсійного аналізу з порівняннями Бонферроні.

Результати. Для всіх біомоторних та фізіологічних змінних було виявлено статистично значущу взаємодію факторів Група × Час (усі $p < .001$; часткова $\eta^2 = 0.64$ – 0.82). У TRXГ зафіксовано статистично значущо вищі показники покращення за всіма досліджуваними параметрами порівняно з учасниками ФКГ та КГ. Зокрема, великі ефекти взаємодії спостерігалися для показників спринту ($F(2.57) = 75.32$, $p < .001$, $\eta^2 = 0.73$), спритності ($\eta^2 = 0.82$), стрибка з контрпрухом ($\eta^2 = 0.78$), компонентного складу тіла, частоти серцевих скорочень у стані спокою та артеріального тиску.

Висновки. Отримані результати свідчать про те, що функціональне колове тренування підвищує біомоторні та фізіологічні параметри. Крім того, інтеграція вправ із використанням підвісних петель забезпечує вищі показники покращення, ніж застосування виключно функціонального колового тренування, та може створювати додаткові переваги за умови включення до прогресивно структурованої програми кондиційної підготовки під керівництвом тренера.

Ключові слова: баскетболісти підліткового віку, тренування з використанням підвісних петель, функціональне колове тренування, біомоторні здібності, фізіологічні адаптації, кондиційна підготовка.

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Assessing the Effects of Transition Small-Sided Game Format and Work-to-Rest Ratio on Training Load in Soccer Players

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Abstract

Background. Small-sided games (SSGs) are widely used in soccer training to simultaneously develop physical and physiological performance. However, transition-specific SSG formats combined with work-to-rest ratio manipulation may further influence training load, although their interactive effects remain unclear.

Objectives. This study aimed to examine the effects of transition small-sided game format and work-to-rest ratio on internal and external training load in university soccer players.

Materials and Methods. Eighteen male university soccer players participated in this study. Two transition game formats (3v3v3+2 and 3v3v3+2 Change) and four work-to-rest ratios (4:4, 4:2, 2:2, and 2:1) were applied. Internal load was assessed using heart rate responses, and external load was measured using Global Navigation Satellite System (GNSS) devices. A two-way repeated-measures ANOVA was used to analyze the data.

Results. Both the work-to-rest ratio and the playing format significantly affected internal load, with higher mean heart rate and greater time spent above 80% of HR under shorter recovery (4:2), as well as higher mean heart rate under the No-Change format overall. External load variables showed significant main and interaction effects, with the 2:2 ratio producing the highest total distance, acceleration, and deceleration, while and the 3v3v3+2 Change format combined with the 2:2 ratio eliciting the greatest high-intensity running and peak speed. Maximum heart rate indicated a significant Format × Work-to-Rest interaction, although no individual condition-pair comparison remained significant after Bonferroni correction.

Conclusions. The findings suggest that combining transition game format with an appropriate work-to-rest ratio can be used as an effective strategy for manipulating training loads in soccer players.

Keywords: external load, internal load, small-sided games, soccer, training load.

Introduction

Small-sided games (SSGs) are a fundamental component of contemporary soccer training because of their capacity to simultaneously develop physical, technical, and tactical attributes within sport-specific contexts (Nagy et al., 2020; Farhani et al., 2022). Unlike isolated conditioning drills, SSGs replicate the intermittent, unpredictable nature of competitive match play, making them an ecologically valid and time-efficient training tool (Chen et al., 2023; de Dios-Álvarez et al., 2024). As a result, SSGs are widely adopted

across elite and sub-elite levels to improve soccer-specific fitness while maintaining tactical relevance.

Training load during SSGs is highly sensitive to structural manipulations, including player number, pitch dimensions, bout duration, and work-to-rest ratio (Alcántara et al., 2021; Farhani et al., 2025), enabling coaches to selectively target physiological adaptations from aerobic capacity to high-intensity repeated-effort performance (Nagy et al., 2020; Farhani et al., 2022). Among these variables, work-to-rest ratio is particularly critical, as it governs recovery between bouts and determines the cumulative and peak demands placed on players. Beyond conventional SSG configurations, transitional moments the rapid shift between attacking and defending phases following a change in possession are among the most physically and tactically demanding phases of match play,

characterized by elevated high-speed running, accelerations, and cognitive load, often surpassing the demands recorded during sustained possession sequences (Bortnik et al., 2022, 2024). Physical demands during transitional play also differ across playing positions, highlighting the positional specificity required in training design (Bortnik et al., 2024).

In response, transition-specific SSG formats transition games have emerged as a targeted training modality. Asian-Clemente et al. (2022) demonstrated that transition games can elicit high-speed running volumes comparable to competition, suggesting their potential to replicate worst-case match demands, and varying player number within transition games substantially modulates physical loading (Asian-Clemente et al., 2024a), while conventional SSGs may not consistently replicate the most extreme physical scenarios experienced in match play (de Dios-Álvarez et al., 2024).

Despite growing interest in transition game formats and the well-established influence of work-to-rest manipulation on training load in conventional SSGs, the interaction between these two variables remains insufficiently examined, and no study has systematically investigated how different transition game formats combined with varying work-to-rest ratios affect overall training load in soccer players. This gap limits practitioners' ability to make evidence-based decisions when designing sessions intended to replicate the physiological demands of competitive transitions. Therefore, the purpose of this study was to examine the effects of transition game format and work-to-rest ratio on training load in small-sided soccer games, to provide practical recommendations for optimizing the specificity and effectiveness of soccer conditioning programs.

Materials and Methods

Participants

Eighteen male university soccer players participated in this study (age: 19.6 ± 0.69 years; body mass: 65.07 ± 8.51 kg; height: 173.61 ± 7.36 cm; body mass index: 21.3 ± 2.03 kg·m⁻²; body fat: $13.23 \pm 3.94\%$; VO₂max: 50.94 ± 2.58 mL·kg⁻¹·min⁻¹). All participants were healthy, had at least 5 years of competitive soccer experience at the high school or university level, and trained at least 5 days per week; goalkeepers, injured players, and those unable to complete the protocol were excluded. Participants were recruited using purposive sampling. All players completed the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) to estimate VO₂max, calculated using the equation of Karakoç et al. (2012): $VO_{2\max} (\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = \text{distance (m)} \times 0.0084 + 36.4$. Based on performance ranking, the top 22 players were selected; 18 were randomly assigned into six groups of three, while the remaining four (ranked 19–22) acted as neutral players during the games but were not included in the analysis. Group allocation ensured no significant baseline differences between groups. All participants provided written informed consent, and the study was approved by the Ethics Committee of Kasem Bundit University, Thailand (KBU-HREC 009/69), in accordance with the Declaration of Helsinki.

Procedure

On each experimental day, participants drew lots to determine the SSG format and work-to-rest ratio to be

completed; the order of all eight experimental conditions (two SSG formats $\times$ four work-to-rest ratios) was fully randomized for each participant to control for potential order effects. All sessions began with a standardized 15-minute warm-up (5 min light jogging, 8 min dynamic stretching, and 2 min neuromuscular activation comprising three 10-m maximal sprints; Eniseler et al., 2017). Both formats were played as 3v3v3+2 on a 55 $\times$ 20-m pitch (~ 100 m² per player), following prior recommendations (Dimitriadis et al., 2022).

In the transition SSG without spatial change (3v3v3+2), players were divided into three colour-coded teams of three; two teams collaborated to maintain possession while the third defended and attempted to regain the ball, transferring it to the non-possessioning team before transitioning to attack, while the team losing the ball immediately assumed the defensive role. In the transition SSG with spatial change (3v3v3+2 Change), the possessing team was required to complete seven consecutive passes before transferring the ball to the opposite zone; if the defending team intercepted or dispossessed the attackers, they transferred the ball to the far zone, and the team losing possession transitioned to defense (Figure 1).

In both formats, two neutral players (floaters) supported the attacking team (Clemente, 2022). Unlimited ball touches were permitted, and a replacement ball was reintroduced immediately whenever the ball left play, with consistent verbal encouragement from coaches throughout.

The work-to-rest ratios applied were 1:1 and 1:0.5. Under 1:1, participants completed either four 4-minute sets with 4-minute recovery, or eight 2-minute sets with 2-minute recovery; under 1:0.5, participants completed either four 4-minute sets with 2-minute recovery, or eight 2-minute sets with 1-minute recovery (Clemente, 2022). Immediately following each session, heart rate (HR) responses and locomotor data were recorded. HR variables included peak HR, mean HR, and time spent in the 70–79%, 80–89%, and 90–100% HRmax zones (Nagy et al., 2020). Locomotor variables comprised total distance, high-speed running (>19.8 km·h⁻¹), sprint distance (>25.2 km·h⁻¹), peak speed, and the number of accelerations and decelerations (>2.5 m·s⁻²) (Beato et al., 2023). Sessions were conducted between 16:00–18:00 h at 30–33°C ambient temperature, with a minimum 48-hour washout period between sessions (Papanikolaou et al., 2021).

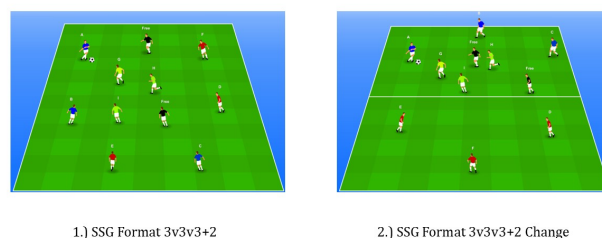


Fig. 1. SSG Transition Format Training (3v3v3+2).

Instrument

Internal training load was assessed via HR responses using a Polar H10 chest strap (Polar Electro Oy, Kempele, Finland), a device with demonstrated validity and reliability at rest and during incremental exercise (Schaffarczyk et al.,

2022). HRmax, HRmean, and the percentage of time spent in the 70–79% (moderate), 80–89% (high), and 90–100% (very high) HRmax zones were extracted, consistent with classification frameworks applied in SSG research (Nagy et al., 2020a). Individual HRmax was estimated using the age-predicted formula ($220 - \text{age in years}$), given the impracticality of maximal exercise testing within this field-based training protocol.

External load was quantified using 10 Hz global navigation satellite system (GNSS) units (PlayerData Edge, Scotland; Wilmot et al., 2025); each participant was assigned the same device throughout the study, in line with recommended GNSS measurement practice for team sports (Bataller-Cervero et al., 2019; Beato et al., 2018). Devices were activated at least 15 minutes before each session, and data collection began only when a minimum of eight satellites and a horizontal dilution of precision (HDOP) value below 1.0 were confirmed, in line with recommended GNSS data-quality procedures (Malone et al., 2017). Units were secured in a custom-fitted vest between the scapulae, and raw data were downloaded and processed immediately after each session by a qualified sports scientist. The external load variables analyzed were total distance, high-intensity running distance (HIR; $>19.8 \text{ km}\cdot\text{h}^{-1}$), sprint distance (SPR; $>25.2 \text{ km}\cdot\text{h}^{-1}$), peak speed, accelerations (ACC; $>2.5 \text{ m}\cdot\text{s}^{-2}$), and decelerations (DEC; $>2.5 \text{ m}\cdot\text{s}^{-2}$), among the most commonly reported indicators of physical demand in SSG and match-play contexts (Beato et al., 2023).

Data Analysis

All data are presented as mean $\pm$ standard deviation (SD). A two-way repeated-measures ANOVA examined the main effects of playing format (3v3v3+2 vs. 3v3v3+2 Change) and work-to-rest condition (4:4, 4:2, 2:2, and 2:1) as within-subject factors, and their interaction, on all internal and external load variables. Normality was verified using the Shapiro–Wilk test, and sphericity was assessed using Mauchly’s test, with the Greenhouse–Geisser correction applied where violated. Significant effects were followed by Bonferroni-adjusted post hoc comparisons. Effect sizes were reported as partial eta squared (η^2p) and interpreted as small (≥ 0.01), moderate (≥ 0.06), and large (≥ 0.14). Statistical significance was set at $p < 0.05$. All analyses were performed

using Jamovi (version 2.6.17; The Jamovi Project, Sydney, Australia). A priori sample size estimation was performed using G*Power (version 3.1; Faul et al., 2007), specifying an effect size of 1.1, $\alpha = 0.05$, and power ($1 - \beta$) = 0.95, which indicated a minimum required sample of 16 participants; allowing for an anticipated attrition rate of 10%, 22 players were recruited, of whom 18 were retained for the final analysis after ranking on YYIR1-derived VO2max.

Results

Internal and external load values following the SSG sessions are presented in Table 1 and Table 2. The two-way repeated-measures ANOVA results, separated into the main effect of format, the main effect of work-to-rest ratio, and their interaction, are reported for each variable in Table 3 (internal load) and Table 4 (external load).

indicating similar peak cardiovascular responses. HRmean differed significantly ($150.67\text{--}165.44 \text{ bpm}$; $p = .027$; $\eta^2p = 0.168$), with higher values under shorter recovery (4:2 and 2:1), particularly in the 3v3v3+2 format ($165.44 \pm 11.73 \text{ bpm}$ at 2:1). %HRmean showed a similar trend but did not reach significance ($75.67\text{--}83.00\%$; $p = .063$; $\eta^2p = 0.164$). Time at 80%HR differed significantly ($31.67\text{--}49.67 \text{ min}$; $p = .016$; $\eta^2p = 0.162$), with greater exposure under reduced recovery, while 70%HR ($p = .224$) and 90%HR ($p = .164$) did not differ significantly. Overall, reducing recovery duration increased mean physiological load and time at high intensity, with large effect sizes ($\eta^2p \geq 0.14$).

In the Change condition ($6.42 \pm 0.54 \text{ m}\cdot\text{s}^{-1}$). Acceleration ($17.00\text{--}26.44$; $p = .004$; $\eta^2p = 0.232$) and deceleration ($20.44\text{--}30.89$; $p = .001$; $\eta^2p = 0.233$) were also highest at 2:2. Sprint distance differed significantly overall ($0.00\text{--}2.44 \text{ m}$; $p = .025$; $\eta^2p = 0.123$), though no pairwise comparisons survived Bonferroni correction. Overall, the 2:2 work-to-rest ratio elicited the greatest total distance regardless of format, whereas the 3v3v3+2 Change format combined with 2:2 produced the greatest high-intensity running, peak speed, and deceleration count; effect sizes were moderate for sprint distance ($\eta^2p = 0.123$) and large for all other variables ($\eta^2p = 0.232\text{--}0.818$).

Post hoc comparisons (Bonferroni-adjusted) further clarify these separated effects. For HRmean, values were higher under 4:2 than 4:4 (mean difference [MD] = -12.67 bpm ; $p < .001$), and higher under the No-Change format than

Table 1. Internal loads during different SSG formats

Variable	Small-Sided Game Formats (n=18)				Small-Sided Game Formats (n=18)				F ¹	p ¹	η ² p ¹
	3v3v3+2				3v3v3+2 Change						
	4:4	4:2	2:2	2:1	4:4	4:2	2:2	2:1			
HRmax (bpm)	182.11±7.46	183.78±6.19	185.67±5.45	184.00±6.58	185.67±10.40	180.44±9.69	177.56±8.77	182.89±9.66	1.95	0.119	0.103
%HRmax	91.22±3.84	92.22±3.02	93.11±2.81	92.22±3.25	93.11±5.21	90.33±4.90	89.00±4.42	91.67±4.45	2.13	0.092	0.111
HRmean (bpm)	151.67±9.36	164.33±8.80*	155.56±13.01	165.44±11.73*	150.67±13.66	159.22±12.20	151.33±9.09	151.00±11.73	3.44	0.027	0.168
%HRmean	75.78±4.62	82.33±4.34*	78.00±6.53	83.00±5.94*	75.67±6.81	79.78±6.30	76.00±4.55	82.56±5.94	3.35	0.063	0.164
70%HR (%)	27.00±10.14	21.78±8.36	28.89±7.83	22.44±16.96	25.33±7.31	25.11±13.49	31.44±9.69	26.33±12.28	1.49	0.224	0.081
80%HR (%)	36.00±11.19	49.67±16.34*	36.33±13.00	47.11±17.70*	31.67±14.71	43.11±19.22	35.22±11.85	48.44±24.50*	3.28	0.016	0.162
90%HR (%)	6.44±12.88	17.67±22.92	11.78±16.43	21.78±25.35	10.56±18.46	13.89±25.97	4.78±13.55	11.22±10.25	1.69	0.164	0.091

* Significant difference compared with 3v3v3+2 (4:4) ($p < 0.05$).

Table 2. External loads during different SSG formats

Variable	Small-Sided Game Formats (n=18)				Small-Sided Game Formats (n=18)				F ¹	p ¹	η ² p ¹
	3v3v3+2				3v3v3+2 Change						
	4:4	4:2	2:2	2:1	4:4	4:2	2:2	2:1			
Total Distance (m)	2197±261	2003±207*	2382±233 #	2214±270	2134±304	1892±121*	2132±270 #	1838±254*	76.6	<.001	0.818
High Intensity (m)	18.89±16.49	5.56±14.77*	18.89±16.83	18.78±15.73	47.56±67.17*	13.56±27.65	104.67±88.75*	11.56±11.47	10.2	<.001	0.375
Sprint (m)	0	0.56±1.62	0	1.33±3.88	0.67±1.94	0	2.44±4.73	0	2.39	0.025	0.123
Max Speed (m/s)	5.99±0.41	5.48±0.69*	5.99±0.41	5.99±0.76	6.06±0.65	5.51±0.45*	6.42±0.54 #	5.52±0.49*	6.25	<.001	0.269
ACC (n)	25.33±6.54	21.22±6.19	25.44±4.95	21.78±8.92	20.56±7.67	18.89±4.79*	26.44±3.63	17.00±5.09*	5.13	0.004	0.232
DEC (n)	24.89±7.78	20.44±10.01	27.11±7.98	22.78±10.80	23.78±7.73	24.67±6.04	30.89±8.05 #	20.44±6.55	5.16	0.001	0.233

* Significant difference compared with 3v3v3+2 (4:4) (p < 0.05). # Significant difference compared with 3v3v3+2 (4:2) (p < 0.05).

Table 3. Two-way repeated-measures ANOVA results for internal load variables (main effects and interaction).

Variable	Format (3v3v3+2 vs. Change)			Work-to-Rest Ratio			Format × Work-to-Rest		
	F	p	η^2p	F	p	η^2p	F	p	η^2p
HRmax (bpm)	1.846	0.192	0.098	0.666	0.577	0.038	3.252	0.029	0.161
%HRmax	1.882	0.188	0.100	0.678	0.569	0.038	3.668	0.018	0.177
HRmean (bpm)	5.61	0.030	0.248	3.81	0.015	0.183	1.85	0.150	0.098
%HRmean	0.041	0.843	0.002	7.217	<.001	0.298	1.16	0.334	0.064
70%HR (%)	0.705	0.413	0.040	2.508	0.069	0.129	0.654	0.584	0.037
80%HR (%)	1.101	0.309	0.061	7.349	<.001	0.302	0.373	0.773	0.021
90%HR (%)	1.77	0.201	0.094	2.08	0.114	0.109	1.2	0.319	0.066

df = 1, 17 for the main effect of Format; df = 3, 51 for the main effect of Work-to-Rest ratio and for the Format × Work-to-Rest interaction. F and p values are as computed in the two-way repeated-measures ANOVA (Type III sums of squares); η^2p (partial eta squared) was derived from F and the corresponding degrees of freedom. Bonferroni-adjusted post hoc comparisons for each significant effect are described in the Results text.

Table 4. Two-way repeated-measures ANOVA results for external load variables (main effects and interaction).

Variable	Format (3v3v3+2 vs. Change)			Work-to-Rest Ratio			Format × Work-to-Rest		
	F	p	η^2p	F	p	η^2p	F	p	η^2p
Total Distance (m)	213	<.001	0.926	65.4	<.001	0.794	37.6	<.001	0.689
High Intensity (m)	14.99	0.001	0.469	9.97	<.001	0.370	8.64	<.001	0.337
Sprint (m)	0.525	0.479	0.030	1.091	0.361	0.060	4.721	0.013	0.217
Max Speed (m/s)	0.028	0.868	0.002	8.293	<.001	0.328	5.682	0.002	0.251
ACC (n)	8.73	0.009	0.339	8.16	<.001	0.324	1.54	0.215	0.083
DEC (n)	1.06	0.318	0.059	13.59	<.001	0.444	1.85	0.150	0.098

df = 1, 17 for the main effect of Format; df = 3, 51 for the main effect of Work-to-Rest ratio and for the Format × Work-to-Rest interaction, except the Sprint distance × interaction term, for which Mauchly's test indicated a sphericity violation and the reported p value reflects the Greenhouse–Geisser correction (F and η^2p are unaffected by this correction). Bonferroni-adjusted post hoc comparisons for each significant effect are described in the Results text.

the Change format overall (MD = 6.19 bpm; p = .030). For %HRmean, 4:2 exceeded 4:4 (MD = -6.56%; p < .001). For time at 80%HR, 4:2 exceeded both 4:4 (MD = -12.56%; p = .002) and 2:2 (MD = 10.61%; p = .034). For HRmax and %HRmax, although the Format × Work-to-Rest interaction reached significance (Table 3), no individual pairwise comparison survived Bonferroni correction (all p ≥ .109), indicating a diffuse rather than localized interaction pattern.

Post hoc comparisons (Bonferroni-adjusted) show that total distance was higher under the No-Change format than the Change format overall (MD = 200 m; p < .001), and the Format × Work-to-Rest interaction was driven primarily by the 2:2 conditions in both formats, which exceeded most other combinations (all p ≤ .018). High-intensity running distance was higher under the Change format overall (MD = -28.8 m; p = .001), and the interaction was

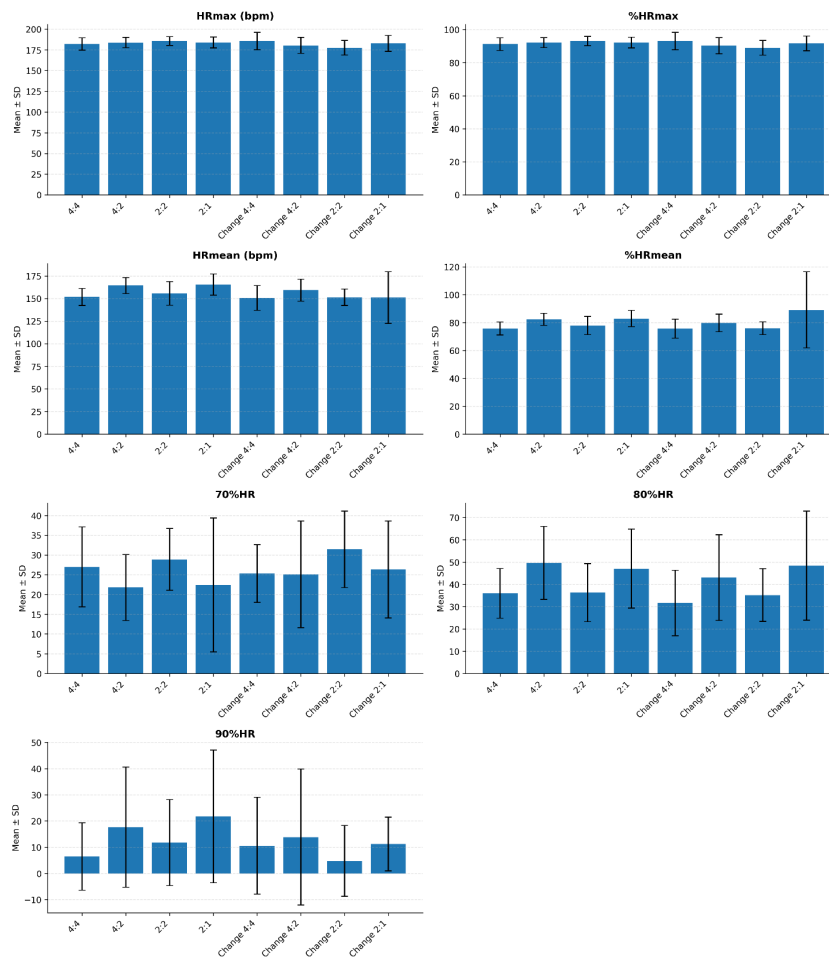


Fig. 2. Internal load responses across SSG formats.

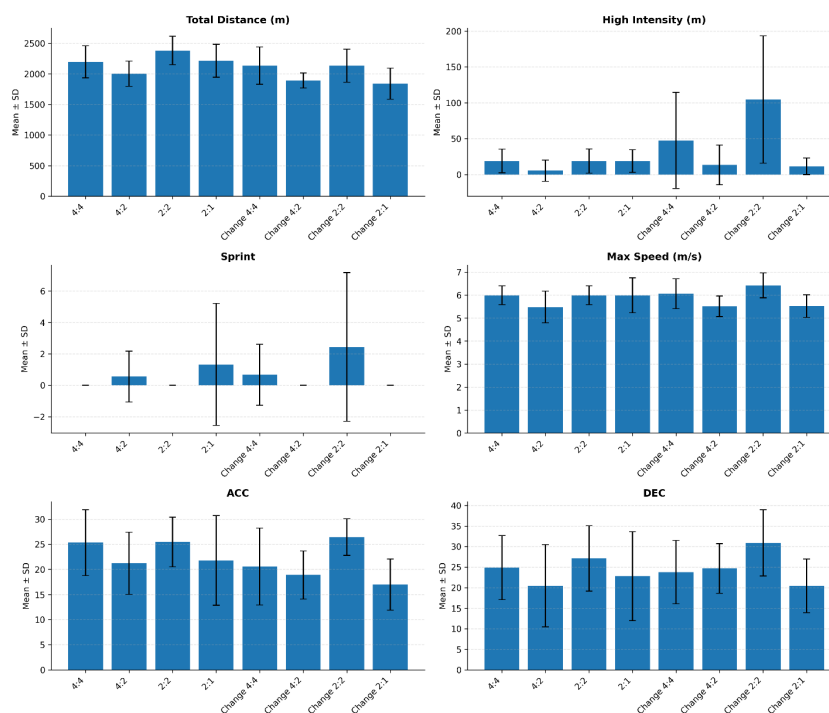


Fig. 3. External load responses across SSG formats.

driven by the Change-format 2:2 condition, which exceeded every other combination (all $p \leq .045$). Maximum speed showed a comparable pattern, with the Change-format 2:2 condition exceeding the other Change-format conditions (all $p \leq .047$). Regarding sprint distance, cross-checking the Format $\times$ Work-to-Rest interaction term against the authors' original Jamovi statistical output identified a discrepancy: the summary report had listed $p = .115$ for this term, but the native output shows $F = 4.721$, $p = .013$ (Greenhouse-Geisser-corrected for a sphericity violation), which is significant. Table 4 and this response have been corrected accordingly. As with HRmax and %HRmax above, no individual pairwise comparison for this interaction survived Bonferroni correction (all $p = 1.000$), so the significant interaction should be interpreted as a diffuse pattern across conditions rather than attributable to any single condition pair.

Figure 2 illustrates the internal load responses across SSG formats and work-to-rest conditions. HRmax and %HRmax remain relatively stable across all conditions, supporting the absence of significant differences, whereas HRmean (≈ 150 – 165 bpm) and %HRmean (≈ 75 – 83%) increase under shorter recovery (4:2 and 2:1), reflecting greater accumulated physiological stress; time spent at 80%HR shows a similar increase under reduced recovery, consistent with the moderate effect sizes observed statistically.

Figure 3 shows that total distance peaks in the 2:2 condition (≈ 2382 m), while high-intensity running is markedly higher in the transition format with spatial change (≈ 104.67 m); max speed is also greatest in this condition (≈ 6.42 m·s⁻¹). Acceleration (≈ 26.44) and deceleration (≈ 30.89) are consistently elevated at 2:2, indicating greater movement demands, while sprint distance remains low (0– 2.44 m) and variable across conditions. Overall, the graphical trends support the statistical findings, showing that transition-based SSGs combined with a 2:2 work-to-rest ratio impose the highest physical demands.

Discussion

The present study examined the effects of transition SSG format and work-to-rest ratio on internal and external training load in university-level soccer players. Three principal findings emerged: (1) work-to-rest ratio significantly elevated HRmean and the percentage of time at 80–89% HRmax under shorter recovery (4:2 and 2:1); (2) the 3v3v3+2 Change format with 2:2 work-to-rest elicited the greatest high-intensity running, peak speed, and neuromuscular demands; and (3) HRmax and %HRmax were unaffected by format or recovery manipulation.

The absence of significant differences in HRmax and %HRmax aligns with the well-established capacity of SSGs to elicit near-maximal cardiac responses regardless of structural manipulation. Köklü et al. (2017) reported that HRmax was unaffected by bout duration in young soccer players, and Farhani et al. (2022) similarly found no format effect on peak HR when varying bout duration and player number, confirming that both transition formats used here are physiologically demanding at the upper end of the cardiovascular spectrum, even under varying recovery durations. In contrast, HRmean and time at 80–89% HRmax were significantly elevated under reduced recovery,

indicating that inter-bout rest duration is the primary driver of sustained cardiovascular strain. Branquinho et al. (2021) similarly found that shorter recovery produced higher HRmean, attributing this to incomplete physiological restoration between bouts, while de Dios-Álvarez et al. (2023) reported that 1-minute recovery increased RPE and attenuated locomotor quality, whereas 2-minute recovery better balanced cardiovascular intensity with movement output. The large effect sizes observed here for HRmean ($\eta^2 p = 0.168$) and the 80%HR zone ($\eta^2 p = 0.162$) are consistent with these reports and indicate that recovery duration can serve as a practical load-adjustment tool without changing the playing format.

Regarding external load, total distance was most strongly influenced by work-to-rest ratio ($\eta^2 p = 0.818$), with the 2:2 condition producing the highest locomotor output across both formats, indicating that recovery duration is the dominant variable governing total movement volume, outweighing the influence of game format. Alcántara et al. (2021) reported comparable findings in youth players, showing that proportionate recovery intervals preserved locomotor output per bout while reducing the rest-to-work ratio progressively diminished total distance; de Dios-Álvarez et al. (2023) further confirmed that a 2-minute recovery optimized the balance between total distance and neuromuscular quality, paralleling the superior locomotor output observed under the 2:2 condition here. The reduced total distance under the 4:2 and 2:1 condition likely reflects fatigue-induced movement suppression when phosphocreatine replenishment and metabolic clearance are insufficient between bouts (Kryściak et al., 2023).

The markedly elevated high-intensity running distance in the 3v3v3+2 Change format under the 2:2 condition (104.67 ± 88.75 m) is the most practically distinctive finding of this study: the spatial transfer requirement completing seven passes before switching zones creates directional running corridors that replicate the locomotor structure of counter-attacking transitions in match play. Asian-Clemente et al. (2023) found that larger transition game formats generated significantly greater high-speed running and peak speed than smaller configurations, attributing this to the spatial demands of positional recovery after each transition, and Asian-Clemente et al. (2024b) similarly demonstrated that transition games produced greater distances above 21 km·h⁻¹ and more high-intensity mechanical actions than official matches. The high inter-individual variability ($SD = 88.75$ m) likely reflects positional differences in transitional movement strategy, consistent with evidence that full backs and strikers cover greater high-speed distances than midfielders during transitions (Bortnik et al., 2022). The near-zero sprint distances across all conditions (0.00– 2.44 m) reflect the recognized limitation of small-format SSGs in generating true sprint velocities above 25 km·h⁻¹, given the pitch-space constraints inherent in 3v3v3+2 designs (Gualtieri et al., 2023).

Acceleration and deceleration counts were highest under the 2:2 condition, with the Change format producing the greatest neuromuscular demands overall. Kryściak et al. (2023) demonstrated that short-bout SSG training elicited significant acid-base balance alterations in youth players, reflecting the repeated acceleration–deceleration cycles that stress anaerobic energy systems and neuromuscular tissue.

The significant reduction in ACC and DEC under the 2:1 condition, despite its short bout duration, demonstrates that excessively compressed recovery impairs explosive mechanical output a dissociation that is practically important, since the 2:1 condition maintained high HRmean yet compromised neuromuscular quality, producing cardiovascular overload without a corresponding mechanical training stimulus. Peak speed followed the same pattern, with the Change 2:2 condition generating the highest values ($6.42 \pm 0.54 \text{ m}\cdot\text{s}^{-1} \approx 23.1 \text{ km}\cdot\text{h}^{-1}$), approaching the high-speed running threshold used in elite match analyses, while the 4:2 condition consistently produced the lowest values across both formats (McLean et al., 2016; Köklü et al., 2017).

From a practical standpoint, when the primary objective is to maximize aerobic intensity and time at high HR zones, the 4:2 or 2:1 work-to-rest conditions are most appropriate; when the goal is to optimize high-speed locomotor output, peak speed, and neuromuscular loading, the 3v3v3+2 Change format with 2:2 work-to-rest is recommended. Farhani et al. (2025) emphasized that SSG bout structure must simultaneously address physiological and technical-tactical objectives, while Branquinho et al. (2021) highlighted that work-to-rest ratio manipulation is an accessible and logistically uncomplicated load-management strategy. Collectively, these findings reinforce the position that work-to-rest ratio deserves priority as a programming parameter alongside pitch size and player number (Alcántara et al., 2021; de Dios-Álvarez et al., 2023; Köklü et al., 2017), and that transition-specific SSG formats provide a complementary tool for overloading high-speed demands that possession-based SSGs may systematically underexpose.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, although the sample size ($n = 18$) exceeded the a priori target established via G*Power (16 participants), the sample remained relatively small and comprised a single cohort, which may still limit the detection of smaller effects for some variables. Second, participants were exclusively male university-level players; the findings may not generalize to female players, youth athletes, or players competing at higher (professional/elite) or lower competitive levels. Third, although the order of the eight experimental conditions was fully randomized for each participant to minimize order effects, cumulative fatigue across repeated sessions cannot be entirely excluded. Fourth, some GNSS-derived external-load variables, particularly high-intensity running distance (SD up to 88.75 m) and sprint distance, showed high inter-individual variability, likely reflecting positional differences in movement behaviour, and should be interpreted with caution. Future studies should include larger and more diverse samples, including female and multi-level cohorts, to confirm the generalizability of these findings.

Conclusions

The present study demonstrated that both transition game format and work-to-rest ratio significantly influenced training load responses during small-sided soccer games. Shorter recovery conditions (4:2 and 2:1) increased internal

load, as evidenced by higher HRmean values and greater time in high-intensity heart rate zones, indicating elevated accumulated cardiovascular stress. In contrast, the 2:2 work-to-rest ratio elicited the highest external load overall: total distance was greatest under the 3v3v3+2 (non-Change) format at 2:2, whereas the 3v3v3+2 Change format combined with 2:2 produced the greatest high-intensity running, peak speed, and neuromuscular demands (accelerations and decelerations). These findings suggest that work-to-rest ratio primarily modulated internal load, while transition-based game formats were more effective in increasing external load, especially high-speed and explosive actions; peak heart rate responses remained stable across all conditions, indicating that SSGs consistently provide a near-maximal cardiovascular stimulus regardless of structural manipulation.

This study contributes novel evidence on the combined effects of transition game formats and work-to-rest ratios, an area that has been insufficiently explored. The results offer practical implications for coaches: shorter recovery durations can be used to increase aerobic and cardiovascular stress, whereas transition formats combined with balanced recovery (2:2) are more suitable for developing high-intensity locomotor and neuromuscular performance. Future research should investigate the long-term adaptations to these training configurations, as well as their effects across different playing levels, positional roles, and competitive contexts, to further optimize the design of soccer-specific conditioning programs.

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Ethics Approval

This study was approved by the Ethics Committee of Kasem Bundit University, Thailand (KBU-HREC 009/69), and was conducted in accordance with the Declaration of Helsinki.

Informed Consent Statement

All participants were informed about the study procedures prior to participation, and written informed consent was obtained from all participants.

Data Availability Statement

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

AI Transparency Statement

The authors declare that artificial intelligence (AI)-assisted tools were used exclusively to improve the linguistic quality, grammar, readability, and formatting of the manuscript. AI tools were not used to generate, analyze, interpret, or manipulate the research data, statistical analyses, results, or scientific conclusions.

Conflicts of Interest

The authors declare no conflicts of interest.

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Оцінювання впливу формату перехідних ігор неповними складами та співвідношення режимів вправ і відпочинку на тренувальне навантаження у футболістів

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

Реферат. Стаття: 10 с., 4 табл., 3 рис., 30 джерел.

Обґрунтування. Ігри неповними складами (ІНС) широко використовуються у тренувальному процесі футболістів для одночасного розвитку фізичних та фізіологічних показників. Проте специфічні формати перехідних ігор неповними складами у поєднанні з маніпулюванням співвідношення режимів вправ і відпочинку можуть додатково впливати на тренувальне навантаження, хоча їхній ефект взаємодії залишається малодослідженим.

Мета дослідження. Мета цього дослідження полягала у вивченні впливу формату перехідних ігор неповними складами та співвідношення режимів вправ і відпочинку на внутрішнє та зовнішнє тренувальне навантаження футболістів університетських команд.

Матеріали та методи. У дослідженні взяли участь 18 футболістів чоловічої статі університетських команд. Було застосовано два формати перехідних ігор (3v3v3+2 та 3v3v3+2 зміна) та чотири режими співвідношення вправ і відпочинку (4:4, 4:2, 2:2 та 2:1). Внутрішнє навантаження оцінювали за показниками частоти серцевих скорочень (ЧСС), а зовнішнє навантаження вимірювали за допомогою пристроїв Глобальної навігаційної супутникової системи (GNSS). Для аналізу даних використовували двофакторний дисперсійний аналіз із повторними вимірюваннями.

Результати. Як співвідношення режимів вправ і відпочинку, так і формат гри суттєво впливали на внутрішнє навантаження: вища середня частота серцевих скорочень (ЧСС) та більша кількість часу, проведеного вище порогу 80% від

ЧСС, спостерігалися за умов коротшого відпочинку (4:2), а також вища середня ЧСС зафіксована загалом для формату без змін. Показники зовнішнього навантаження продемонстрували значні головні ефекти та ефекти взаємодії: співвідношення 2:2 забезпечило найбільшу загальну дистанцію, кількість прискорень та сповільнень, тоді як формат 3v3v3+2 зі зміною у поєднанні зі співвідношенням 2:2 викликав найвищу інтенсивність бігу та пікову швидкість. Максимальна ЧСС продемонструвала значну взаємодію факторів Формат × Вправи-Відпочинок, хоча жодне індивідуальне попарне порівняння умов не залишилося статистично значущим після застосування поправки Бонферроні.

Висновки. Отримані результати свідчать про те, що поєднання формату перехідних ігор із належним співвідношенням режимів вправ і відпочинку можна використовувати як ефективну стратегію для регулювання тренувальних навантажень у футболістів.

Ключові слова: зовнішнє навантаження, внутрішнє навантаження, ігри неповними складами, футбол, тренувальне навантаження.

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Static and Dynamic Yoga Asanas vs Combined Yoga: Which is More Effective for Enhancing Flexibility and Balance in Perimenopausal Women?

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Abstract

Background. Perimenopause is often accompanied by declines in flexibility and balance, increasing the risk of falls and reducing quality of life. Static and dynamic yoga are each linked to gains in flexibility and postural stability, but no study has directly compared static, dynamic, and combined yoga to determine which approach most effectively improves these outcomes in perimenopausal women.

Objectives. This study aimed to evaluate the effects of static, dynamic, and combined yoga practices on flexibility and balance in perimenopausal women.

Materials and Methods. A three-arm randomized controlled trial allocated 36 perimenopausal women (1:1:1) to static, dynamic, or combined yoga, delivered over six weeks (two 50-minute sessions per week). Flexibility was measured with the sit-and-reach test (cm). Balance was measured with a timed beam-crossing test: participants crossed a 2.5 m wooden beam at a self-selected pace, and crossing time (s; 60-second cap) was converted to a balance score (60 – crossing time, in seconds); higher scores indicated better balance. The primary analysis was ANCOVA on post-test scores, controlling for baseline (pre-test) values.

Results. Groups were equivalent at baseline (both $p > 0.19$). After controlling for baseline scores (ANCOVA), the combined group showed significantly greater post-intervention flexibility and balance than the static group (both $p \leq 0.001$) and the dynamic group (flexibility, $p = 0.007$; balance, $p < 0.001$). No significant difference was observed between static and dynamic yoga for either outcome (flexibility, $p = 0.34$; balance, $p > 0.99$; Bonferroni-adjusted); given the small per-group sample ($n = 12$), the study was underpowered to detect this contrast, and equivalence should not be inferred.

Conclusions. Combined static-dynamic yoga produced greater gains in flexibility and balance than either modality alone in perimenopausal women. These findings suggest that combined yoga programs are a promising non-pharmacological option for community-based physical activity strategies in this population; effects on fall incidence and quality of life were not directly assessed and warrant dedicated future study.

Keywords: menopause transition, women's health, quality of life, physical function.

Introduction

Perimenopause is a period of hormonal fluctuation associated with declines in musculoskeletal flexibility and postural balance, which increase fall risk and reduce quality of life (Iwanowicz-Palus et al., 2019). Because

these declines are potentially modifiable, physical activity interventions delivered during this transition may help preserve functional capacity and independence (Martin-Key et al., 2023). Establishing which forms of exercise most effectively improve flexibility and balance in this population is therefore a clinically relevant problem, not only a general wellness question.

Yoga is a low-cost, accessible intervention with reported benefits for flexibility and postural stability across age groups (Gothe & McAuley, 2016; Krejčí et al., 2022). Static

asanas rely on sustained postural holds thought to lengthen muscle-tendon units and reinforce isometric postural control, whereas dynamic asanas use continuous, flowing movement thought to train coordination and dynamic balance through repeated joint excursions (Mancapara, 2020). Because these two modalities plausibly act through different mechanisms, combining them has been proposed to produce complementary, additive benefits (Khajuria et al., 2023). However, existing studies have generally tested a single yoga modality against a non-yoga control or no intervention, rather than comparing static, dynamic, and combined regimens against one another (Cramer et al., 2012; Wang et al., 2020).

Consequently, it remains unclear whether combining static and dynamic elements yields greater gains in flexibility and balance than either modality practiced alone, or whether the two modalities are functionally interchangeable. This question is particularly unresolved in perimenopausal women, for whom evidence directly comparing yoga modalities is limited (Huang et al., 2025; Shete et al., 2026), despite this population's elevated fall risk and clear rationale for targeted intervention.

Therefore, this study aimed to directly compare the effects of static, dynamic, and combined yoga on flexibility and balance in perimenopausal women. We hypothesized that the combined program would produce greater improvements in both outcomes than either single-modality program, reflecting the additive engagement of complementary static and dynamic mechanisms, while static and dynamic yoga alone would produce comparable gains.

Materials and Methods

Participants

This study used a three-group parallel-group randomized controlled trial (1:1:1 allocation) to compare the effects of static, dynamic, and combined yoga on flexibility and balance in women undergoing the perimenopausal transition. Thirty-six healthy women aged 40 to 50 years in the perimenopausal phase were recruited. Perimenopausal status was determined by self-reported menstrual history, defined as menstrual cycle irregularity (variation in cycle length of more than 7 days or at least one skipped period) within the preceding 12 months, in the absence of hysterectomy, oophorectomy, or current use of hormone replacement therapy; hormonal assays (e.g., follicle-stimulating hormone) were not performed. Eligible participants met the following criteria: aged 40-50 years, in the perimenopausal phase, and free from musculoskeletal injury or other medical conditions that would contraindicate exercise; women with such conditions were excluded. Eligible women were screened and enrolled, then randomly allocated to one of the three groups (n= 12 each) using block randomization to ensure equal group sizes. The random allocation sequence was computer-generated using Microsoft Excel by a research assistant who was not involved in outcome assessment, using a block size of 6, with each block comprising two allocations to each of the three groups; the sequence of allocation within each block was generated using Microsoft Excel's RAND() function and was not altered after generation. Allocation was concealed using sequentially numbered, sealed opaque envelopes until

participants were assigned to the intervention groups. Due to the nature of the intervention, participants and instructors could not be blinded. However, the outcome assessor was blinded to group allocation. Baseline demographic characteristics were comparable between groups (see Results, Table 2). The study protocol was approved by the STIKES Guna Bangsa Health Research Ethics Committee (Approval Number: 026/KEPK/VI/2026) and conducted in accordance with the Declaration of Helsinki and is reported in line with the CONSORT guidelines (Figure 1).

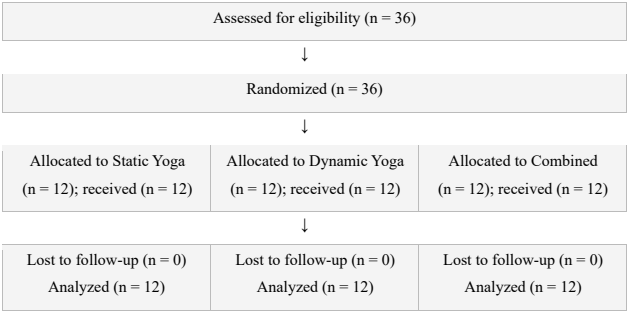


Fig. 1. CONSORT 2010 participant flow diagram.

Study Organization

The yoga intervention lasted for six weeks with two sessions per week, each lasting 50 minutes. Following baseline assessments, the six-week yoga intervention was administered. Each group underwent a different type of yoga intervention: the static yoga group performed a sequence of asanas with static movements (poses held) according to traditional yoga principles, the dynamic yoga group practiced asanas in a flowing sequence of movements, and the third group received a combined yoga regimen that alternated between static and dynamic asanas. For the static yoga group and combined yoga group postures (static part) of each asana, The hold is maintained for 10–20 seconds during weeks 1–2 and increased to 10–30 seconds from weeks 3 to 6, followed by proper breathing technique. In the case of the dynamic yoga group and the combined yoga group (dynamic part), the posture of asanas was performed continuously with a range of 3 to 10 rounds (Dynamic Group 5-10 rounds, Combined group 3-6 rounds). A round is counted when the participants perform each asana once, one after another, in a sequence. Details of the intervention programs are presented in Table 1.

In the first and second weeks, the static yoga group focused on maintaining postures for extended periods, such as Vajrasana, Supta Vajrasana, and Tadasana, and other mentioned asanas aimed at enhancing flexibility and body balance by elongating muscles and stabilizing posture, while the dybamic yoga group performed, the same asanas in a continuous manner without holding the postures. The continuous lengthening and shortening of muscles attached to various joints focussed on improving blood circulation, body strength, agility, and balance. The combined yoga group included both static and dynamic elements, performing asanas like Vajrasana, Supta Vajrasana, and Trikonasana, which mixed static and dynamic movements to improve balance and flexibility. In the third and fourth weeks, the

Table 1. 6-week yoga programs for perimenopausal women

Week	Part of training	Core Movement Types per Group		
		Static Yoga	Dynamic Yoga	Combined Yoga
1 – 2	Warming up: 10 min	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).
	Main Part: 30 – 40 min	Sitting: Vajrasana, Supta Vajrasana, Pascimottanasana Standing: Tadasana, Trikonasana, Parshvakonasana Lying on back: Pavanamuktasana, Padottanasana Round= 1-3 times Holding time=10-20 sec. in each asana*	Sitting: Vajrasana, Supta Vajrasana, Pascimottanasana Standing: Tadasana, Trikonasana, Parshvakonasana Lying on back: Pavanamuktasana, Padottanasana Round = 5-10 times * Holding time=Nil (continuously)	Sitting: Vajrasana, Supta Vajrasana, Pascimottanasana Standing: Tadasana, Trikonasana, Parshvakonasana Lying on back: Pavanamuktasana, Padottanasana For Static part Round= Once Holding time= 10-20 sec. in each asana* + For Dynamic part Round= 3-6 times* Holding time= Nil (continuously)
	Cooling down: 5 – 6 min	Loosening & Sabasana	Loosening & Sabasana	Loosening & Sabasana
3 – 4	Warming up: 10 min	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).
	Main Part: 30 – 40 min	Sitting: Janusirsasana, Upavistakonasana Standing: Tadasana, Poorvatanasana Lying on back: Pavanamuktasana, Padottanasana Round = 1-3 times* Holding time=10-30 sec. in each asana*	Sitting: Janusirsasana, Upavistakonasana Standing: Tadasana, Poorvatanasana Lying on back: Pavanamuktasana, Padottanasana Repetition 5-10* times Holding time= Nil (continuously)	Sitting: Janusirsasana, Upavistakonasana Standing: Tadasana, Poorvatanasana Lying on back: Pavanamuktasana, Padottanasana For Static part Round= Once Holding time= 10-30 sec. in each asana* + For Dynamic part Round = 3-6 times* Holding time= Nil (continuously)
	Cooling down: 5 – 6 min	Loosening & Sabasana	Loosening & Sabasana	Loosening & Sabasana
5 – 6	Warming up: 10 min	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).	Stretching and bending exercises (Toe bending, Ankle bending, Wrist stretching, Finger stretching, Elbow stretching).
	Main Part: 30 – 40 min	Sitting: Baddhakonasana, Ashvinimudra Standing: Tadasana, Parshvakonasana Lying on stomach: Bhujangasana, Shalabhasana Round= 1-3 times* Holding time=10-30 sec. in each asana*	Sitting: Baddhakonasana, Ashvinimudra Standing: Tadasana, Parshvakonasana Lying on stomach: Bhujangasana, Shalabhasana Round = 5-10* times Holding time= Nil (continuously)	Sitting: Baddhakonasana, Ashvinimudra Standing: Tadasana, Parshvakonasana Lying on stomach: Bhujangasana, Shalabhasana For Static part Round= Once Holding time=10-30 sec. in each asana* + For Dynamic part Rounds = 3-6 times* Holding time= Nil (continuously)
	Cooling down: 5 – 6 min	Loosening & Sabasana	Loosening & Sabasana	Loosening & Sabasana

Note. *- Repetition as per the individual capacity of the participants.

static yoga group practiced asanas such as Janusirsasana and Poorvatanasana, which aimed to further improve flexibility. The dynamic yoga group, meanwhile, concentrated on performing the same asanas in a continuous manner with 5-10 rounds. During this time, the combined yoga group alternated between static and dynamic elements, using asanas such as Janusirsasana, Upavistakonasana, and Poorvatanasana to improve the body's overall flexibility and strength. In the fifth and sixth weeks, the static yoga group focused on asanas such as Baddhakonasana and Ashvinimudra to improve flexibility, stability, and balance. Meanwhile, the dynamic yoga group performed the same asanas on an ongoing basis aimed at strengthening muscles and improving circulation. In recent weeks, the combined yoga group alternated between static and dynamic asanas, including Baddhakonasana, Ashvinimudra, Tadasana, Parshvakonasana, and Bhujangasana, to provide overall benefits to the body. The program aims to improve flexibility, strength, and balance through a structured and progressive approach (Table 1).

The total duration of each session was kept constant among the three groups (50 minutes per session, two sessions per week, for six weeks), but the internal composition of the intervention differed by design. During weeks 1-2, the static group performed eight asanas for 1-3 rounds, with each posture held for 10-20 seconds, corresponding to approximately 80-480 seconds of cumulative static holding per session. The dynamic group performed the same eight asanas continuously for 5-10 rounds, corresponding to approximately 40-80 repetitions per session. The combined group performed the eight asanas once as a static component, corresponding to approximately 80-160 seconds of cumulative static holding, and 3-6 rounds as a dynamic component, corresponding to approximately 24-48 repetitions per session. During weeks 3-6, the programmes comprised six asanas. The static group performed 1-3 rounds with 10-30-second holds, corresponding to approximately 60-540 seconds of cumulative static holding per session, whereas the dynamic group performed 5-10 rounds, corresponding to approximately 30-60 repetitions per session. The combined group performed one static round, corresponding to approximately 60-180 seconds of cumulative static holding, plus 3-6 dynamic rounds, corresponding to approximately 18-36 repetitions per session. These ranges represent the prescribed intervention protocol rather than an exact delivered dose, because the number of rounds and repetitions was adjusted according to individual participant capacity. Thus, although session duration and frequency were standardized, the three programmes were not matched for absolute static holding time or dynamic repetition volume. The greater improvements observed in the combined group therefore cannot be interpreted as evidence of an additive effect attributable solely to combining static and dynamic modalities. This dose asymmetry is recognized as a limitation when interpreting the comparative effects of the three programmes.

Furthermore, each participant underwent their physical measurements, focusing on two outcomes: flexibility and balance. Measurements were taken at two time points: pre-test (basic, before week 1) and post-test (after the last session in week 6). Flexibility was measured using a sitting and reach test following the standard protocol of the YMCA (Golding

et al., 1982). Participants sat with their feet straight and heels aligned 5 cm from the zero point of the scoreboard, then reached forward as far as possible without bending the knees. Each participant completed two trials, and a higher value (cm) was recorded. Balance was assessed using a time-crossing test on a wooden block (2.5 m long, 20 cm high, 10 cm wide). Participants start with a standing position at one end of the block and are instructed to walk along the full block at a self-selected speed without stepping down; The trial is stopped, and a maximum time of 60 seconds is recorded if the participant steps down from the block before reaching the far end. Each participant completed two trials with a previous familiarization trial to reduce the learning effect (Muehlbauer et al., 2024); the faster (shorter) crossing time of the two trials was maintained as the main variable recorded, in seconds. For reporting and analysis, these crossing times were converted into balance scores using the formula: $\text{score} = 60 - \text{crossing time (in seconds)}$, so that higher scores reflect faster and more stable crossings; the transformed balance score (in seconds) was the one reported in all tables. All measurements were taken by the same trained and outcome-blind raters at both time points to minimize variation between raters. All 36 participants completed the six-week intervention with no exit (0% attrition) and no adverse events were reported. Overall participant attendance was excellent, with a mean of 11.97 out of 12 scheduled sessions attended (SD = 0.17; 99.8%): Static group = 12 ± 0.0 , Dynamic group = 12.0 ± 0.0 , Combined group = 11.9 ± 0.3 sessions. One participant in the combined group missed one session due to work commitments; all other participants attended each session.

Statistical Analysis

All analyses were conducted in IBM SPSS Statistics version 29. Descriptive statistics (mean $\pm$ SD with 95% confidence intervals based on the t-distribution) were computed for each group. Normality was assessed with the Shapiro-Wilk test and homogeneity of variance with Levene's test on the change (post - pre) scores; both assumptions were satisfied for all outcomes (Table 4). Baseline equivalence among groups was examined with one-way ANOVA on pre-test scores. Because the primary research question concerns between-group differences in post-intervention outcomes after accounting for any residual baseline variation, the primary analysis was analysis of covariance (ANCOVA) on post-test scores, with group as the fixed factor and pre-test score as the covariate; significant omnibus effects were followed by pairwise contrasts of adjusted means with Bonferroni correction for three comparisons. Assumptions specific to the ANCOVA model were assessed directly, including homogeneity of regressions slopes (Group $\times$ baseline-covariate interaction) and diagnostics of the model residuals (normality, homogeneity of variance, independence via the Durbin-Watson statistic, and influential-case screening via studentized residuals and Cook's distance). Because baseline demographic comparisons revealed a significant between-group difference in age, a sensitivity ANCOVA additionally adjusting for age was conducted for both outcomes. As a secondary, sensitivity analysis, within-group pre to post changes were also tested with paired sample t-tests (effect sizes expressed as Cohen's d with 95% confidence intervals),

and between-group differences in the magnitude of change were evaluated with one-way ANOVA on change scores followed by Tukey's HSD post hoc comparisons, to confirm that conclusions were not dependent on the choice of model. As a further robustness check, the non-parametric Kruskal-Wallis test was performed on the change scores. Statistical significance was set at $p < 0.05$.

Results

Table 2. General Characteristics of participants

Variable	N = 36		
	Static (n = 12)	Dynamic (n = 12)	Combined (n = 12)
Age, years	49.33 ± 0.88	49.58 ± 0.67	48.08 ± 1.56
Body weight, kg	56.75 ± 14.68	56.83 ± 5.31	52.33 ± 8.95
Height, cm	149.67 ± 3.31	147.58 ± 4.91	151.92 ± 8.25
BMI, kg/m ²	25.38 ± 6.69	26.15 ± 2.72	22.71 ± 3.73

Baseline demographic characteristics are summarized in Table 2. One-way ANOVAs comparing the three groups revealed a statistically significant difference in age, $F_{(2,33)} = 6.12$, $p = 0.006$; Tukey-adjusted post hoc comparisons showed the Combined group (48.08 ± 1.56 years) was significantly younger than both the Static group (49.33 ± 0.88 years; $p = 0.028$) and the Dynamic group (49.58 ± 0.67 years; $p = 0.006$), while Static and Dynamic did not differ ($p = 0.780$). Not other baseline demographic variable differed significantly between group: body weight, $F_{(2,33)} = 0.59$, $p = 0.560$; height, $F_{(2,33)} = 1.80$, $p = 0.180$; BMI, $F_{(2,33)} = 1.53$, $p = 0.230$. No Statistically significant baseline differences were observed for the primary outcomes, flexibility ($F_{(2,33)} = 1.71$, $p = 0.197$, $\eta^2 = 0.094$) or balance ($F_{(2,33)} = 1.23$, $p = 0.305$, $\eta^2 = 0.069$). Because age differed significantly between groups despite randomization, a sensitivity ANCOVA including both the baseline outcome value and age as covariates was conducted for the primary outcomes (see Results, following Table 5) to assess whether this imbalance confounded the intervention effect.

Table 3. Flexibility and balance before and after the intervention

Outcome	Group (n = 12)	Pre, Mean ± SD (95% CI)	Post, Mean ± SD (95% CI)
Flexibility (cm)	Static Yoga	20.95 ± 1.65 (19.90–22.00)	22.74 ± 1.70 (21.66–23.83)
	Dynamic Yoga	20.27 ± 1.31 (19.43–21.10)	22.47 ± 1.26 (21.66–23.27)
	Combined	19.77 ± 1.72 (18.67–20.86)	22.73 ± 1.67 (21.67–23.79)
Balance (s)	Static Yoga	19.73 ± 1.39 (18.85–20.62)	21.81 ± 0.99 (21.17–22.44)
	Dynamic Yoga	20.48 ± 1.52 (19.51–21.44)	22.32 ± 1.32 (21.48–23.15)
	Combined	19.61 ± 1.48 (18.67–20.55)	22.89 ± 1.38 (22.02–23.77)

Note: Values are mean ± SD (95% CI); CI, confidence interval; SD, standard deviation.

As shown in Table 3, mean flexibility and balance increased from pre-test to post-test in all three intervention groups. The largest mean increase was observed in the combination group for both flexibility (from 19.77 to 22.73 cm) and balance (from 19.61 to 22.89 s).

Table 4. Tests of normality and homogeneity of variance

Outcome	Group	Shapiro-Wilk, W (p)	Levene's F (p)
Flexibility (cm)	Static	0.911 (0.220)	2.289 (0.117)
	Dynamic	0.950 (0.631)	–
	Combined	0.911 (0.223)	–
Balance (s)	Static	0.965 (0.857)	2.366 (0.110)
	Dynamic	0.897 (0.144)	–
	Combined	0.891 (0.120)	–

Note: W, Shapiro-Wilk statistic; F, Levene's test statistic.

Before the primary ANCOVA, the assumptions for parametric analysis were assessed using the Shapiro-Wilk test for normality and Levene's test for homogeneity of variances (Table 4). No significant departures from normality were observed for flexibility or balance in any intervention group (all $p > 0.05$). Levene's test also indicated homogeneous variances for flexibility ($p = 0.117$) and balance ($p = 0.110$). In addition to these preliminary checks, the assumptions specific to the ANCOVA model itself were assessed directly (Table 5): the homogeneity of regression slopes assumption was tested via the Group x baseline covariate interaction and was not significant for either outcome (flexibility: $F_{(2,29)} = 0.745$, $p = 0.484$; balance: $F_{(2,29)} = 0.362$, $p = 0.699$), supporting the standard common slope ANCOVA model. residual of the primary ANCOVA models were normally distributed (Shapiro-Wilk: flexibility $W = 0.963$, $p = 0.268$; balance $W = 0.952$, $p = 0.116$) and homoscedastic (Levene's test: flexibility $F = 1.83$, $p = 0.176$; balance $F = 2.01$, $p = 0.151$), with no evidence of autocorrelation (Durbin-Watson: flexibility $d = 1.98$; balance $d = 2.04$, both within the acceptable range of 1.5 – 2.5) and no influential cases (all studentized residuals < 3.0 and Cook's distances < 1.0). These findings supported the use of the planned parametric ANCOVA.

Table 5. Diagnostic assessment of the primary ANCOVA model assumptions

Diagnostic	Flexibility	Balance
Group × baseline interaction	$F_{(2,29)} = 0.745$, $p = .484$	$F_{(2,29)} = 0.362$, $p = .699$
Shapiro-Wilk	$W = 0.963$, $p = .268$	$W = 0.952$, $p = .116$
Levene's test	$F = 1.83$, $p = .176$	$F = 2.01$, $p = .151$
Durbin-Watson	$d = 1.98$	$d = 2.04$
Influential observations	None	None

Note: Durbin-Watson values of 1.5–2.5 were considered acceptable; influential observations were assessed using studentized residuals and Cook's D.

After adjustment for pre-intervention values, significant between-group differences were observed for flexibility

Table 6. ANCOVA results for flexibility and balance adjusted for baseline

Outcome	F	df	p	Group (Mean ± SE)			Partial η^2
				Static	Dynamic	Combined	
Flexibility (cm)	11.807	2,32	<0.001	22.16 ± 0.16	22.52 ± 0.16	23.26 ± 0.16	0.425
Balance (s)	13.188	2,32	<0.001	21.96 ± 0.19	21.93 ± 0.19	23.13 ± 0.19	0.452

Note: Values are adjusted means ± SE; SE, standard error.

($F(2,32) = 11.807$, $p < 0.001$, partial $\eta^2 = 0.425$) and balance ($F(2,32) = 13.188$, $p < 0.001$, partial $\eta^2 = 0.452$). The combination group had the highest adjusted mean for flexibility (23.26 cm) and balance (23.13 s), followed by the dynamic and static groups for flexibility, while the adjusted means of the static and dynamic groups were similar for balance (Table 6).

Table 7. Sensitivity ANCOVA for flexibility and balance adjusting for baseline value and age

Outcome	F (Group, adjusted for baseline + age)	df	p	Partial η^2
Flexibility (cm)	10.21	2, 31	< 0.001	0.398
Balance (s)	11.58	2, 31	< 0.001	0.428

Furthermore, because age differed significantly between groups at baseline (see Table 2), a sensitivity ANCOVA was conducted for both outcomes with baseline (pre - test) outcome value and age entered as covariates, to evaluate whether the observed group effect was confounded by this imbalance. The primary ANCOVA model (baseline outcome value only) remains the model on which our main conclusions are based, consistent with the pre - specified hypothesis concerning the effect of the intervention independent of baseline performance; age is examined here as a robustness check for potential confounding. The group effect on post - intervention scores remained significant and of comparable magnitude after adjusting for age: flexibility $F_{(2,31)} = 10.21$, $p < 0.001$, partial $\eta^2 = 0.398$; balance $F_{(2,31)} = 11.58$, $p < 0.001$, partial $\eta^2 = 0.428$. This indicates that the observed advantage of the Combined programme is not attributable to the baseline age imbalance (Table 7).

Bonferroni-adjusted pairwise comparisons are presented in Table 8. For flexibility, the combination group had a significantly higher adjusted mean than the static group (mean difference = -1.095 cm, $p < 0.001$) and the dynamic group (mean difference = -0.733 cm, $p = 0.007$). No significant difference was observed between the static and dynamic groups (mean difference = -0.362 cm,

$p = 0.344$). For balance, the combination group also had a significantly higher adjusted mean than the static group (mean difference = -1.174 s, $p < 0.001$) and the dynamic group (mean difference = -1.206 s, $p < 0.001$). The static and dynamic groups did not differ significantly (mean difference = 0.032 s, $p > 0.999$).

Table 9. Changes in flexibility and balance and effect sizes

Outcome	Group	Mean $\Delta \pm$ SD	p	Cohen's d (95% CI)
Flexibility (cm)	Static	1.79 ± 0.38	<0.001	4.68 (2.49–6.88)
	Dynamic	2.20 ± 0.58	<0.001	3.77 (1.96–5.58)
	Combined	2.97 ± 0.62	<0.001	4.76 (2.53–7.00)
Balance (s)	Static	2.08 ± 0.60	<0.001	3.47 (1.78–5.15)
	Dynamic	1.84 ± 0.63	<0.001	2.92 (1.46–4.38)
	Combined	3.28 ± 0.97	<0.001	3.40 (1.74–5.05)

Note: Δ , post-test – pre-test; SD, standard deviation; CI, confidence interval.

Within-group changes are shown in Table 9. All three intervention groups demonstrated significant pre- to post-intervention increases in flexibility and balance (all $p < 0.001$). The combination group showed the largest mean change in flexibility ($\Delta = 2.97$ cm) and balance ($\Delta = 3.28$ s). Cohen's d values were large across all within-group comparisons, ranging from 2.92 to 4.76.

Table 10. Between-group differences in change

Outcome	F	df	p	η^2 (95% CI)
Flexibility (Δ , cm)	14.655	2,33	<0.001	0.470 (0.189–0.620)
Balance (Δ , s)	12.757	2,33	<0.001	0.436 (0.155–0.594)

Note: Δ , post-test – pre-test; η^2 , eta-squared; CI, confidence interval.

As a sensitivity analysis, one-way ANOVA of change scores (Table 10) confirmed significant between-group

Table 8. Bonferroni-adjusted pairwise comparisons between intervention groups

Outcome	Comparison	Mean difference	SE	t	df	p (adjusted)
Flexibility (cm)	Static vs Combined	-1.095	0.230	-4.752	32	<0.001
	Dynamic vs Combined	-0.733	0.221	-3.310	32	0.007
	Static vs Dynamic	-0.362	0.223	-1.622	32	0.344
Balance (s)	Static vs Combined	-1.174	0.264	-4.445	32	<0.001
	Dynamic vs Combined	-1.206	0.272	-4.430	32	<0.001
	Static vs Dynamic	+0.032	0.270	0.119	32	>0.999

Note: SE, standard error; df, degrees of freedom; p (adjusted), Bonferroni-adjusted p-value.

Table 11. Tukey-adjusted pairwise comparisons of change

Outcome	Comparison	Mean difference	q	P (Tukey)	95% CI	Cohen's d
Flexibility (Δ , cm)	Static vs Dynamic	-0.41	2.62	0.169	-0.95 to 0.13	-0.756
	Static vs Combined	-1.18	7.54	<0.001	-1.72 to -0.63	-2.177
	Dynamic vs Combined	-0.77	4.92	0.004	-1.31 to -0.23	-1.420
Balance (Δ , s)	Static vs Dynamic	+0.23	1.08	0.729	-0.52 to 0.99	0.311
	Static vs Combined	-1.21	5.58	0.001	-1.96 to -0.46	-1.610
	Dynamic vs Combined	-1.44	6.65	<0.001	-2.19 to -0.69	-1.921

Note: Δ , post-test – pre-test; q, studentized range statistic; p (Tukey), Tukey-adjusted p-value; CI, confidence interval.

differences for flexibility ($F_{(2,33)} = 14.655$, $p < 0.001$, $\eta^2 = 0.470$) and balance ($F_{(2,33)} = 12.757$, $p < 0.001$, $\eta^2 = 0.436$). These findings were consistent with the primary ANCOVA.

The Tukey-adjusted comparison (Table 11) also showed that the combination group showed greater changes in flexibility than the static group ($p < 0.001$) and the dynamic group ($p = 0.004$). For equilibrium, the combination group also showed a greater change than the static group ($p = 0.001$) and the dynamic group ($p < 0.001$). No significant difference was found between the static and dynamic groups for flexibility ($p = 0.169$) or balance ($p = 0.729$).

Table 12. Kruskal–Wallis sensitivity analysis of change

Outcome	H	df	p
Flexibility (Δ , cm)	17.713	2	<0.001
Balance (Δ , s)	11.349	2	0.003

Note: Δ , post-test – pre-test; H, Kruskal–Wallis test statistic.

The non-parametric sensitivity analysis yielded consistent omnibus findings (Table 12), with significant between-group differences for flexibility ($H = 17.713$, $df = 2$, $p < 0.001$) and balance ($H = 11.349$, $df = 2$, $p = 0.003$).

Discussion

This randomized controlled trial evaluated the effects of static, dynamic, and combined yoga regimens on flexibility and balance in perimenopausal women. Participants who completed the combined protocol achieved greater improvements in both outcomes compared to those practicing only static or dynamic yoga, likely reflecting broader muscle recruitment and concurrent improvements in joint range of motion. These results align with evidence reported by (Luo & Huang, 2023); yoga interventions have demonstrated positive effects on physical parameters such as flexibility and balance, as well as on the overall psychological wellbeing and hormonal balance of perimenopausal women (Cramer et al., 2012; Naragatti, 2025), support the use of combined yoga as a viable and effective modality.

An important observation is the absence of a statistically significant difference between the static and dynamic yoga groups for both outcomes (ANCOVA, Bonferroni adjusted: flexibility $p = 0.344$; balance $p > 0.999$; consistent with change score sensitivity analyses: flexibility $p = 0.169$; balance $p = 0.729$). Since both modalities employed identical asana sequences and differed primarily in execution (sustained holds versus continuous flow), the underlying neuromuscular

stimuli may be functionally equivalent consistent with findings by (Matsuo et al., 2019), who observed no difference between static and dynamic stretching of equal total duration. Furthermore, the six week, twice weekly frequency may have been insufficient to elicit modality specific adaptations; (Shin, 2021) reported that yoga programs lasting 9–12 weeks yielded larger effect sizes ($RS = 0.70$) compared to those lasting less than eight weeks ($ES = 0.54$). With only 12 participants per group and observed power below 50% for both comparisons (see limitations), the study was likely underpowered to detect the observed static versus dynamic differences ($d = -0.756$ for flexibility, $d = 0.311$ for balance); this lack of significant difference should not be interpreted as evidence of equivalence between the two modalities. Future, larger, and longer duration trials are needed to clarify these modalities are truly comparable or subtly different.

Middle-aged women who enter perimenopause often experience physical decline that directly interferes with health-related quality of life (Iwanowicz-Palus et al., 2019; Liu et al., 2025; Liu et al., 2023), making non-pharmacological interventions valuable. A randomized trial conducted by (Abiç & Yilmaz Vefikuluçay, 2024) found that a twice-weekly, ten-week yoga programme significant reduced Menopause Assessment Scale (MRS) symptom severity score from 16 to 5, with a $p < 0.05$. Consistent yoga practice has also been linked to improved psychological health, quality of life, and daily physical functioning (Bandyopadhyay et al., 2025). Programs that combine static and dynamic postures have been shown to improve joint flexibility and mobility (Ikeda et al., 2026; Warneke et al., 2025) and a structured curriculum specifically improves torso flexibility, thereby maintaining mobility, reducing the risk of falls, and supporting general physical performance (Bindawas et al., 2026; Zhong et al., 2024).

Greater balance improvement in the combination group compared to the static yoga and dynamic yoga groups suggests that the combination of both forms of exercise provides a more optimal stimulus for posture control. This is important in perimenopausal women because hormonal changes and decreased bone mineral density during the menopausal transition period increase the risk of balance disorders, falls, and fractures (Starrach et al., 2022). Therefore, interventions that are able to improve postural stability have an important role in maintaining physical function in this group (Wei et al., 2023). Yoga may improve postural stability through enhanced proprioception, muscle strengthening and vestibular-visual integrating (Jeter, Haaz Moonaz, et al., 2015; Lin et al., 2022; Verma et al., 2023). The integration of asanas, breathing techniques, and meditation

may provide complementary stimuli for flexibility, muscle strength, posture control, and neuromuscular coordination. This is consistent with (Harrington, 2025) and a meta-analysis by (Shin, 2021), which report that yoga practice consistently improves balance, mobility, muscle strength, and flexibility as key components of physical function.

Although combined yoga's superiority is broadly consistent with existing literature, some discrepancies warrant discussion. (Petty et al., 2022) similarly found no significant differences between static and dynamic yoga six weeks, but in young adults (mean age $\approx$ 20 years) with different baseline neuromuscular characteristics and hormonal profiles from perimenopausal women, limiting direct comparability. Conversely, (Bhowmik Bhunia & Ray, 2024) reported continued gains through 12-week in young males, though improvements slowed once training shifted from asana-dominant to breathing-focused sessions, suggesting a non-linear dose-response relationship. Furthermore, (Abiç & Yilmaz Vefikuluçay, 2024) similarly found greater symptom reduction with a 10-week yoga programme in menopausal women. Together, these findings indicate that yoga's effects depend on population characteristics, intervention duration, session frequency, and the specific balance of static, dynamic, and breathing components within the programme.

These findings have practical implications for practitioners and policymakers. Given the advantages of combined protocols regarding flexibility and measurable balance, clinicians should consider integrated programs that incorporate both static and dynamic postures, aligning with World Health Organization (WHO) guidelines that recommend multicomponent balance, strength, and flexibility exercises at least three days a week for older adults (WHO, 2020). Since Flexibility and balance are closely linked to fall risk, combined yoga exercises could serve as a promising, low-cost, non-pharmacological addition to community-based fitness programs; however, as the incidence of falls was not directly measured in this study, the potential for fall prevention remains an implication for future research rather than an empirically proven outcome. Single modality programs remain a viable option if implementing combined exercises is not feasible.

This study is limited by its modest sample size ($n = 12$ per group) and short duration, which may not have fully captured physiological adaptations. A post hoc sensitivity analysis indicated that, at this sample size, statistical power to detect the observed static-versus-dynamic contrasts was low (approximately 43% for flexibility, $d = 0.76$; approximately 11% for balance, $d = 0.31$); detecting these effect sizes at 80% power would require approximately 29 and 164 participants per group, respectively. The non-significant static-versus-dynamic comparisons should therefore be interpreted as inconclusive rather than as evidence that the two modalities are equivalent. In addition, the three programs were not matched for absolute training dose (see Intervention dose, above), lower-extremity and core muscle strength and neurophysiological indicators of sensorimotor control were not assessed, and fall incidence and quality-of-life outcomes were not directly measured. Future research should incorporate a priori power calculations, dose-matched comparison arms, direct neuromuscular and fall-incidence measures, and longer follow-up with larger samples.

Conclusions

Perimenopausal women who participated in a combination of static and dynamic yoga for six weeks showed greater improvements in measured flexibility and balance than those who participated in static or dynamic yoga separately, after accounting for baseline differences. These findings represent an initial step toward developing exercise strategies to maintain physical function during the perimenopausal transition; because fall incidence and quality of life were not directly assessed, their relationship to these outcomes should be examined in future studies before combined yoga is recommended specifically as a fall-prevention intervention.

Ethics Approval

The study protocol was approved by the STIKES Guna Bangsa Health Research Ethics Committee (Approval Number: 026/KEPK/VI/2026) and conducted in accordance with the principles of the Declaration of Helsinki.

Informed Consent

Written informed consent was obtained from all participants prior to enrollment. Participants were informed about the study procedures, potential risks and benefits, and their right to withdraw at any time without penalty before providing written consent.

Data Availability Statement

The datasets generated and analysed during the current study are not publicly available due to ethical and privacy restrictions protecting participant confidentiality but are available from the corresponding author upon reasonable request and with approval from the STIKES Guna Bangsa Health Research Ethics Committee.

AI Transparency Statement

The author used AI-assisted tools for language editing only during manuscript preparation. All scientific content, data analysis, and conclusions are the authors' original work. The authors take full responsibility for all content.

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Conflicts of Interest

No conflicts of interest are present to disclose.

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Статичні та динамічні асани йоги порівняно з комбінованою йогою: що є ефективнішим для покращення гнучкості та рівноваги у жінок у перименопаузі?

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

Реферат. Стаття: 11 с., 12 табл., 1 рис., 30 джерел.

Передумови. Перименопауза часто супроводжується зниженням гнучкості та здатності підтримувати рівновагу, що підвищує ризик падінь і знижує якість життя. Як статична, так і динамічна йога пов'язані з покращенням гнучкості та постуральної стійкості, однак досліджень, у яких безпосередньо порівнювали б статичну, динамічну та комбіновану йогу з метою визначення найбільш ефективного підходу для покращення цих показників у жінок у перименопаузі, раніше не проводили.

Мета. Оцінити вплив статичної, динамічної та комбінованої практики йоги на гнучкість і рівновагу у жінок у перименопаузі.

Матеріали та методи. У тригруповому рандомізованому контрольованому дослідженні 36 жінок у перименопаузі були розподілені у співвідношенні 1:1:1 до груп статичної, динамічної або комбінованої йоги. Програма тривала шість тижнів і передбачала два 50-хвилинні заняття на тиждень. Гнучкість оцінювали за допомогою тесту «нахил уперед сидячи» (см). Рівновагу визначали за результатами тесту проходження по гімнастичній лаві з реєстрацією часу: учасниці долали дерев'яну опору завдовжки 2,5 м у самостійно обраному темпі, а час проходження (с; максимальний час — 60 с) перераховували у показник рівноваги за формулою $60 - \text{час проходження (с)}$; вищі значення відповідали кращій рівновазі. Основний аналіз проводили за допомогою ANCOVA для показників після завершення втручання з контролем вихідних значень до початку дослідження.

Результати. На початковому етапі групи не відрізнялися за досліджуваними показниками (в обох випадках $p > 0,19$). Після контролю вихідних значень за допомогою ANCOVA комбінована йога забезпечила статистично значуще кращі післяекспериментальні показники гнучкості та рівноваги порівняно зі статичною йогою (в обох випадках $p \leq 0,001$) і динамічною йогою (гнучкість: $p = 0,007$; рівновага: $p < 0,001$). Статистично значущих відмінностей між статичною та динамічною йогою не виявлено ані за показником гнучкості ($p = 0,34$), ані за показником рівноваги ($p > 0,99$; з поправкою Бонферроні). Водночас через невелику чисельність кожної групи ($n = 12$) статистична потужність дослідження була недостатньою для надійного виявлення відмінностей між цими двома видами йоги, тому робити висновок про їх еквівалентність не можна.

Висновки. Комбінована статично-динамічна йога забезпечила більш виражене покращення гнучкості та рівноваги у жінок у перименопаузі порівняно із застосуванням кожного з цих видів йоги окремо. Отримані результати свідчать, що комбіновані програми йоги можуть бути перспективним немедикаментозним засобом у межах програм фізичної активності на рівні громади для цієї популяції. Водночас вплив таких програм на частоту падінь і якість життя безпосередньо не оцінювали, що потребує окремого вивчення у подальших дослідженнях.

Ключові слова: перехід до менопаузи, здоров'я жінок, якість життя, фізичне функціонування.

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Physical Activity During Physical Education Lessons Among Omani Female Students: Levels and Correlates

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

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Abstract

Objectives. This study aimed to examine physical activity levels and determinants throughout physical education (PE) lessons among Omani Cycle Two female students.

Materials and Methods. A cross-sectional descriptive-analytical design was employed with 190 Cycle Two female students in Muscat Governorate's public schools, Oman. ActiGraph wGT3X-BT accelerometers were used to measure physical activity during PE lessons. Anthropometric measurements comprised body mass index (BMI) and body fat percentage. Grip strength and 30-m sprint tested physical fitness. Data analysis used descriptive statistics, Spearman's correlation, multiple linear regression, and one-way analysis of variance (ANOVA) ($p < .05$).

Results. Participants accumulated 22.72 ± 5.40 minutes of moderate-to-vigorous physical activity (MVPA) on average, indicating high levels of health-enhancing physical activity. Sprint performance, vigorous physical activity ($\rho = -.177$, $p = .015$) and MVPA ($\rho = -.168$, $p = .021$) were significantly correlated, and independently predicted MVPA ($\beta = -.234$, $p = .002$). Grade level also independently predicted MVPA ($\beta = -.331$, $p < .001$), where Grade 6 students attained the highest MVPA level ($p < .05$). However, BMI, body fat percentage, and handgrip strength had no significant association with MVPA.

Conclusions. Cycle Two female students accumulated substantial MVPA in PE. The principal correlates of MVPA were sprint performance and grade level, contrasting body composition and handgrip strength. The findings encourage learner-centred, movement-oriented PE programs, suggesting PE curriculum development and physical activity enhancement among Omani schoolgirls.

Keywords: physical education, physical activity, accelerometry, physical fitness, body composition, female students.

Introduction

Physical activity during childhood and adolescence is essential for healthy physical, psychological, and social development. Physical education (PE) helps children develop lifelong physical activity, literacy and good habits, since they spend most of their time in school. Students' moderate-to-vigorous physical activity (MVPA) is widely used as an indicator of PE lesson quality and curriculum effectiveness (Siedentop & Van der Mars, 2022; Fairclough & Stratton, 2005, 2006).

Besides these, a lot of PE lessons do not guarantee MVPA levels for students. Observational studies show that a lot of the lesson time is taken up with recommendations, management or inactivity rather than valuable movement (Greenockle et al., 1990; Simons-Morton et al., 1994). Physical activity

levels are affected by the lesson content, instructor behavior, teaching strategies, and student attributes such as age, grade level and gender.

The core curriculum in Oman concentrates on movement ability, physical fitness, healthy lifestyle, teamwork and long-term physical activity. Al-Sinani (2018) states that the PE curriculum of Cycle Two (Grades 5-7) is learner-centred, encouraging active participation and holistic student development. However, there is limited data on the physical activity levels of female Omani Cycle Two students through PE.

Children's physical activity is most closely associated with body composition and fitness. Previous studies have associated lower body fat and a healthy BMI with increased physical activity, fitness and health. Obesity, however, decreases physical activity and performance (Mota et al., 2002; Gao, 2011; Dewi, 2021). Cardiorespiratory fitness, muscle strength, flexibility and health were better in active children (Kaminska et al., 2012; Chen, 2018; Gu, 2016; Oliveira, 2017; Peralta, 2020; Yang, 2019; Adi, 2024).

Demographics also affect physical activity. International data indicate that boys accumulate more MVPA and that participation in physical activity declines with age, but the magnitude of these differences varies across settings and cultures (Trost et al., 1996; Ishii et al., 2015; Harvey et al., 2016; Viciano et al., 2019; Majcug et al., 2023). These distinctions and student PE participation are influenced by biological maturation, changing motivations, increased academic demands and more complex educational experiences. International research is growing, but there are still research gaps. Physical activity, body composition, demographics and health-related physical fitness have been studied mainly in isolation (Trost et al., 1996; Sallis et al., 2000; Ishii et al., 2015; Fairclough & Stratton, 2005; Siedentop & Van der Mars, 2022). Therefore, grade level is more than a merely demographic characteristic; it measures developmental progression as well.

Research in the Gulf countries is limited, particularly among Omani Cycle Two female students. Thus, the relationship between students' activity levels, body composition, physical fitness and grade level and whether Omani PE sessions provide sufficient health-enhancing physical activity is unknown. Although accelerometer studies have objectively assessed physical activity among schoolchildren (Pate et al., 2006), comparable evidence from Omani female students remains scarce.

Based on the previous information, this study aimed to explore the levels and associated factors of physical activity during PE lessons among Omani Cycle Two female students. In particular, it identified physical activity levels of students in PE lessons, investigated the variations based on grade level, and explored the association between physical activity, body composition indicators, and selected factors of health-related physical fitness. Relying on both the theoretical and empirical data, it was hypothesized: (H1) students would accumulate sufficient levels of moderate-to-vigorous physical activity (MVPA) during PE lessons; (H2) higher physical activity levels would be significantly associated with more favorable body composition and health-related physical fitness indicators; and (H3) physical activity levels would differ significantly according to grade level.

Materials and Methods

Participants

The Ministry of Education's latest data report shows that there are 261,804 students in Cycle Two in Omani public schools in 2024-2025. Targeted public school girls in Muscat Governorate from grades 5-7. Participants were purposively recruited from three public schools in Muscat Governorate. Six classes were included from each school (18 classes in total), comprising two Grade 5, two Grade 6, and two Grade 7 classes per school. Six female PE teachers participated in the study, with two teachers from each school involved in teaching the participating classes. The need sample size was estimated by G*Power software (Version 3.1.9.7) using one-way ANOVA with three grade level groups. Based on a medium effect size ($f = 0.25$), statistical power of 0.80, and significance level of $\alpha = .05$, we calculated a baseline sample size of 159 students (53 per grade level).

The study consisted of 190 female students; 66 from Grade 5 (34.7%), 68 from Grade 6 (35.8%), and 56 from Grade 7 (29.5%). This sample size was larger than the required sample size, and therefore the proposed analyses were powered. The study participants were, on average, 11.69 ± 0.99 years old, 146.97 ± 8.04 cm in height, 43.21 ± 13.23 kg in body weight, 19.71 ± 4.78 kg/m² BMI and $26.8 \pm 6.9\%$ body fat. Eligible participants were female Grade 5-7 students who regularly participated in PE, were physically able to complete testing, and provided parental consent and student assent. Students with conditions preventing participation, incomplete measurements, or withdrawal were excluded.

Study Design

A quantitative cross-sectional descriptive-analytical design was used to investigate physical activity levels among Cycle Two female students in PE classes, registered in Omani public schools.

Data Collection Procedures and Ethical Consideration

Anthropometric measurements were conducted after participants were asked to put on lightweight clothes and take off their shoes. Qualified researchers and PE teachers adhered to standardized testing methods under comparable conditions to a regular PE lesson. The PE lessons followed the usual 45-minute format adopted in Omani schools and were the basic instructional unit of the PE curriculum. Each lesson included theoretical and practical educational components and consisted of approximately 5-10 min warm-up, 30-35 min main educational and practical activities, and about 5 min cool-down. The classes were held under regular teaching circumstances in the schools that participated in the study and averaged 30-32 students.

Data collection was performed within the 2024-2025 academic year via standardized examinations amid physical education lessons. Moreover, ethical approval from the Research Ethics Committee of Sultan Qaboos University and administrative approval from the Ministry of Education and schools were acquired beforehand. In addition, both written informed consent forms from the parents or legal guardians of the participants and students' assent were gathered. The Ethical Committee of the Deanship of Higher Studies and Scientific Research at Sultan Qaboos University authorized the study procedure (Approval No. IG/EDU/PHED/25/02), and it was conducted per the ethical principles of the Declaration of Helsinki (World Medical Association, 2013).

Instruments

Physical Activity

In this study, children and adolescents' objectively measured physical activity was assessed using the widely used, validated ActiGraph wGT3X-BT triaxial accelerometer (ActiGraph LLC, Pensacola, FL, USA). The accelerometer was initiated with ActiLife software (Version 6.13.3) per manufacturer instructions. The equipment recorded movement in 15 s epochs to capture the periodic activity patterns of young children. All regular physical education

students had an accelerometer fixed on the right iliac crest, on an elastic belt. Accelerometer cut-points recommended by Evenson et al. (2008) that were age-specific were used in this tool to classify body movements into inactive behaviour, light physical activity, moderate physical activity and vigorous physical activity.

Anthropometric Measurements

Anthropological and body composition characteristics included height, weight, BMI, and PBFM. The students were standing upright on the analyser stage, barefoot, in light clothing and holding hand electrodes for the assessment. To ensure accurate measurements, they were told not to eat, drink or exercise before the examination. A Tanita MC-780U Plus body composition analyser (Tanita Corporation, Tokyo, Japan) measured body weight and body fat %, while a portable Seca 220 stadiometer (Seca GmbH, Hamburg, Germany) recorded standing height. Body mass was rounded to 0.1kg and height to 0.5 cm.

Calculating BMI:

$$\text{BMI} = \text{Weight (kg)} / \text{Height (m}^2\text{)}.$$

Student weight was classified as normal, overweight, or obese using Cole et al. (2000) age- and sex-specific BMI cut-off values from the International Obesity Task Force (IOTF).

Physical Fitness Components

Grip strength was measured with a calibrated handgrip dynamometer according to the EUROFIT Physical Fitness Test Battery (Council of Europe, 1988). Students stood erect and stretched their dominant hand fully parallel to the body, not touching the trunk. All participants underwent two trials, and the highest weight (kg) was analysed. Grip strength was a useful field measure of muscle strength in relation to health-related fitness. Speed was assessed by the 30-m sprint test that is valid and reliable for young children.

Students performed a maximum 30-m sprint from standing. Sprint time was recorded to the nearest 0.01s using standard testing techniques as used in previous paediatric fitness investigations (Castro-Piñero et al., 2010; Ortega et al., 2011).

Data Analysis

The data were analyzed using IBM SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA). All statistical analyses were two-sided, with significance set at $p < .05$. Descriptive statistics (frequencies, percentages, means, and standard deviations) were used to describe participant characteristics and physical activity data. The Shapiro-Wilk test was used to test normality of continuous variables. One-way analysis of variance (ANOVA) was used to compare grade-level physical activity levels, and Scheffé post hoc comparisons were used when significant differences were found. Group differences were calculated with partial eta squared (η^2), which were interpreted with Cohen's criteria. The relationship between physical activity, body composition and fitness were analyzed using Spearman's rank order correlation coefficients (ρ). Multiple linear regression determined independent factors of MVPA. Preliminary tests of the normality, linearity, homoscedasticity, independence of errors, and multicollinearity assumptions were performed. Linear regression assumptions were checked using VIF, tolerance values and residual diagnostics.

Results

Descriptive Statistics of Participant Characteristics and Study Variables (H1)

Participants accumulated a mean of 22.72 min of MVPA per PE lesson, supporting H1 (Table 1).

Table 1. Descriptive Statistics of Participant Characteristics and Study Variables by Grade Level (N = 190)

Variable	Grade 5 (n = 66) M ± SD	Grade 6 (n = 68) M ± SD	Grade 7 (n = 56) M ± SD	Overall (N = 190) M ± SD
Age (years)	10.75 ± 0.45	11.58 ± 0.47	12.95 ± 0.43	11.69 ± 0.99
Height (cm)	140.94 ± 6.02	147.55 ± 7.14	153.38 ± 5.57	146.97 ± 8.02
Weight (kg)	36.83 ± 9.20	45.24 ± 14.35	48.26 ± 12.95	43.21 ± 13.19
BMI (kg/m ²)	18.29 ± 3.84	20.50 ± 5.25	20.43 ± 4.86	19.71 ± 4.77
BF (%)	25.62 ± 5.66	27.29 ± 8.10	27.14 ± 6.30	26.80 ± 6.9
SED (Min/PE session)	3.78 ± 2.19	9.81 ± 4.70	5.56 ± 2.55	6.46 ± 4.26
LPA (Min/PE session)	5.80 ± 2.05	6.31 ± 3.22	6.57 ± 2.33	6.21 ± 2.61
MPA (Min/PE session)	3.23 ± 0.87	3.63 ± 1.15	3.01 ± 0.96	3.31 ± 1.03
VPA (Min/PE session)	18.85 ± 3.48	23.70 ± 4.84	14.86 ± 3.49	19.41 ± 5.37
MVPA (Min/PE session)	22.08 ± 3.11	27.33 ± 4.49	17.87 ± 3.66	22.72 ± 5.40
Grip Strength (kg)	15.46 ± 3.99	18.37 ± 4.29	20.96 ± 5.96	18.12 ± 5.22
30-m Sprint Time (s)	7.15 ± 1.43	6.74 ± 0.86	6.91 ± 0.85	6.93 ± 1.09

Note. N = total sample size; n = subgroup sample size; M = mean; SD = standard deviation; BMI = body mass index; BF = body fat; SED = sedentary time; LPA = light physical activity; MPA = moderate physical activity; VPA = vigorous physical activity; MVPA = moderate-to-vigorous physical activity; PE = physical education

Associations Between Physical Activity, Body Composition, and Physical Fitness (H2)

Spearman Correlation

Sprint time was negatively associated with VPA and MVPA, whereas BMI, body fat percentage, and handgrip strength were not significantly associated with physical activity (Table 2), partially supporting H2.

Table 2. Spearman's Rho Correlations Between Physical Activity, Body Composition, and Physical Fitness Variables in the Overall Study Sample (N = 190)

Correlations					
Variable		BMI	BF	GS	Sprint
SED	ρ	0.137	0.107	0.059	0.058
	Sig.	0.059	0.141	0.420	0.429
LPA	ρ	-0.085	-0.118	-0.141	0.137
	Sig.	0.242	0.106	0.052	0.060
MPA	ρ	-0.032	-0.033	-0.127	-0.014
	Sig.	0.659	0.651	0.081	0.843
VPA	ρ	0.040	0.087	0.049	-.177*
	Sig.	0.584	0.232	0.501	0.015
MVPA	ρ	0.045	0.095	0.016	-.168*
	Sig.	0.539	0.193	0.824	0.021

Note. BMI = body mass index; BF = body fat percentage; GS = handgrip strength; SED = sedentary time; LPA = light physical activity; MPA = moderate physical activity; VPA = vigorous physical activity; MVPA = moderate-to-vigorous physical activity. r_s = Spearman's rho. $p < .05$, $p < .01$.

Multiple linear regression Analysis

The results of the multiple linear regression analysis to examine the independent prediction of MVPA by body composition, physical fitness and grade level are presented in Table 3. MVPA was selected as the dependent variable as it is the main health-improving outcome of physical activity and the primary outcome of the study. The overall regression model was statistically significant, $F(5, 184) = 6.71$, $p < .001$, accounting for 15.4% of the variance in MVPA ($R^2 = .154$, adjusted $R^2 = .131$). The grade level ($B = -2.23$, 95% CI $[-3.22, -1.23]$, $\beta = -.331$, $p < .001$) and the 30-m sprint time ($B = -1.15$, 95% CI $[-1.88, -0.43]$, $\beta = -.234$, $p = .002$) were both significant independent predictors. However, body fat percentage, BMI, and handgrip strength were not significant (all $p > .05$). The results partially support Hypothesis 2, with higher MVPA being associated with better sprint performance and lower grade level.

Differences in Physical Activity According to Grade Level (H3)

Grade-level differences were significant for SED, MPA, VPA, and MVPA, but not LPA (Table 4). The largest effects occurred for MVPA ($\eta^2 = .506$), VPA ($\eta^2 = .445$), and SED

Table 3. Multiple Linear Regression Predicting Moderate-to-Vigorous Physical Activity (MVPA) from Body Composition, Physical Fitness, and Grade Level (N = 190)

Multiple linear regression Model					
Predictor	B	SE	β	p	95% CI for B
Independent Variables	GS	0.016	0.093	0.016	0.863 $[-0.17, 0.20]$
	Sprint	-1.153	0.367	-0.234	0.002 $[-1.88, -0.43]$
	BMI	0.052	0.188	0.046	0.784 $[-0.32, 0.42]$
	BF	0.105	0.122	0.134	0.390 $[-0.14, 0.35]$
	Grade level	-2.228	0.505	-0.331	< .001 $[-3.22, -1.23]$

Note. MVPA = moderate-to-vigorous physical activity; GS = handgrip strength; BMI = body mass index; BF = body fat percentage; B = unstandardized regression coefficient; SE = standard error; β = standardized regression coefficient; CI = confidence interval.

($\eta^2 = .374$). Grade 6 students accumulated significantly more MVPA than Grade 5 (MD = 5.24, 95% CI $[3.61, 6.86]$) and Grade 7 students (MD = 9.46, 95% CI $[7.76, 11.16]$), while Grade 5 also exceeded Grade 7 (MD = 4.22, 95% CI $[2.51, 5.93]$; all $p < .001$). These findings supported H3.

Table 4. One-Way ANOVA Comparing Physical Activity Variables Across Grade Levels (N = 190)

Dependent Variable	SS	F	df	p	Partial η^2	Interpretation
SED	1284.986	55.794	2	< .001	0.374	Large
LPA	18.787	1.387	2	0.252	0.015	Small
MPA	12.636	6.254	2	0.002	0.063	Medium
VPA	2433.444	75.076	2	< .001	0.445	large
MVPA	2788.301	95.861	2	< .001	0.506	large

Note. One-way ANOVA was performed using grade level (Grades 5, 6, and 7) as the independent variable. Partial eta squared (η^2) was interpreted according to Cohen's guidelines: small = .01, medium = .06, and large = .14. Pairwise comparisons were conducted using the Scheffé post hoc test when the omnibus ANOVA was statistically significant. Statistical significance was established at $p < .05$.

Discussion

The present study examined the levels and associated factors of physical activity in PE lessons among Omani female students in Cycle Two, via objectively assessed physical activity, body composition, physical fitness, and grade level. This study found substantial MVPA during PE lessons, with sprint performance and grade level emerging as the principal correlates of MVPA among Omani Cycle Two female students.

The mean of 23 minutes of MVPA per PE instruction supported Hypothesis 1. The Omani Basic Education curriculum promotes movement, active participation and lifelong health (Al-Sinani, 2018). It also allows for MVPA as an indicator of quality of PE lessons (Fairclough & Stratton, 2005, 2006; Siedentop & Van der Mars, 2022). This study differs from previous studies, which have shown that students

lose time when PE lessons do not adhere to guidelines and management (Greenockle et al., 1990; Simons-Morton et al., 1994), by showing that students were active for most of the class. This direct comparison should be treated with caution, due to differences in length of course, curriculum and method of accelerometry. The data suggest that quality PE classes can help children significantly improve their daily activity. Omani PE programmes are based on active, learner-centered education.

Sprint performance was significantly associated with both VPA and MVPA and independently predicted MVPA, whereas BMI, body fat percentage, and grip strength were not significant predictors of MVPA, partially supporting Hypothesis 2. Although the level of physical activity is decreased in obese children (Trost et al., 2001), this study suggests that teacher-directed activities give comparative opportunities for all children. High-intensity PE lessons were more associated with locomotor fitness than anthropometrics or muscle strength. Running games, relays, and other intense physical activities demand rapid force production, neuromuscular coordination, and repetitive locomotion (e.g., sprinting). Grip strength is focused upper-limb isometric strength, not lower-body locomotion; hence its lack of significance in MVPA is logically reasonable. Similar relationships between VPA and speed-related fitness were observed in young pupils by Chen et al. (2018), Kaminska et al. (2012), and Gu et al. (2016).

The regression analysis shows that sprint performance and grade level are better predictors of MVPA than anthropometrics and grip strength. Locomotor fitness, not body composition or muscle strength, seems to be important for participation in PE and active participation. Furthermore, grade-level differences in sedentary behavior, moderate physical activity, VPA and MVPA were consistent with Hypothesis 3. Specifically, 6th grade children had the highest VPA and MVPA and 5th and 7th grade children had the lowest activity levels. These findings are in line with previous studies showing an association between middle school grades and decreases in physical activity (Reeves, 2016). This non-linear development is influenced by age but also by biological maturation, motivation and educational situation. Moreover, Grade 6 children are at an intermediate stage with good physical abilities, motor competence and passion for engagement, hence intense participation in PE activities. This decline in physical activity throughout adolescence is reflected by the Lower Grade 7 levels, as academic demands, developmental changes, and increased self-consciousness become more prevalent (Trost et al., 1996; Ishii et al., 2015; Harvey et al., 2016; Viciano et al., 2019; Majcug et al., 2023). This aligns with Shervey & DiPerna (2017), where physical activity declines that are age- and grade-related are not only connected to PE but also to school contexts, including recess, implying wider developmental and behavioral changes. Even with the absence of direct investigation of these mechanisms, they are similar to the ecological and developmental frameworks, suggesting individual and environmental factor interaction impacting physical activity behavior (Sallis et al., 2000; Fairclough & Stratton, 2005; Siedentop & Van der Mars, 2022). Therefore, the findings of this study emphasize the significance of creating developmentally adequate and engaging PE classes to maintain participation in vigorous physical activities,

especially among older female students. The regression model was statistically significant but only accounted for 15.4% of the variation in MVPA, indicating relatively modest explanatory power. Therefore, students' activity level during PE is influenced by more than their physical fitness, body type and grade level. Such factors may further contribute to the differences, such as the lesson materials, teaching methods, teacher behavior, class organization, interaction with peers, motivation, school facilities and activities outside of school. Thus, the model should not be regarded as a full account of MVPA. Rather, it should be seen as evidence that both grade level and sprint success are part of a bigger educational and behavioral picture.

In practice, PE teachers should reduce instruction and transition times, group students into small groups or activity stations, and use movement-based assignments to reduce waiting time. Task difficulty should be appropriate to students' fitness and motor skills. Running games, relays, circuits, and other developmentally appropriate activities can maintain MVPA. Older female students with lower MVPA need enhanced interest and variety of activities to remain engaged. Periodic objective assessment of lesson activities may also assist teachers in evaluating MVPA opportunities.

Strengths of this study methodology include objective accelerometer-based measures in this study, examination of physical activity, fitness, body composition and grade level simultaneously and the focus on Cycle Two female students, but there are limitations. First, cross-sectional studies do not permit causal inferences between physical activity and parameters studied. The female participants were sampled from public schools in Muscat Governorate; thus, the results may not be generalizable to male students, private institutions and other regions. Third, the results might not be representative of students' daily physical activity, since it only measures PE class activity. Lastly, extracurricular sports, socioeconomic level, school facilities, and instructor qualities were not considered. Longitudinal and school-based interventional studies with more diverse populations are therefore needed to assess causal relationships and strategies for increasing MVPA in childhood and early adolescence.

Conclusion

Participating students acquired comparably prominent levels of MVPA in PE lessons, which demonstrated the provision of significant opportunities for health-improving physical activity. The sole significant physical fitness-associated factor and independent predictor of MVPA was sprint performance. Moreover, BMI, body fat percentage, and grip strength did not have a significant correlation with the levels of physical activity. In addition, on the level of grade differences that were identified, Grade 6 students attained the highest levels of VPA and MVPA, which in turn emphasized the impact of developmental and educational factors on the students' engagement. The findings offer new evidence on the correlates of PE active participation, adding to the restricted data on objectively assessed physical activity among female students in the Gulf region. Moreover, they encourage the continuation of the implementation of learner-centred, movement-oriented programs, with an emphasis on the significance of prominent engagement

among older students. Overall, the present study offers data aiding educators, curriculum developers, and policymakers in enhancing PE programs to foster long-term physical activity and healthier lifestyles for Omani schoolgirls.

Ethics Approval

The study was authorized by the Ethical Committee of the Deanship of Higher Studies and Scientific Research at Sultan Qaboos University under the (Approval No. IG/EDU/PHED/25/02), and it was conducted per the ethical principles of the Declaration of Helsinki (World Medical Association, 2013).

Informed Consent

Both written informed consent forms from the parents or legal guardians of the participants and students' assent were gathered.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

AI Transparency Statement

The authors used AI-assisted tools for language editing only and take full responsibility for the content.

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Фізична активність оманських учениць під час уроків фізичного виховання: рівні та кореляти

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

Реферат. Стаття: 8 с., 4 табл., 32 джерела.

Мета дослідження. Це дослідження мало на меті вивчити рівні фізичної активності та детермінанти під час уроків фізичного виховання (ФВ) серед оманських учениць другого ступеня навчання.

Матеріали та методи. У роботі було застосовано крос-секційний дескриптивно-аналітичний дизайн; вибірку дослідження становили 190 учениць другого ступеня навчання державних шкіл провінції (мухафази) Маскат, Оман. Для вимірювання фізичної активності під час уроків ФВ використовувалися акселерометри ActiGraph wGT3X-BT. Антропометричні вимірювання включали визначення індексу маси тіла (ІМТ) та відсотка жирової маси в організмі. З метою оцінки

фізичної підготовленості застосовували тести на силу стискання кисті (динамометрія) та біг на 30 метрів. Статистичний аналіз даних проводився з використанням описової статистики, кореляції Спірмена, множинної лінійної регресії та одно-факторного дисперсійного аналізу при рівні значущості ($p < .05$).

Результати. Учасниці дослідження в середньому накопичували 22.72 ± 5.40 хвилини фізичної активності помірної та високої інтенсивності (ПВФА), що свідчить про високі рівні корисної для здоров'я рухової активності. Результативність спринту, фізична активність високої інтенсивності ($r = -.177$, $p = .015$) та ПВФА ($r = -.168$, $p = .021$) статистично значущо корелювали між собою, а також виступали незалежним предиктором ПВФА ($\beta = -.234$, $p = .002$). Клас навчання також виявився незалежним предиктором ПВФА ($\beta = -.331$, $p < .001$), причому учениці 6-х класів продемонстрували найвищий рівень ПВФА ($p < .05$). Проте ІМТ, відсоток жирової маси в організмі та сила стискання кисті не мали статистично значущого зв'язку з ПВФА.

Висновки. Учениці другого ступеня навчання акумулювали значний показник ПВФА на уроках ФВ. Основними корелятами ПВФА виявилися результативність у спринті та клас навчання, на відміну від компонентного складу тіла та сили стискання кисті. Отримані результати обґрунтовують доцільність упровадження учнівсько-центрованих та рухово-спрямованих програм ФВ, що свідчить на користь модернізації навчальних планів із ФВ та підвищення фізичної активності серед оманських школярів.

Ключові слова: фізичне виховання, фізична активність, акселерометрія, фізична підготовленість, склад тіла, учениці.

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