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Review Article

The Meta-Problem in Scientific Research in Physical Education and Sport: Architecture and Pathways to Knowledge

Oleg Khudolii[1ABCD], Olha Ivashchenko[1ABCD] and Mykola Khudolii[1ABCD]

[1]Kharkiv State Academy of Physical Culture

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

Corresponding Author: Olha Ivashchenko, e-mail: ivashchenko.olha21@gmail.com
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Abstract

Background. Contemporary scientific research increasingly faces not a shortage of data, but a shortage of an adequate level of generalization at which data can be transformed into knowledge. In many applied fields, including physical education and sport, technically correct studies often remain fragmented because they are not integrated into a broader explanatory framework.

Purpose. To systematize approaches to understanding the meta-problem and its operationalization in research on physical education and sport.

Materials and Methods. The study was conducted as a theoretical-methodological analysis with elements of retrospective empirical verification. The logic of the work was based on the assumption that productive research programs are formed not only around local hypotheses, but around higher-order concepts that determine research architecture, sequence of proof, and pathways to new knowledge. Conceptual analysis, comparative methodological synthesis, and retrospective examination of completed doctoral studies devoted to modeling learning, training, and motor development processes were applied.

Results. The meta-problem was interpreted as a higher-level conceptual construct preceding the formulation of topic, aim, hypothesis, and methods. It determines the framework within which these elements acquire coherence and scientific meaning. It was shown that in physical education and sport, learning, upbringing, and training may be interpreted as derivative forms of a unified process of detecting deviations from a functionally optimal mode and correcting them. The central contradiction of development lies in the need to change while preserving functional stability. Under conditions of local and limited positive factor effects, classical two-group designs have restricted explanatory value, whereas factorial designs, repeated measurements, and response-surface approaches are more productive for identifying optimal regimes.

Conclusions. The meta-problem should be considered as a methodological level organizing the critical path of scientific inquiry. Its practical value lies in improving research design, manuscript evaluation, and the production of cumulative scientific knowledge.

Keywords: meta-problem, scientific research, research design, methodology, knowledge generation, physical education, sport science, factorial experiment, adaptive processes, evidence synthesis.

Introduction

Contemporary scientific research increasingly faces not a shortage of data, but a shortage of the level of generalization at which data can be transformed into knowledge. The availability of statistically significant results, a large number of publications, or a wide range of methods does not in itself ensure scientific progress if there is no conceptual framework capable of integrating individual findings into a coherent explanatory logic (Wasserstein & Lazar, 2016; Chalmers & Glasziou, 2009; Sutton et al., 2009). Any new knowledge emerges as a result of resolving a contradiction identified within the object of study. If the object defines the boundaries of inquiry, the problem determines the direction of its development. From a methodological perspective, the formulation of the problem provides an integrated representation of the research subject, determines the system of essential relationships among its elements, and creates the foundation for hypothesis generation. Consequently, the productivity of research depends not only on the choice of

methods but also on how adequately the central contradiction of the object is identified and formulated. In this context, the concept of the meta-problem becomes particularly important.

The meta-problem defines the conceptual framework of a study within which the topic, aim, hypothesis, and system of methods are formulated. While the topic delineates the subject area, the aim specifies the expected outcome, and the hypothesis proposes a testable assumption, the meta-problem establishes the framework within which these elements acquire meaning and mutual coherence (Kuhn, 1962; Lakatos, 1970; Popper, 2005). In different methodological traditions, this issue has been addressed through the concepts of scientific problems, anomalies, research programmes, or the conceptual core of a theory. Common to these approaches is the recognition that the development of knowledge is determined not by the accumulation of facts alone, but by the identification and resolution of internal contradictions in the explanation of the object. At the same time, the level of generalization at which such a contradiction can organize a coherent research programme remains insufficiently explored. The issue concerns not an individual research question, but a level of understanding at which the sources of change, limits of effects, criteria of evidence, and directions of inquiry become intelligible (Bertalanffy, 1968; Ioannidis, 2016).

In the field of physical education and sport, such a perspective is particularly important because the processes under investigation are characterized by multifactoriality, nonlinear dynamics, developmental phases, adaptive limits, and complex interactions among pedagogical, biological, and social factors (Impellizzeri & Marcora, 2009; Kiely, 2012; Balyi et al., 2013). Under these conditions, the study of isolated effects often produces fragmented conclusions, whereas both practical and scientific significance depend on understanding how to manage change without compromising the functional effectiveness of the system (Bishop et al., 2008; Halson, 2014).

The theoretical foundation of this approach is grounded in previous studies on programmed learning of motor actions, factorial experimentation, modeling of pedagogical processes, optimization of training regimes, and the analysis of residual effects of adaptation (Khudolii, 2019; Ivashchenko, 2020; Box & Wilson, 1951; Collins et al., 2009). These lines of inquiry demonstrate that new knowledge emerges not from a simple comparison of two groups or from merely recording differences between indicators, but from identifying regularities within the space of possible modes of system functioning (Kiely, 2012; Halson, 2014).

The meta-problem functions as a methodological core not only in experimental studies. It is also present in bibliographic reviews, narrative reviews, systematic reviews, and meta-analyses as the level that determines the logic of source identification, criteria for material selection, limits of generalization, and the admissibility of evidence synthesis (Grant & Booth, 2009; Page et al., 2021; Khudolii, 2026). In this sense, review-based and experimental studies represent different phases of a unified process of knowledge generation.

More broadly, every research project possesses a higher-order structure that organizes its critical path: the emergence of an idea, mapping of existing evidence, synthesis of knowledge, experimental verification, and refinement of explanatory models. It is precisely this organizing function that is performed by the meta-problem. In its absence, a study may remain technically correct while being conceptually weak (Chalmers & Glasziou, 2009).

Despite the practical importance of this perspective, the procedures for formulating a meta-problem and operationalizing it within the field of physical education and sport remain insufficiently systematized (Bishop et al., 2006; Kiely, 2012; Coutts et al., 2018). In most cases, attention is focused on specific methods, whereas the transition from the conceptual level to research design, variable systems, and evidence structures remains outside the scope of dedicated methodological analysis. Yet such an approach has substantial potential to enhance scientific validity, reproducibility of findings, and the practical effectiveness of research programmes (Collins et al., 2009; Glasziou et al., 2014; Khudolii, 2026).

In the present study, the meta-problem is considered as the central contradiction of the research object, formulated at a level of generalization that allows the integration of the topic, aim, system of hypotheses, experimental design, and procedures for interpreting results into a unified logic of knowledge generation. Therefore, the analysis of the meta-problem is associated not only with the formulation of research tasks but also with the architecture of the entire scientific inquiry.

The purpose of the study was to systematize approaches to understanding the meta-problem and its operationalization in research on physical education and sport.

Materials and Methods

The study was conducted as a theoretical–methodological analysis supplemented by elements of retrospective empirical verification. The logic of the investigation was based on the assumption that productive research programmes are formed not only around individual hypotheses or local experimental questions, but also around higher-order concepts that determine research architecture, the sequence of evidence generation, and pathways to new knowledge (Kuhn, 1962; Lakatos, 1970).

The methodological foundation of the study was the conceptualization of the meta-problem as a construct of a higher level of generalization. Within the framework of this work, the meta-problem was defined as an integrative research construct that unites individual questions, objectives, variables, and procedures into a coherent programme of scientific inquiry (Bertalanffy, 1968; Khudolii, 2026). Unlike a local problem, which is focused on identifying a specific effect, a meta-problem is directed toward revealing regularities that can be reused, modeled, generalized, and transferred across contexts.

The study was implemented in three stages.

At the first stage, a conceptual analysis of the defining characteristics of the meta-problem was conducted. Particular attention was given to its capacity to establish a long-term research logic, integrate theoretical and empirical components, determine criteria for method selection, and create conditions for the accumulation of cumulative scientific knowledge (Lakatos, 1970; Ioannidis, 2016).

At the second stage, an algorithm for the operationalization of the meta-problem in applied research was reconstructed. The transition from the conceptual to the operational level was analyzed through a sequence of procedures including the formulation of sub-problems, specification of research objectives, selection of influencing factors, identification of effectiveness indicators, construction of experimental designs, and selection of statistical and modeling tools for data interpretation (Box & Wilson, 1951; Collins et al., 2009).

At the third stage, retrospective empirical verification of the proposed approach was performed using completed doctoral research projects in the field of physical education and sport devoted to the modeling of learning processes, training systems, and motor skill development (Khudolii, 2019; Ivashchenko, 2020). The analysis focused on the internal structure of the research programmes, including the scope of the original problem, the logic of progression from theory to experimentation, the reproducibility of procedures, and the capacity of the obtained results for generalization and practical transfer.

The productivity of a meta-problem as the organizational core of research was evaluated according to the following criteria: (a) its ability to generate a series of interconnected experiments; (b) consistency between theoretical assumptions and research design; (c) the possibility of developing predictive or control-oriented models; and (d) the production of results extending beyond a single sample or specific empirical situation (Lakatos, 1970; Ioannidis, 2016).

A limitation of the study is the case-based nature of the empirical verification and its concentration on materials originating from a single scientific tradition. At the same time, this approach provides a high degree of comparability across cases and makes it possible to trace the mechanisms through which a conceptual idea is transformed into a reproducible scientific outcome.

Results

Theoretical Nature of the Meta-Problem

The analysis provides grounds for considering the meta-problem as the central contradiction of the research object that determines the architecture of scientific inquiry and integrates the topic, aim, hypothesis, and methods into a unified logic of knowledge generation. While the topic defines the subject area, the aim specifies the expected outcome, and the hypothesis formulates assumptions regarding relationships among variables, the meta-problem establishes the framework within which these elements acquire scientific meaning. In the domains of learning, education, and training, this framework is associated with the regularities that ensure effective system functioning under changing environmental demands (Table 1).

Table 1. Hierarchy of Research Organization Levels

Level of Organization	Primary Function	Type of Outcome
Research Topic	Delineation of the subject area	Boundaries of the research field
Research Aim	Definition of the expected outcome	Direction of inquiry
Hypothesis	Formulation of a testable assumption	Empirical verification of relationships
Research Objectives	Operationalization of research stages	Sequence of procedures
Research Methods	Data collection and analysis	Empirical findings
Meta-Problem	Integration of all levels into a coherent logic	Generation of new knowledge

The Meta-Problem and the Knowledge Generation Cycle

The findings indicate that a meta-problem acquires scientific value only when it is consistently examined through different forms of research. Theoretical, review-based, and experimental studies constitute a unified cycle of knowledge generation: idea → practical verification → analysis of secondary sources → experimental testing → model refinement → new idea. Without operationalization and empirical verification, a meta-problem remains merely a conceptual construct (Table 2).

Table 2. Algorithm for the Operationalization of a Meta-Problem

Stage	Content	Expected Outcome
1	Formulation of the meta-problem	Conceptual framework
2	Identification of sub-problems	Structure of inquiry
3	Specification of factors	Independent variables
4	Selection of indicators	Dependent variables
5	Design construction	Valid verification scheme
6	Selection of analytical models	Data-processing tools
7	Generalization	New model / new knowledge

Process-Based Interpretation of Learning, Education, and Training

The analysis demonstrates that learning, education, and training may be interpreted as derivative forms of a single process: the detection of deviations from a functionally appropriate mode of activity and their correction. Within this perspective, the primary issue is not the pedagogical intervention itself, but the necessity of restoring the system to a functionally effective state. Learning develops the system's ability to independently recover an appropriate mode of action when errors occur, whereas physical education and training strengthen the regulatory mechanisms that sustain effective motor performance under changing conditions.

The Central Contradiction of Development

It was found that developmental processes are fundamentally based on the contradiction between the necessity to change and the necessity to preserve functional stability. Insufficient change limits adaptation to new conditions, whereas excessive or uncontrolled change leads to system disorganization. Effective management of development therefore depends on selecting modes of influence that promote progress without compromising functional stability.

Residual Effects as a Mechanism of Change Accumulation

The results indicate that every effective influence leaves a residual effect—a temporary functional reorganization that may be reinforced by subsequent influences, lost because of excessive intervals, or distorted by excessive loading. The residual trace is not maintained when the recovery interval extends into a forgetting phase and is disrupted when a repeated influence is imposed during a state of pronounced

functional fatigue. Consequently, the productivity of the process depends on the balance between preservation of the residual effect and the degree of system fatigue.

Formal Interpretation of the Central Contradiction

To describe controlled biological and pedagogical processes, a model may be used in which changes in the functional state, Y, depend on time or accumulated influence, X, and are determined by the simultaneous action of growth-promoting and self-limiting factors:

$$\frac{dY}{dX} = mY - rY^2$$

where mY represents the stimulating component of development, and rY^2 represents the internal inhibitory factor associated with resource depletion, system saturation, or increasing regulatory resistance.

The obtained expression demonstrates that any developmental process contains an inherent contradiction between the tendency toward growth and the mechanisms responsible for stabilization. It is precisely this interaction that gives rise to the nonlinear character of biological, learning, and adaptive processes..

Growth Models as a Manifestation of Contradiction Resolution

The analysis revealed that learning curves, training adaptations, and functional development trajectories may be interpreted as observable manifestations of the relationship between stimulation and internal inhibition. Rapid initial progress reflects the predominance of beneficial influences; deceleration indicates the strengthening of internal constraints; a plateau corresponds to a temporary equilibrium; and regression reflects the dominance of destabilizing factors. Consequently, growth models represent not merely changes in indicators over time but the process through which the central contradiction of the system is resolved.

Figure 1 illustrates the nonlinear nature of the learning process, in which an initial phase of accelerated improvement gradually transitions into a phase of deceleration and eventually reaches a plateau, reflecting the increasing influence of internal system constraints. The findings also demonstrate the substantial effect of functional state on the dynamics of motor skill acquisition. Under conditions of high work capacity, learning is characterized by a faster increase in the level of mastery and a shorter initial acquisition phase. In contrast, reduced work capacity prolongs the initial stage of learning and slows the accumulation of positive changes. Thus, the rate of skill development is determined not only by the number of repetitions but also by the functional state of the system, which defines the balance between stimulating and limiting factors. In this context, learning curves represent the process of resolving the central contradiction of development: the need to modify the functional state of the system while simultaneously preserving its stability (Table 3).

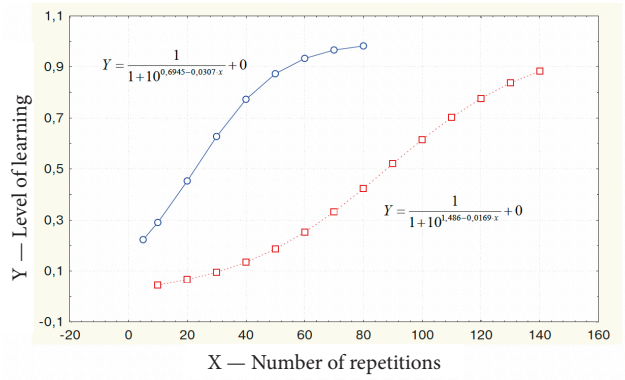

Fig. 1. Typical growth models of learning and adaptation processes (adapted from Khudolii, Doctoral Dissertation, p. 296, Fig. 5.3). Relationship between the level of mastery of the bent-arm headstand and the performance capacity of young gymnasts: (a) increase in the level of skill acquisition (Y) as a function of the number of repetitions under conditions of high work capacity; (b) increase in the level of skill acquisition (Y) as a function of the number of repetitions (X) under conditions of low work capacity.

The Meta-Problem and the Choice of Experimental Design

The analysis showed that when a factor exerts a local and limited positive influence, the central procedural task is not merely to verify the existence of an effect but to identify the region of influence within which the rate of beneficial change is maximized. Under such conditions, classical two-group designs based on comparisons between experimental and control groups provide only limited information, as they establish the presence of an average difference between two selected conditions. For the investigation of learning, training, and adaptation processes, multifactorial designs, repeated-measures approaches, longitudinal studies, and response-surface models are more appropriate (Table 4).

Table 4. Correspondence Between Research Objectives and Experimental Designs

Research Objective	Most Appropriate Design
Detection of an effect	Control–experimental group design
Identification of an optimum	Full factorial experiment
Analysis of temporal dynamics	Longitudinal design
Investigation of factor interactions	Multifactorial design
Classification of states	Discriminant analysis

Table 3. Interpretation of the Central Contradiction Across Different Processes

Process	Stimulating Component	Inhibitory Component	Outcome
Learning	Repetition, information	Forgetting, fatigue	Learning curve
Training	Training load	Resource depletion	Increase in training adaptation
Adaptation	Beneficial stress	Homeostatic limits	Nonlinear adaptation
Science	New data, new methods	Weak design	New knowledge

Methodology as a System of Knowledge Generation

The preceding findings make it possible to view research methodology not as a set of procedures applied after data collection, but as a coherent architecture for generating knowledge. The meta-problem determines the essential properties of the object of analysis and the set of relevant variables. The nature of the process under investigation defines the requirements for experimental planning, measurement structure, and design selection. Statistical methods should be anticipated during the design phase, while data structures should remain open to reanalysis and the application of more sophisticated multifactorial models (Box & Wilson, 1951; Collins et al., 2009; Ivashchenko et al., 2016; Ivashchenko et al., 2018; Ioannidis, 2016). Consequently, conceptual foundations, experimental design, analytical procedures, and data openness jointly ensure the transition from empirical observations to new knowledge (Table 5).

Table 5. Components of Methodology as a Knowledge Generation System

Component	Function
Methodological foundation	Explanation of the nature of the object
Meta-problem	Organization of the logic of inquiry
Design	Validity of verification
Statistics	Analysis of data structure
Data openness	Reproducibility and reanalysis
Generalization	Generation of new knowledge

Operationalization of a Meta-Problem: An Example from Physical Education and Sport

To illustrate the process of meta-problem operationalization, its implementation within a research programme devoted to the preparation of young gymnasts is considered (Khudolii, 2010, 2019). In this case, the meta-problem emerges as a contradiction between the need to improve athletic performance and the limited adaptive capacities of the organism. On the one hand, the achievement of high sporting results requires an increase in the volume and specificity of training interventions. On the other hand, excessive training loads lead to the depletion of functional reserves, reduced learning effectiveness, and an increased risk of maladaptation. Consequently, the central question concerns the identification of regularities governing the organization of the training process that enable performance improvement without compromising the functional stability of the system.

During the operationalization of this meta-problem, a series of interconnected sub-problems was identified, each reflecting a particular aspect of the central contradiction. These included the identification of informative indicators of functional and motor preparedness, the development of models describing age-related changes in preparedness, the investigation of immediate, delayed, and cumulative training effects, the identification of regularities in motor learning, the determination of optimal exercise–rest regimes, and the substantiation of training process structure and pedagogical control systems.

At the next stage, influencing factors and effectiveness indicators were specified. Independent variables included training load magnitude, work-to-rest regimes, the ratio of physical and technical training means, and the duration of training interventions. Dependent variables included indicators of functional state, levels of motor preparedness, effectiveness of learning gymnastic skills, and measures of athletic performance.

The resolution of the meta-problem required not a single experiment but a sequential system of interconnected studies. To achieve this, parametric modeling, 2^k factorial experiments, growth models, methods for analyzing immediate, delayed, and cumulative training effects, as well as procedures for forecasting and programming the training process were employed. This approach enabled the transition from isolated empirical observations to the identification of stable regularities governing the functioning of the young athlete preparation system.

As a result, a series of interconnected models was developed, including models of functional and motor preparedness in young gymnasts, models of training loads, models of motor learning processes, models of training process management, and methodological guidelines for programming long-term athlete development. These findings provided the foundation for the construction of an integrated concept of young gymnast preparation and enabled a transition from the description of isolated effects to the management of motor function development processes.

This example demonstrates that a meta-problem cannot be reduced to the formulation of a single research question. Rather, it functions as an organizational core that generates a system of interconnected studies, determines the logic of transition from theoretical conception to experimental verification, and ensures the accumulation of cumulative knowledge. It is precisely this capacity to generate a sequence of interrelated investigations that distinguishes a meta-problem from a local scientific problem. In physical education and sport, this is manifested as the search for regularities governing change in ways that promote development without loss of effectiveness (Khudolii, 2019; Ivashchenko, 2020; Ivashchenko et al., 2016; Ivashchenko et al., 2018). Thus, a meta-problem serves as a mechanism for transforming individual empirical observations into a research programme, and a research programme into new scientific knowledge.

Discussion

The findings of the present study support the view that the meta-problem should not be regarded as an auxiliary methodological term but rather as a distinct level of research organization that determines the relationship between conceptualization of the object, selection of an evidentiary strategy, and generation of new knowledge. From this perspective, scientific progress depends not merely on the accumulation of empirical findings but on the capacity to integrate those findings into a broader explanatory framework (Kuhn, 1962; Lakatos, 1970; Ioannidis, 2016). It is precisely this integrative function that is performed by the meta-problem.

The proposed approach refines the conventional understanding of research structure, in which the topic, hypothesis, and methods are often treated as the central components. The present analysis suggests that these

elements acquire their full meaning only within a broader organizational framework. Without such a framework, a study may remain technically rigorous while being conceptually fragmented, testing an isolated effect without understanding its place within the structure of the process under investigation. Similar limitations have been repeatedly identified in methodological literature as one of the major causes of the low cumulative value of applied research (Glasziou et al., 2014; Wasserstein & Lazar, 2016).

The results further indicate that such reductionism is particularly problematic in physical education and sport. Learning, training, and adaptation processes are characterized by nonlinear dynamics, developmental phases, effect thresholds, and interactions among multiple factors (Kiely, 2012; Halson, 2014). Under these conditions, traditional two-group designs can reveal differences between selected conditions but often fail to answer more fundamental questions: Where does the beneficial effect begin? Within which range is the optimum achieved? When does a plateau emerge? Under what conditions do overload and regression occur? Consequently, multifactorial designs, repeated-measures approaches, and response-surface methodologies provide a more productive framework because they allow researchers to investigate the space of possible operating regimes rather than isolated comparisons. This conclusion is consistent with empirical studies on physical education, motor learning, and training adaptation (Box & Wilson, 1951; Collins et al., 2009; Ivashchenko et al., 2016; Ivashchenko et al., 2018).

An important outcome of the study is the process-oriented interpretation of learning, education, and training as forms of controlled correction of deviations from functionally appropriate modes of activity. Such an interpretation shifts the focus away from the transmission of information or mechanical repetition of exercises and toward the mechanisms of error detection, feedback, and restoration of effective action patterns. Within this framework, learning may be understood as the development of a system's capacity for self-correction, whereas training represents the enhancement of regulatory mechanisms that maintain effectiveness under changing conditions. This interpretation is consistent with contemporary theories of motor learning, in which feedback, error correction, and adaptive control occupy a central position.

The proposed interpretation is also consistent with the concept of the central contradiction of development. Every adaptive system must simultaneously change in response to new demands and preserve the stability of its essential functions. Excessive stability results in stagnation, whereas excessive change leads to disorganization. Therefore, the effectiveness of pedagogical and training interventions is determined not by the magnitude of the stimulus itself but by the ability to regulate the boundary between stimulation and disruption, adaptation and overload, renewal and preservation of structure. This logic corresponds closely to contemporary views of adaptation as a dynamic balance between stress and recovery (Kiely, 2012; Halson, 2014).

A further contribution of the study is the interpretation of residual effects as a mechanism through which change accumulates over time. If every productive intervention leaves a temporary functional trace, then the overall outcome depends on the relationship between the preservation of that trace and the level of system fatigue. Excessively long intervals shift the process toward forgetting, whereas excessively dense repetitions increase the risk of functional exhaustion. Consequently, the management of recovery intervals, training volume, and intervention structure becomes not merely a technical issue but a central component of developmental logic. Similar mechanisms have been described in studies of adaptation and training process planning.

The formal model proposed in this study, in which system dynamics are represented as an interaction between forces of stimulation and forces of regulation, is not intended to serve as a universal description of all biological and pedagogical processes. Its value lies primarily in its heuristic potential. The model provides a conceptual explanation for why development rarely follows a linear trajectory, why periods of rapid progress are often followed by plateaus, and why regression may occur despite continued intervention. From this perspective, growth models can be interpreted as observable manifestations of the interaction between stimulation and regulation within the system.

The findings also support the view that methodology should be understood not merely as a collection of technical procedures but as a system for generating knowledge. Within such a framework, statistical methods must be aligned with research design at the planning stage, while data structures should preserve opportunities for reanalysis, investigation of factor interactions, and application of more advanced analytical models. The use of factorial and discriminant analyses in pedagogical control and the study of motor skill development provides a practical example of this logic (Ivashchenko et al., 2016; Ivashchenko et al., 2018). This perspective is consistent with contemporary principles of reproducible research and open science (Ioannidis, 2016).

The practical significance of the proposed concept lies in its potential application as a tool for evaluating scientific studies. Any research project may be assessed according to whether it possesses a meta-level of organization: whether a conceptual core has been identified, whether the design corresponds to the nature of the process under investigation, and whether the collected data allow the identification of mechanisms rather than merely differences between mean values. For editorial and peer-review practice, this perspective provides an additional criterion for assessing the scientific quality of manuscripts.

The principal limitation of the present study is its theoretical and methodological nature, together with its reliance on a single scientific tradition for empirical verification. Nevertheless, this concentration of material made it possible to evaluate the proposed concept at the same level of generalization at which it was formulated, tracing the connection between conceptual foundations, experimental design, and reproducible outcomes across a series of interconnected research programmes. Future research may focus on interdisciplinary validation of the model in other fields of knowledge and on the development of formalized criteria for identifying meta-problems in contemporary scientific literature.

Conclusions

The meta-problem represents the central contradiction of the research object and serves as the methodological

construct that determines the architecture of scientific inquiry, the logic of evidence generation, and the criteria for producing new knowledge. It functions as the organizing framework through which research questions, hypotheses, methods, and interpretations acquire coherence and scientific significance.

A meta-problem attains scientific value only when it is operationalized and subjected to empirical verification. Without translation into a system of variables, an experimental design, and an evidence-generating procedure, it remains a purely theoretical construct.

In the field of physical education and sport, learning, education, and training may be interpreted as derivative manifestations of a unified process involving the identification of deviations from functionally appropriate modes of activity and their subsequent correction. This perspective makes it possible to conceptualize human development as a controlled process aimed at maintaining effectiveness under changing environmental and functional conditions.

The central mechanism underlying development is the contradiction between the necessity for change and the necessity for preserving functional stability. The effectiveness of pedagogical and training interventions is therefore determined by the capacity to regulate the relationship among stimulation, adaptation, and system constraints.

When the positive influence of a factor is local and limited, traditional control–experimental group designs possess restricted explanatory value. More informative approaches for identifying optimal operating regimes include multifactorial experimental designs, repeated-measures strategies, longitudinal studies, and response-surface methodologies.

Research methodology should be regarded as an integrated system that combines knowledge about the nature of the object, experimental planning, embedded analytical procedures, and data openness that allows repeated multifactorial analysis. Such integration provides the foundation for transforming empirical observations into cumulative scientific knowledge.

The practical significance of the meta-problem concept lies in its potential application as a framework for research design, manuscript evaluation, and assessment of whether a study is capable of generating not only isolated findings but also cumulative and transferable scientific knowledge.

Ethics Approval

This study was conducted in accordance with the ethical principles of scientific research, standards of academic integrity, and the provisions of the Declaration of Helsinki relevant to analytical and theoretical investigations. The study was theoretical and methodological in nature and did not involve human participants, clinical interventions, collection of personal data, or the use of biological materials. Therefore, approval from an institutional ethics committee was not required.

Informed Consent

Informed consent was not required because the study did not involve human participants, surveys, interviews, observations, or the use of identifiable personal data.

Data Availability Statement

The data supporting the findings of this study are contained within the article. The study is based on the analysis of materials available in the public scientific domain and on the synthesis of findings reported in previously published research.

AI Transparency Statement

Artificial intelligence tools were used during manuscript preparation as supportive instruments for language editing, text refinement, content organization, and technical editorial assistance. All conceptual contributions, scientific interpretations, final formulations, and responsibility for the content of the article remain solely with the authors.

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Conflict of Interest Statement

The authors declares no actual or potential conflict of interest related to the publication of this study.

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Мета-проблема в науковому дослідженні у фізичному вихованні і спорті: архітектура і шляхи до знання

Олег Худолій[1ABCD], Ольга Іващенко[1ABCD], Микола Худолій[1ABCD]

[1]Харківська державна академія фізичної культури

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

Реферат. Стаття: 9 с., 5 табл., 1 рис., 26 джерел.

Актуальність. Сучасне наукове дослідження дедалі частіше стикається не з нестачею даних, а з нестачею належного рівня узагальнення, на якому дані можуть бути перетворені на знання. У багатьох прикладних галузях, зокрема у фізичному вихованні і спорті, технічно коректні дослідження нерідко залишаються фрагментарними через відсутність ширшої пояснювальної рамки.

Мета. Систематизувати підходи до розуміння мета-проблеми та її операціоналізації у дослідженнях з фізичного виховання і спорту.

Матеріали і методи. Дослідження виконано у форматі теоретико-методологічного аналізу з елементами ретроспективної емпіричної верифікації. Логіка роботи ґрунтувалася на припущенні, що продуктивні дослідницькі програми формуються не лише навколо локальних гіпотез, а навколо концептів вищого рівня узагальнення, які визначають архітектуру дослідження, послідовність доказування та шляхи отримання нового знання. Використано концептуальний аналіз, порівняльний методологічний синтез і ретроспективний аналіз завершених докторських досліджень, присвячених моделюванню процесів навчання, тренування та розвитку рухових здібностей.

Результати. Мета-проблему інтерпретовано як концептуальну конструкцію вищого рівня, що передує формулюванню теми, мети, гіпотези та вибору методів. Вона визначає рамку, у межах якої ці елементи набувають змістової узгодженості та наукового сенсу. Показано, що у фізичному вихованні і спорті навчання, виховання і тренування можуть розглядатися як похідні форми єдиного процесу виявлення відхилень від функціонально доцільного режиму діяльності та їх корекції. Центральне протиріччя розвитку полягає у необхідності змінюватися при одночасному збереженні функціональної стійкості. За умов локального та обмеженого позитивного впливу фактора класичні двогрупові схеми мають обмежену пояснювальну цінність, тоді як факторні плани, серійні вимірювання та моделі поверхні відгуку є більш продуктивними для пошуку оптимальних режимів.

Висновки. Мета-проблему доцільно розглядати як методологічний рівень, що організує критичний шлях наукового пошуку. Її практичне значення полягає в удосконаленні дизайну досліджень, експертизи рукописів і продукуванні кумулятивного наукового знання.

Ключові слова: мета-проблема, наукове дослідження, дизайн дослідження, методологія, генерація знання, фізичне виховання, спортивна наука, факторний експеримент, адаптаційні процеси, синтез доказів.

Information about the Authors:

Khudolii Oleg: khudolii.oleg@gmail.com; https://orcid.org/0000-0002-5605-9939; Department of Olympic and Professional Sports, Kharkiv State Academy of Physical Culture, Klochkivska St, 99, Kharkiv, 61022, Ukraine.

Ivashchenko Olha: ivashchenko.olha21@gmail.com; https://orcid.org/0000-0002-2708-5636; Department of Theory and Methods of Physical Education, Kharkiv State Academy of Physical Culture; Klochkivska St, 99, Kharkiv, 61022, Ukraine.

Khudolii Mykola: khudolii.mykola88@gmail.com; https://orcid.org/0009-0002-1482-6498; Kharkiv State Academy of Physical Culture, Klochkivska St, 99, Kharkiv, 61022, Ukraine.

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Review Article

Learning and Development in Digitally Mediated Physical Education: A Bibliometric and Thematic Evolution Analysis of Online, Open Distance, and Technology-Enhanced Learning (2015–2025)

Joseph Lobo[1,2ABCDE]

[1]Bulacan State University
[2]INTI International University

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

Corresponding Author: Joseph Lobo, e-mail: joseph.lobo@bulsu.edu.ph
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Abstract

Objectives. As physical education increasingly intersects with digital learning, artificial intelligence, and flexible modes of delivery, the field faces a critical question of how movement-based education can remain pedagogically meaningful in technologically mediated environments. This study mapped the global scholarship on digitally mediated physical education from 2015 to 2025, focusing on online, open-distance, and technology-enhanced learning.

Materials and Methods. Using a bibliometric design with thematic evolution analysis, 1,358 Scopus-indexed documents were examined using Bibliometrix/Biblioshiny and VOSviewer.

Results. The results revealed a rapidly expanding and interdisciplinary field shaped by the convergence of pedagogy, educational technology, artificial intelligence, public health, and computational learning systems. Conceptually, the literature was anchored in artificial intelligence, COVID-19, online learning, higher education, blended learning, distance learning, virtual reality, physical activity, digital technology, and educational technology. Bibliographic coupling and co-citation analyses showed that the field is sustained by both core pedagogical traditions and emerging technological knowledge bases. Thematic evolution indicated a progression from early ICT and blended learning applications toward pandemic-responsive online physical education and, more recently, AI-supported, immersive, teacher-oriented, and learner-centered digital pedagogies.

Conclusions. The study positions digitally mediated physical education as a developing learning-and-development field requiring stronger pedagogical, ethical, and theoretical grounding.

Keywords: digitally mediated physical education, online learning, open distance learning, artificial intelligence, bibliometric analysis, thematic evolution.

Introduction

Physical Education (PE) occupies a distinctive position in educational scholarship because it is not limited to the transmission of content knowledge or the performance of isolated movement skills. Rather, PE functions as an embodied learning environment where movement, cognition, affect, social interaction, health behavior, and personal development intersect. Bailey et al. (2009) emphasized that PE and school sport may contribute to learners' physical, social, affective, and cognitive development when educational claims are supported by sound pedagogical practice. Lubans et al. (2010) further positioned fundamental movement skills as important foundations for children's and adolescents' physical, cognitive, and social development. In relation to instructional outcomes, Lonsdale et al. (2013) showed that PE-based interventions can increase students' moderate-to-vigorous physical activity when lessons are intentionally structured. Motivation is also central to PE's developmental function, as Haerens et al. (2010) linked students' motivational profiles in PE with the adoption of a

physically active lifestyle. These perspectives suggest that PE should be understood as a learning-and-development field in which movement experiences are connected to competence, motivation, participation, and long-term health-oriented behavior.

The increasing presence of digital technologies has complicated and expanded this traditional understanding of PE. Digital mediation does not simply transfer PE content from gymnasium to screen; it reconfigures how movement is demonstrated, practiced, monitored, assessed, and experienced. Gard (2014) anticipated that digitized health and PE would reshape how students encounter movement, health knowledge, and bodily learning. Enright and Gard (2016) similarly argued that media and digital technologies influence how sport and movement learning are socially and pedagogically organized. In broader educational settings, Boelens et al. (2017) identified flexibility, interaction, learning-process support, and affective climate as key design challenges in blended learning environments. Garrison and Kanuka (2004) further argued that blended learning has transformative potential when online and face-to-face learning are meaningfully integrated. Applied to PE, these arguments indicate that digital, blended, and open distance modes should not be viewed as neutral delivery systems, but as pedagogical environments that reshape participation, feedback, embodiment, and learner engagement.

The expansion of online learning, artificial intelligence, virtual reality, learning analytics, mobile learning, and teacher-facing digital tools has further widened the scope of digitally mediated PE. Rasheed et al. (2020) showed that the online component of blended learning introduces challenges related to learner self-regulation, technological readiness, teacher competence, and institutional support. In teacher education, Phelps et al. (2021) found that preservice PE teachers use technology for planning, instruction, and assessment, but also encounter barriers that point to the need for stronger technology-related preparation. Merchant et al. (2014) demonstrated that virtual reality-based instruction can influence learning outcomes across K-12 and higher education settings. Ifenthaler and Yau (2020) showed that learning analytics can support study success when data are used to provide meaningful feedback and learner support. Crompton and Burke (2023) documented the rapid expansion of artificial intelligence in higher education, suggesting that AI-supported learning has become increasingly important in contemporary digital pedagogy. These developments indicate that digitally mediated PE is no longer limited to online instruction or pandemic-era remote teaching, but now includes intelligent, immersive, data-informed, and technology-enhanced approaches to movement learning and learner development.

Despite this expansion, scholarship on digitally mediated PE remains marked by a methodological and pedagogical contradiction. On the one hand, digital learning, artificial intelligence, online instruction, open distance education, virtual reality, and educational technologies are increasingly being used to describe new possibilities for PE. On the other hand, much of this scholarship is dispersed across PE pedagogy, educational technology, public health, teacher education, sport science, and computationally oriented research, making it difficult to determine whether the field is developing around the embodied, relational, and developmental purposes of PE or being absorbed into broader technology-driven educational discourse. This creates a scientific problem for PE scholarship because the expansion of digital tools does not automatically clarify how movement learning, motivation, feedback, participation, teacher preparation, and learner development are being conceptually organized in digitally mediated environments. Without a bibliometric and thematic synthesis, the field risks appearing as a collection of platform-based, pandemic-responsive, AI-oriented, or EdTech-adjacent studies rather than as a coherent PE-centered learning-and-development research area. Donthu et al. (2021) noted that bibliometric analysis is useful for examining large volumes of scientific data and identifying the evolutionary nuances and emerging areas of a field, while Aria and Cuccurullo (2017) emphasized that science mapping tools such as Bibliometrix support comprehensive workflows for identifying the structure and development of research fields. Therefore, this study conducts a bibliometric and thematic evolution analysis of digitally mediated PE scholarship from 2015 to 2025, focusing on online, open distance, and technology-enhanced learning. By doing so, it aims to clarify how digitally mediated PE has developed as a PE-centered learning-and-development field, identify the intellectual and conceptual structures shaping its growth, and explain how pedagogical, technological, and learner-development concerns have transformed over time.

Materials and Methods

Research design

This study employed a bibliometric research design complemented by thematic evolution analysis to map the development of digitally mediated physical education scholarship from 2015 to 2025. The analysis focused on literature related to online learning, open distance learning, blended and hybrid learning, e-learning, artificial intelligence, virtual learning, educational technology, and other technology-enhanced approaches in Physical Education. A bibliometric approach was appropriate because it enabled the systematic examination of publication trends, citation patterns, collaboration networks, conceptual structures, and intellectual foundations within the field (Hoang, 2025). Thematic evolution analysis further supported the identification of how major topics shifted over time, particularly from early digital and blended learning applications toward online instruction, AI-supported learning, immersive technologies, and learner-centered digital pedagogy.

Data Source and Search Strategy

Table 1 summarizes the search strategy and inclusion parameters of the study, including the Scopus retrieval date. The bibliographic data were retrieved from Scopus using the TITLE-ABS-KEY field, which enabled the capture of records whose titles, abstracts, or keywords reflected the focus of the study. Scopus was selected because it provides structured bibliographic metadata suitable for bibliometric analysis, including source titles, author information, affiliations, citations, abstracts, and keywords. The search strategy combined Physical Education-related terms with digital learning and technology-related terms to ensure that

the corpus remained anchored in PE while capturing its interdisciplinary links with online learning, open distance education, blended learning, artificial intelligence, virtual learning, and educational technology.

The search was intentionally broad because digitally mediated PE is indexed across several overlapping terminologies. However, records were retrieved only when PE-related terms such as "physical education," "movement education," "sport pedagogy," "physical education teacher education," or "PETE" intersected with digital or technology-related terms within the same TITLE-ABS-KEY search field. This PE-centered search architecture was used to minimize the retrieval of general educational technology, artificial intelligence, or online learning studies that were not connected to PE, movement learning, sport pedagogy, or PETE. The search was restricted to English-language articles, reviews, and conference papers published from 2015 to 2025.

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 "physical educat*" OR "movement education" OR "sport pedagogy" OR "physical education teacher education" OR "PETE") AND ("online learning" OR "online teaching" OR "online instruction" OR "online education" OR "distance learning" OR "distance education" OR "open distance learning" OR "open and distance learning" OR "ODL" OR "remote learning" OR "remote teaching" OR "remote instruction" OR "e-learning" OR "elearning" OR "mobile learning" OR "m-learning" OR "virtual learning" OR "virtual teaching" OR "virtual instruction" OR "digital learning" OR "digital teaching" OR "digital instruction" OR "technology-enhanced learning" OR "technology enhanced learning" OR "blended learning" OR "hybrid learning" OR "flexible learning" OR "modular distance learning" OR "emergency remote teaching" OR "learning management system" OR "LMS" OR "digital platform" OR "online platform" OR "ICT" OR "educational technology" OR "digital technology" OR "artificial intelligence" OR AI)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))
Language	English
Document types	Article, Review and Conference Papers
Retrieval date	April 24, 2026
Final timespan of corpus	2015-2025

Eligibility Criteria and Corpus Delimitation

Records were included if they were indexed in Scopus as English-language articles, reviews, or conference papers published between 2015 and 2025 and were substantively connected to digitally mediated PE. The initial search yielded 1,605 records, which were screened and manually refined to ensure PE-centered relevance. Records were retained when they focused on online or open distance PE, blended or hybrid PE, technology-enhanced PE pedagogy, AI-supported PE, virtual or digital movement learning, PE teacher education, sport pedagogy, physical activity instruction, or PE-related learner development. Records were excluded when they primarily belonged to general educational technology, AI in education, online learning, open distance education, computer science, public health, or generic higher education without an explicit PE, movement education, sport pedagogy, or physical activity instruction focus.

Screening was conducted through an iterative eligibility-verification process. Titles, abstracts, author keywords, index keywords, source titles, and subject-area information were examined to determine whether each record was aligned with digitally mediated PE. Borderline records were rechecked after data cleaning, particularly those positioned between PE, general EdTech, AI-supported education, public health, and computational learning systems. Following corpus delimitation, the final dataset comprised 1,358 documents published across 525 sources and authored by 3,399 scholars. The corpus consisted of journal articles (n = 1,005), conference papers (n = 307), and reviews (n = 46).

Data Cleaning and Preprocessing

The retrieved records were screened and cleaned before analysis to improve consistency, relevance, and reliability. The process involved checking bibliographic fields for formatting inconsistencies, removing records outside the retained document categories, and manually excluding documents that did not align with the study's focus on digitally mediated PE. Titles, abstracts, author keywords, index keywords, source titles, and subject-area information were examined to determine whether each record demonstrated an explicit connection to PE, movement learning, sport pedagogy, physical activity instruction, PETE, or PE-related learner development. Furthermore, a verification pass was conducted after the initial cleaning to recheck borderline records, particularly those positioned between PE, general educational technology, AI-supported education, public health, online learning, and computational learning systems. Records with uncertain relevance were reassessed against the eligibility criteria and were retained only when their PE-centered or movement-learning connection was explicit in the bibliographic information. Author's Keywords were also reviewed and standardized to reduce fragmentation caused by spelling variation, capitalization, hyphenation, singular and plural forms, and closely related terms. A thesaurus file was used in VOSviewer to merge equivalent terms and improve the clarity of keyword co-occurrence, bibliographic coupling, and co-citation visualizations.

Bibliometric Analysis

The cleaned dataset was analyzed using Bibliometrix/Biblioshiny for descriptive bibliometric outputs and thematic

evolution (Aria & Cuccurullo, 2017, 2026), while VOSviewer was used for science mapping and network visualization (Bukar et al., 2023). Descriptive analysis summarized the field's publication growth, source productivity, author contributions, citation characteristics, document types, and collaboration indicators. Co-authorship and country collaboration analyses were used to examine collaborative patterns, while keyword co-occurrence analysis mapped the conceptual structure of the field. Bibliographic coupling at the source level identified contemporary research-front relationships among publication outlets, whereas co-citation analysis examined the shared intellectual foundations of the field. Trend-topic and thematic evolution analyses were also conducted to identify how major themes in digitally mediated Physical Education changed across the study period.

Network Thresholds and Visualization Parameters

Thresholds were selected to balance inclusiveness, readability, and interpretive clarity. Rather than maximizing the number of displayed items, the analysis retained settings that produced coherent and analytically meaningful network structures. The final thresholds were set at a minimum of 5 documents for country co-authorship, 9 occurrences for Author's Keyword co-occurrence, 10 documents for source-level bibliographic coupling, and 20 citations for source co-citation analysis. Author-level co-authorship was initially examined, but the resulting map was not sufficiently clear for interpretation; therefore, the country-level network was emphasized to capture international collaboration patterns more effectively. In the visualizations, nodes represented countries, keywords, sources, or cited sources depending on the analysis conducted, while links indicated the strength of association between items. Node size reflected relative prominence, and colors represented clusters of closely related items.

Source Composition and Interpretive Approach

The final corpus reflected the interdisciplinary character of digitally mediated PE, with sources drawn from PE pedagogy, sport education, educational technology, public health, computer science, and conference-based publication venues. This composition was considered appropriate because digitally mediated PE is not developed exclusively within traditional PE journals, but also through technological, computational, and health-oriented research spaces. Source interpretation distinguished between core PE and sport pedagogy outlets, educational technology and public health journals, and technology-oriented conference proceedings. Core PE and sport pedagogy sources were interpreted as more directly connected to movement learning, pedagogy, teacher education, and learner development, while technology-oriented and conference-based sources were interpreted as evidence of the field's broader digital and computational expansion.

Ethical Statement

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-2026-0145-EX.

Results

Descriptive Profile and Publication Growth

The final dataset comprised 1,358 documents published between 2015 and 2025 across 525 sources, indicating that digitally mediated Physical Education has become a substantial and visible research area. The corpus recorded an annual growth rate of 24.00%, an average document age of 3.90 years, and 9.61 citations per document, with 42,641 references supporting the dataset. The presence of 4,286 Keywords Plus and 3,141 Author Keywords further suggests a thematically diverse field shaped by online learning, distance education, artificial intelligence, digital technologies, blended learning, physical activity, and educational innovation. The authorship and document profile indicate a collaborative and article-driven field. A total of 3,399 authors contributed to the corpus, with 279 single-authored documents and an average of 3.31 co-authors per document. International co-authorship accounted for 15.39%, suggesting moderate cross-national collaboration. Journal articles dominated the corpus (n = 1,005), followed by conference papers (n = 307) and reviews (n = 46), reflecting the field's grounding in peer-reviewed research while also showing the influence of technology- and innovation-oriented conference outputs. Annual production, shown in Figure 1, demonstrates strong growth across the period. Output increased from 32 publications in 2015 to 56 in 2019, then rose sharply during the pandemic period, reaching 91 in 2020 and 218 in 2021. Although production declined in 2022 and 2023, it accelerated again in the most recent years, reaching 223 publications in 2024 and peaking at 275 in 2025. This pattern suggests that digitally mediated PE has moved beyond a temporary COVID-19 response and has become a sustained research area concerned with digital pedagogy, AI-supported learning, flexible delivery, and learner development.

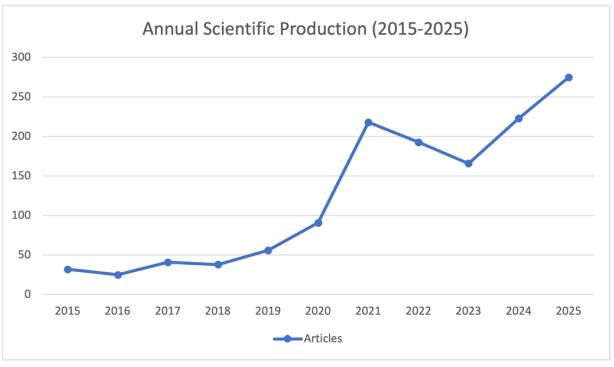

Fig. 1. Annual scientific production in digitally mediated physical education scholarship

Citation impact varied across annual cohorts, largely reflecting differences in citation maturity. Earlier and mid-period publications recorded higher mean total citations

per article, with 2017 showing the highest value (21.34), followed by 2020 (19.87), 2018 (19.05), and 2019 (17.46). When normalized by citable years, 2020 recorded the strongest mean citation performance (2.84 citations per year), suggesting that pandemic-era scholarship became an important point of consolidation for research on online, remote, and digitally mediated physical education. More recent publications, particularly those from 2024 and 2025, should be interpreted cautiously because they have had less time to accumulate citations. The citation profile indicates meaningful scholarly visibility while also reflecting the expected temporal effects of citation accrual.

Leading Sources, Authors, Affiliations and Influential Documents

As shown in Table 2, scholarship on digitally mediated PE is distributed across a distinctly interdisciplinary publication base, shaped by conference proceedings, Physical Education journals, sport pedagogy outlets, educational technology sources, and broader health and public health journals. The Journal of Physics: Conference Series emerged as the most productive source with 44 articles, followed by the ACM International Conference Proceeding Series with 39 articles. This pattern indicates the strong presence of computational, technological, and conference-based scholarship within the field, particularly in relation to artificial intelligence, digital systems, learning technologies, and technology-enhanced educational applications. At the same time, the presence of Journal of Physical Education and Sport with 36 articles, Sport, Education and Society with 27 articles, Journal of Teaching in Physical Education with 26 articles, Retos with 25 articles, European Physical Education Review with 19 articles, and Journal of Physical Education, Recreation and Dance with 19 articles confirms that the field remains firmly anchored in PE pedagogy, sport education, teacher education, and movement-based learning. Additional contributions from Applied Mathematics and Nonlinear Sciences and the International Journal of Environmental Research and Public Health further suggest that digitally mediated PE has developed at the intersection of computational methods, pedagogical innovation, health promotion, and educational development.

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

Sources	Number of articles
Journal of Physics: Conference Series	44
ACM International Conference Proceeding Series	39
Journal of Physical Education and Sport	36
Applied Mathematics and Nonlinear Sciences	33
International Journal of Environmental Research and Public Health	27
Sport, Education and Society	27
Journal of Teaching in Physical Education	26
Retos	25
European Physical Education Review	19
Journal of Physical Education, Recreation and Dance	19

The author citation profile presented in Table 3 likewise points to a recognizable group of influential contributors whose work has shaped the scholarly conversation around technology, pedagogy, online learning, and Physical Education. Goodyear, V. A. emerged as the most cited author within the corpus with 114 citations, followed by Wang, Y. with 108 citations, Casey, A. with 84 citations, and Calderón, A. with 83 citations. Other highly cited authors included Killian, C. M. with 81 citations, Sargent, J. with 68 citations, Armour, K. M. with 59 citations, González-Calvo, G. with 57 citations, Marttinen, R. with 56 citations, and Macphail, A. with 48 citations. This pattern suggests that the field is shaped by scholars working across Physical Education pedagogy, digital technology, online and blended instruction, teacher education, and pandemic-related pedagogical adaptation. Rather than reflecting a purely technical or platform-driven body of research, the author citation profile indicates that digitally mediated PE is strongly informed by pedagogical, sociocultural, and teacher-centered perspectives.

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

Author	Citations
Goodyear, V. A.	114
Wang, Y.	108
Casey, A.	84
Calderón, A.	83
Killian, C. M.	81
Sargent, J.	68
Armour, K. M.	59
González-Calvo, G.	57
Marttinen, R.	56
Macphail, A.	48

Table 4 presents the most locally cited documents, which indicate the key intellectual anchors of the corpus. Casey et al. (2017) ranked first with 53 local citations and 190 global citations, highlighting the field's concern with the relationship between pedagogy, technology, and learning in health and Physical Education. This is followed by Jeong and So (2020)and three were recommended teachers making efforts to improve the online classes offered by the Korea Ministry of Education. A qualitative case study method employing phenomenological procedures to collect and analyze the data was used. The difficulties of operating middle and high school online physical education classes for the first time included (1, whose work on online PE during the pandemic received 47 local citations and 125 global citations, reflecting the strong influence of COVID-19-related remote instruction research. The remaining highly cited documents further show that the field is shaped by four major concerns: digital pedagogy, pandemic-driven instructional change, artificial intelligence, and online or blended PE. Studies by Varea et al. (2022)where close proximity and physical contact is common, particularly in Spain which has a high proximity culture. Significantly, the delivery of PE has changed because of the Covid-19 pandemic, and this brings significant consequences for preservice PE teachers. Purpose: The aim of the paper is to explore the changes of PE during Covid-19 and the effects on

pre-service teachers. Methods: Semi-structured interviews were used to produce data with a group of 12 preservice PE teachers from Spain (four women and eight men, Lee and Lee (2021)including education. AI can also provide special support to learners through academic sustainability or discontinuation predictions. While AI research remains in its early stages, we must examine how it evolves and exerts its potential over time. By utilizing AI in physical education (PE, Mercier et al. (2021)362, Bodsworth and Goodyear (2017), Killian et al. (2019), O'Brien et al. (2020), Howley (2022) and Chan et al. (2021) collectively point to a literature centered on technology integration, teacher adaptation, remote learning, AI-supported PE, and digital instructional models.

At the institutional level, Table 5 indicates an internationally distributed but selective network of affiliations contributing to digitally mediated PE scholarship. Deakin University emerged as the most productive affiliation with 21 articles, followed by the University of Limerick (15) and the University of Granada (11). A second group of productive institutions included Australian Catholic University, Universiti Sains Malaysia, and the University of New Hampshire (10). Additional contributions came from Universiti Putra Malaysia (9), and Dublin City University, Loughborough University, and Lviv Polytechnic National University (8). This affiliation profile suggests that the field is not concentrated in a single geographic or institutional center. Instead, it is sustained by a distributed international network of universities with strengths in PE, sport pedagogy, teacher education, educational technology, and health-related research.

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

Affiliation	Articles
Deakin University	21
University of Limerick	15
University of Granada	11
Australian Catholic University	10
Universiti Sains Malaysia	10
University of New Hampshire	10
Universiti Putra Malaysia	9
Dublin City University	8
Loughborough University	8
Lviv Polytechnic National University	8

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

Document	Local citations	Global citations
Casey, A., Goodyear, V. A., & Armour, K. M. (2017). Rethinking the relationship between pedagogy, technology and learning in health and physical education. Sport, Education and Society, 22(2), 288–304. https://doi.org/10.1080/13573322.2016.1226792	53	190
Jeong, H.-C., & So, W.-Y. (2020). Difficulties of Online Physical Education Classes in Middle and High School and an Efficient Operation Plan to Address Them. International Journal of Environmental Research and Public Health, 17(19), 7279–7279. https://doi.org/10.3390/ijerph17197279	47	125
Varea, V., González-Calvo, G., & García-Monge, A. (2022). Exploring the changes of physical education in the age of Covid-19. Physical Education and Sport Pedagogy, 27(1), 32–42. https://doi.org/10.1080/17408989.2020.1861233	40	127
Lee, H. S., & Lee, J. (2021). Applying Artificial Intelligence in Physical Education and Future Perspectives. Sustainability, 13(1), 351. https://doi.org/10.3390/su13010351	39	149
Mercier, K., Centeio, E., Garn, A., Erwin, H., Marttinen, R., & Foley, J. (2021). Physical Education Teachers' Experiences With Remote Instruction During the Initial Phase of the COVID-19 Pandemic. Journal of Teaching in Physical Education, 40(2), 337–342. https://doi.org/10.1123/jtpe.2020-0272	39	84
Bodsworth, H., & Goodyear, V. A. (2017). Barriers and facilitators to using digital technologies in the Cooperative Learning model in physical education. Physical Education and Sport Pedagogy, 22(6), 563–579. https://doi.org/10.1080/17408989.2017.1294672	36	129
Killian, C. M., Kinder, C. J., & Woods, A. M. (2019). Online and Blended Instruction in K–12 Physical Education: A Scoping Review. Kinesiology Review, 8(2), 110–129. https://doi.org/10.1123/kr.2019-0003	29	56
O'Brien, W., Adamakis, M., O' Brien, N., Onofre, M., Martins, J., Dania, A., Makopoulou, K., Herold, F., Ng, K., & Costa, J. (2020). Implications for European Physical Education Teacher Education during the COVID-19 pandemic: A cross-institutional SWOT analysis. European Journal of Teacher Education, 43(4), 503–522. https://doi.org/10.1080/02619768.2020.1823963	29	101
Howley, D. (2022). Experiences of teaching and learning in K-12 physical education during COVID-19: An international comparative case study. Physical Education and Sport Pedagogy, 27(6), 608–625. https://doi.org/10.1080/17408989.2021.1922658	25	41
Chan, W. K., Leung, K. I., Hoc, C., Wuc, W., Lam, K. Y., Wong, N. L., Chan, C. Y. R., Leung, K. M., & Tse, A. C. Y. (2021). Effectiveness of online teaching in physical education during covid-19 school closures: A survey study of frontline physical education teachers in Hong Kong. Journal of Physical Education and Sport, 21(4), 1622–1628. https://doi.org/10.7752/jpes.2021.04205	24	41

Collaborative Structure of the Field

Author-level co-authorship was initially examined, but the network was not sufficiently clear for interpretation. Collaboration was therefore analyzed at the country level. As shown in Figure 2, 52 countries were connected in the final network, indicating that digitally mediated PE scholarship has developed a broad international collaboration base. The network shows that collaboration is global but unevenly distributed. China appears as the most central hub, with the largest node and multiple cross-national links. Other countries contribute to the connected structure, but with comparatively smaller and less central positions. Overall, the map suggests that the field is internationally networked, yet collaboration remains concentrated around a limited number of highly active countries.

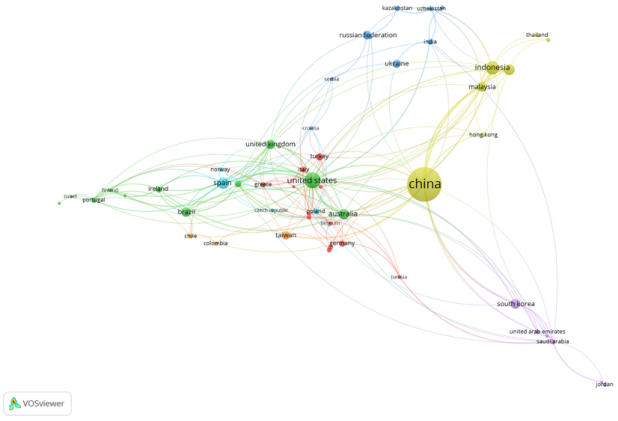

Fig. 2. Country co-authorship network map in digitally mediated physical education scholarship

The countries' collaboration world map in Figure 3 reinforces the international but uneven structure of digitally mediated Physical Education scholarship. Cross-national collaboration is most visible around China, which appears as the most prominent hub, alongside strong linkages involving the United States, Australia, India, Canada, and parts of Europe and Southeast Asia. Although the map shows broad geographic reach, the collaboration pattern remains concentrated among a limited number of highly active countries rather than being evenly distributed across all regions. This suggests that the field has become globally connected, but its international knowledge production is still shaped by selective and dominant research hubs.

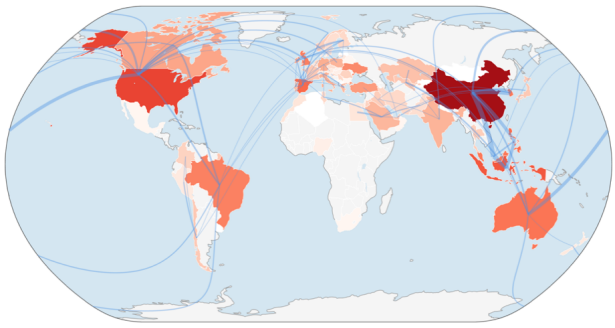

Fig. 3. Countries' collaboration world map in digitally mediated physical education scholarship

Conceptual Structure of the Field

The conceptual structure of digitally mediated PE scholarship was examined through a co-occurrence analysis of Author Keywords using a minimum threshold of 9 occurrences. At this level, 57 connected items formed 5 clusters (Figure 4), indicating that the field is conceptually organized around digital pedagogy, online delivery, teacher development, emerging technologies, and pandemic-related teaching and learning. The red cluster represents digital and blended learning applications in PE, including terms such as "blended learning," "e-learning," "flipped classroom," "gamification," "mobile learning," "motivation," "learning outcomes," "physical activity" and "teacher training." The green cluster reflects AI-driven and advanced technological systems, organized around "artificial intelligence," "machine learning," "deep learning," "big data," "internet of things (IoT)", "virtual reality," "wearable technology" and "online physical education." The blue cluster highlights online learning and teacher education, linking adapted "physical education," "digital learning," "distance learning," "online learning," "physical education teacher education," "professional development" and "teacher education." The yellow cluster captures pedagogical integration and instructional support, with terms such as "assessment," "information and communications technology," "pedagogy," "teachers," "technology integration" and "TPACK." Finally, the purple cluster reflects pandemic-related and learner-centered concerns, centered on "COVID-19," "online teaching," "self-efficacy" and "student engagement." The network shows that the field is structured by the convergence of pedagogy, digital delivery, intelligent technologies, and learner development.

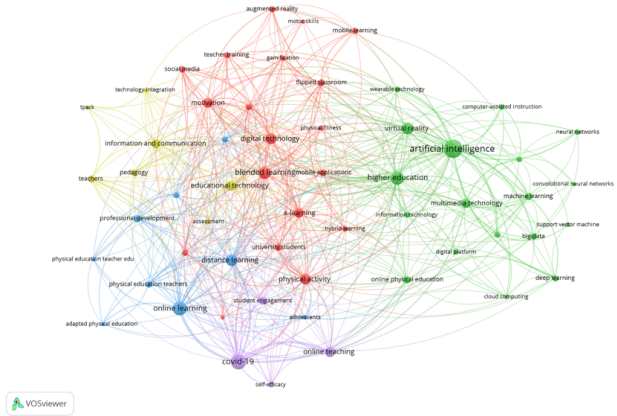

Fig. 4. Co-occurrences network map in digitally mediated physical education scholarship

Table 6 further clarifies the conceptual profile of the field by identifying the most frequent Author Keywords in the corpus. "Artificial intelligence" emerged as the most frequent keyword with 150 occurrences and a total link strength of 116, indicating the growing prominence of intelligent systems and AI-supported applications in digitally mediated PE. "Covid-19" ranked second with 109 occurrences and the highest total link strength (132), confirming the pandemic's strong role in accelerating research on online, remote,

and technology-supported PE. Other frequent keywords included "online learning" (85), "higher education" (81), "blended learning" (66), "distance learning" (64), "virtual reality" (61), "physical activity" (55), "digital technology" (54) and "educational technology" (48). These patterns suggest that the field is conceptually organized around AI, pandemic-responsive teaching, online and distance learning, higher education contexts, immersive technologies, physical activity, and broader educational technology integration.

Table 6. Most frequent Author's Keywords

Rank	Author's Keyword	Occurrences	Total link strength
1	Artificial intelligence	150	116
2	Covid-19	109	132
3	Online learning	85	97
4	Higher education	81	92
5	Blended learning	66	78
6	Distance learning	64	61
7	Virtual reality	61	52
8	Physical activity	55	78
9	Digital technology	54	55
10	Educational technology	48	50

Furthermore, the trend-topics analysis shows a clear temporal shift in digitally mediated Physical Education scholarship. Earlier topics were associated with "multimedia technology," "health and physical education," "adapted physical education," "mobile learning," "flipped classroom" and "digital learning," suggesting an initial emphasis on technology-supported instruction and early digital applications in PE. Around the pandemic period, terms such as "college physical education," "teaching," "COVID-19," "blended learning" and "physical activity" became more visible, reflecting the field's response to remote instruction, flexible delivery, and activity-based learning during educational disruption. In the most recent period, the literature increasingly centered on "online learning," "digital technology," "artificial intelligence," "educational technology," "virtual reality," "gamification" and "student engagement." This pattern suggests that the field has moved from general digital and blended delivery toward more specialized concerns involving AI-supported learning, immersive technologies, learner engagement, and future-oriented digital pedagogy.

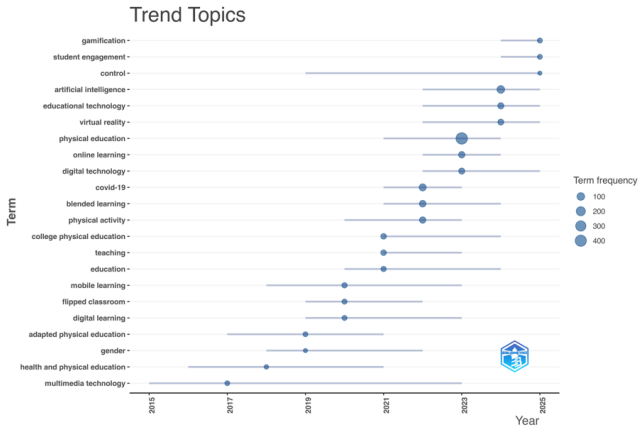

Fig. 5. Trend topics based on Author's Keywords in digitally mediated physical education scholarship

Figure 6 presents the thematic evolution of digitally mediated PE scholarship across four periods. During 2015-2018, the field was mainly shaped by early digital and instructional themes such as "physical education," "ICT," "digital technologies," "blended learning model," "motor activity," "cooperative learning" and "autonomous motivation." In 2019-2021, the themes shifted toward "digital technologies," "blended learning," "COVID-19," "students," "college physical education," "online adapted physical education" and adapted "physical education," reflecting the strong influence of pandemic-related instructional changes. By 2022-2023, the field became more technologically diversified, with themes such as "artificial intelligence," "internet of things," "health promotion," "action recognition," "online education," "teacher education" and "fully online teaching" becoming more visible. In the most recent period, 2024-2025, the literature moved further toward "online learning," "artificial intelligence," "ICT," "pre-service teacher training," "academic self-efficacy," "autonomous motivation," "virtual reality technology" and "digital technologies." The thematic evolution suggests that the field has progressed from early ICT-based and blended learning applications toward a broader digital learning-and-development ecosystem shaped by AI, online delivery, teacher preparation, learner motivation, and immersive technologies.

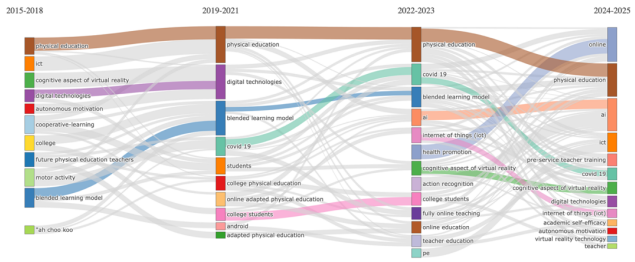

Fig. 6. Thematic Evolution of scholarship in mediated physical education

Intellectual Structure of the Field

The bibliographic coupling map in Figure 7 shows that the contemporary research front of digitally mediated Physical Education is organized into four source clusters. The red cluster represents technology- and computation-oriented outlets, including Journal of Physics: Conference Series, ACM International Conference Proceeding Series, Applied Mathematics and Nonlinear Sciences, and related sources. The green cluster reflects educational technology and public-health-oriented research, with sources such as Education and Information Technologies, Education Sciences, Frontiers in Public Health, and Interactive Learning Environments. The blue cluster represents the core Physical Education and sport pedagogy literature, including Journal of Teaching in Physical Education, Physical Education and Sport Pedagogy, Sport, Education and Society, and European Physical Education Review. The yellow cluster appears as a smaller peripheral conference-based stream. The map suggests that the field is shaped by the convergence of computational innovation, educational technology, public health, and PE pedagogy.

Table 7. Bibliographic coupling clusters of sources

Cluster	Theme	Sources (n)	Representative sources
1	Computational, AI, and Technology-Driven Learning Systems in Physical Education	15	ACM International Conference Proceeding Series; Applied Mathematics and Nonlinear Sciences; Computer-aided Design and Applications; Frontiers in Psychology
2	Digital Pedagogy, Online Learning, and Health-Oriented Educational Development	6	Education and Information Technologies; Education Sciences; Frontiers in Public Health; Interactive Learning Environment
3	Physical Education Pedagogy, Sport Education, and Movement-Based Learning	5	E3S Web of Conferences; European Physical Education Review; Journal of Teaching in Physical Education; Physical Education and Sport Pedagogy

Note: A small peripheral cluster composed of two sources, Journal of Physical Education, Recreation and Dance and Proceedings – 2021 International Conference on Information Technology and Contemporary Sports, TCS 2021, was retained in the visualization but not interpreted as a major cluster due to its limited size. This cluster may indicate a smaller practice-oriented stream linking applied Physical Education, sport technology, and professional innovation.

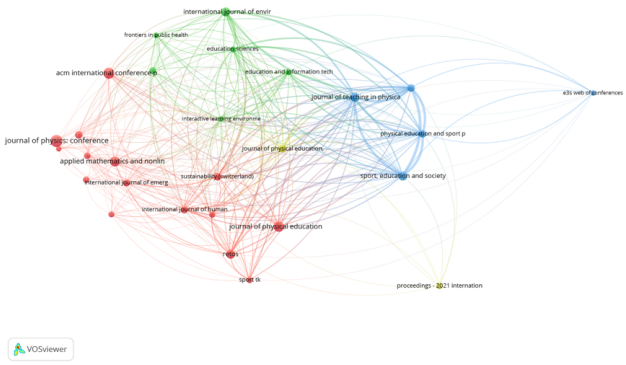

Fig. 7. Bibliographic coupling network in digitally mediated physical education scholarship

Table 7 further clarifies the intellectual structure of the field by showing that the publication front is organized into three major thematic clusters and one small peripheral cluster. Cluster 1 centers on computational, AI, and technology-driven learning systems in PE, bringing together sources linked to artificial intelligence, digital systems, and applied technological innovation. Cluster 2 reflects digital pedagogy, online learning, and health-oriented educational development, highlighting journals focused on educational technology, online instruction, and broader health-related learning contexts. Cluster 3 captures physical education pedagogy, sport education, and movement-based learning, indicating the continued importance of core PE and sport pedagogy outlets in shaping the field. A small peripheral cluster was also observed, suggesting a minor practice-oriented stream related to applied PE, sport technology, and professional innovation. These groupings show that the field is intellectually sustained by the convergence of technological innovation, digital pedagogy, and core Physical Education scholarship.

The co-citation analysis presented in Figure 8 further clarifies the foundational knowledge base of digitally mediated PE scholarship. Using a minimum threshold of 5 citations, the network formed 5 clusters, indicating that the field draws from several related but distinct citation traditions. The red cluster reflects PE pedagogy, assessment, and online education foundations, represented by sources such as Adapted Physical Activity Quarterly, American Journal of Distance Education, Assessment and Evaluation in Higher Education, and Australasian Journal of Educational Technology. The green cluster represents medical, public health, and sport science foundations, including BMC Medical Education, BMC Public Health, BMJ, and British Journal of Sports Medicine. The blue cluster captures computational and analytics-oriented foundations, with sources such as Applied Sciences, CEUR Workshop Proceedings, Complexity, and Computational Intelligence and Neuroscience. The yellow cluster highlights psychology, public health, and behavioral-health perspectives, represented by Frontiers in Psychology, Frontiers in Sports and Active Living, International Journal of Behavioral Nutrition and Physical Activity, and International Journal of Environmental Research and Public Health. Finally, the purple cluster reflects core PE and sport pedagogy foundations, including Acta Gymnica, Asia-Pacific Journal of Health, Sport and Physical Education, Curriculum Studies in Health and Physical Education, and the books Digital Technologies and Learning in Physical Education and Digital Technology in Physical Education. The co-citation structure suggests that the field is grounded in PE pedagogy, public health, educational technology, and computational innovation.

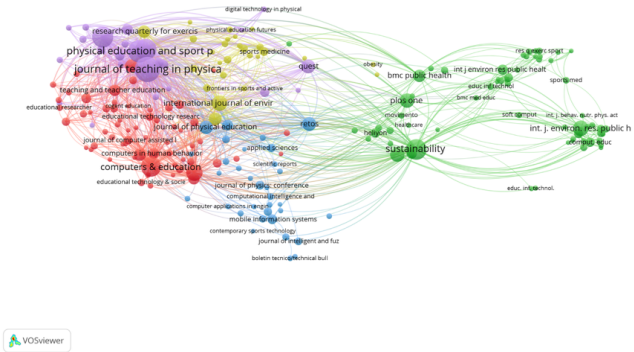

Fig. 8. Co-citation network in digitally mediated physical education scholarship

Discussion

Digitally Mediated Physical Education Has Moved Beyond Emergency Remote Teaching

The findings suggest that digitally mediated PE should no longer be interpreted merely as an emergency response

to educational disruption. Although the pandemic clearly accelerated online and remote PE scholarship, the field now appears to be moving toward a more durable digital learning ecosystem. This shift can be explained by the changing pedagogical function of technology in PE. In earlier applications, digital tools often served as instructional supplements for demonstration, communication, content delivery, or activity monitoring. Overtime, digital mediation became more central to how PE teachers organized participation, feedback, assessment, motivation, and learner interaction, especially when conventional face-to-face movement instruction was disrupted or reconfigured. This transformation reflects a movement from technology as delivery infrastructure to technology as pedagogical mediation. Casey et al. (2017) argued that digital technology in health and PE should be understood through its relationship with pedagogy and learning rather than as a neutral instructional add-on. This interpretation is reinforced by Casey and Jones (2011), who showed that digital technology can enhance student engagement in PE when embedded within meaningful pedagogical design. Similarly, Bodsworth and Goodyear (2017) demonstrated that technology integration becomes educationally valuable when it supports cooperative learning rather than merely digitizing existing practices. Goodyear et al. (2023) further emphasized that online physical activity interventions have potential when designed around engagement, participation, and pedagogical relevance rather than platform use alone. Therefore, the present findings indicate that digitally mediated PE has expanded because the field increasingly recognizes that technology does not simply transmit PE content; it reorganizes the conditions through which movement learning, engagement, feedback, and participation become possible.

Covid-19 Functioned as A Catalyst, Not the Final Identity of the Field

The prominence of COVID-19-related terms should be interpreted as a turning point in the field rather than as evidence that digitally mediated PE is limited to pandemic scholarship. The pandemic accelerated the field because it exposed a central pedagogical tension in PE. Movement learning has historically depended on physical co-presence, direct observation, embodied demonstration, immediate feedback, and social interaction, yet these conditions were suddenly displaced into remote and digitally mediated environments. This disruption forced PE scholars and teachers to examine what could still be preserved, adapted, or redesigned when the gymnasium, playing area, and shared physical space were no longer the default conditions for instruction. Jeong and So (2020)and three were recommended teachers making efforts to improve the online classes offered by the Korea Ministry of Education. A qualitative case study method employing phenomenological procedures to collect and analyze the data was used. The difficulties of operating middle and high school online physical education classes for the first time included (1 showed that online PE during school closures exposed difficulties in participation, feasibility, and instructional operation, making visible the pedagogical vulnerabilities of remote movement-based learning. Varea et al. (2022)where close proximity and physical contact is common, particularly in Spain which has a high proximity culture. Significantly, the delivery of PE has changed because of the Covid-19 pandemic, and this brings significant consequences for preservice PE teachers. Purpose: The aim of the paper is to explore the changes of PE during Covid-19 and the effects on pre-service teachers. Methods: Semi-structured interviews were used to produce data with a group of 12 preservice PE teachers from Spain (four women and eight men similarly argued that the pandemic changed how PE was experienced and delivered, particularly because PE is traditionally embodied, social, and practice-based. Mercier et al. (2021)362 further showed that PE teachers' early experiences with remote instruction revealed substantial challenges in adaptation, communication, and instructional redesign. O'Brien et al. (2020) extended this concern to PETE, showing that the pandemic disrupted not only school PE delivery but also the preparation of future PE teachers. In this sense, COVID-19 became an epistemic catalyst because it made the field confront what counts as meaningful PE when embodiment, feedback, interaction, and participation are mediated through digital systems. The pandemic did not define the final identity of digitally mediated PE; rather, it revealed the pedagogical problems that later research on online learning, AI, virtual environments, and technology-enhanced instruction attempted to address.

The Emerging Field Requires Stronger Alignment Between Technology and Pedagogy

A major implication of the findings is that digitally mediated PE must be guided by pedagogy rather than by technological novelty. The thematic movement toward online learning, AI-supported instruction, teacher education, and digital platforms suggests that the field is evolving because PE teachers and scholars are increasingly required to translate movement-based learning into environments where demonstration, feedback, assessment, and interaction are no longer fully dependent on shared physical space. This creates a pedagogical design problem rather than a purely technical problem. Digital PE becomes meaningful only when technology helps teachers sustain the educational purposes of PE, including movement competence, motivation, inclusion, reflective learning, and lifelong physical activity orientation. Howley (2022) showed that teaching and learning in K-12 PE during COVID-19 varied across contexts, suggesting that digital delivery is shaped by institutional conditions, teacher capacity, and pedagogical interpretation. O' Brien et al. (2022) further demonstrated that pandemic-era PETE affected student teachers' practice and well-being, reinforcing the need to treat digital PE as a professional preparation issue rather than only a delivery issue. Lee and Lee (2021)including education. AI can also provide special support to learners through academic sustainability or discontinuation predictions. While AI research remains in its early stages, we must examine how it evolves and exerts its potential over time. By utilizing AI in physical education (PE positioned artificial intelligence as a future-facing resource for PE, particularly in areas such as learner evaluation, customized instruction, and feedback. However, Zawacki-Richter et al. (2019)2019 cautioned in the broader AI-in-education literature that AI applications often

advance faster than educators' pedagogical understanding of how these systems should shape teaching and learning. These works suggest that the epistemic direction of digitally mediated PE should not be determined by the availability of platforms, AI systems, or digital tools, but by their capacity to support learning quality, feedback, motivation, inclusion, and meaningful movement participation.

Immersive And Intelligent Technologies Are Expanding the Boundaries of PE Learning

The increasing visibility of artificial intelligence, virtual reality, mobile learning, and educational technology suggests that digitally mediated PE is entering a more technologically complex phase. This evolution can be explained by the search for tools that can extend or partially compensate for what PE traditionally provides through direct bodily presence. Terms/themes such as demonstration, movement feedback, spatial awareness, performance observation, peer interaction, and adaptive instruction. AI, VR, wearable technologies, and learning analytics become visible in the field because they promise new ways of monitoring movement, personalizing feedback, simulating activity environments, and supporting learner engagement beyond conventional classroom or gymnasium settings. Radianti et al. (2020) showed that immersive virtual reality in higher education requires careful attention to design elements, learning content, and theory, which is highly relevant for PE because movement learning depends on embodied, spatial, and experiential forms of participation. Bacca et al. (2014) similarly highlighted the educational potential of augmented reality, particularly when immersive technologies are aligned with learning tasks rather than treated as novelty tools. Bond et al. (2020) showed that educational technology research is increasingly tied to behavioral, affective, and cognitive engagement, which provides a useful lens for interpreting digital PE as a learner-development space. However, Goodyear et al. (2019) warned that wearable technologies in health and PE can produce surveillance, self-surveillance, and resistance, suggesting that digitally mediated PE must also be ethically examined. This concern becomes more urgent as AI, wearable devices, learning analytics, and platform-based PE increasingly involve bodily data, performance records, health indicators, movement traces, and learner behavior. Thus, the future of the field depends not only on whether AI, VR, and wearable tools can enhance instruction, but also on whether they can protect student safety, ensure data privacy, prevent harmful surveillance, support autonomy and inclusion, and promote healthy relationships with physical activity.

Future Research Should Foreground Learning and Development Rather Than Technology Alone

The strongest contribution of this field lies in repositioning digitally mediated PE as a learning-and-development environment rather than as a technology-adoption space. The thematic evolution observed in the corpus suggests that the field is gradually shifting from questions of access, delivery, and platform use toward deeper concerns about motivation, engagement, feedback, self-efficacy, teacher preparation, embodied learning, and learner development. PE cannot be evaluated only by whether technology enables instruction to continue; it must also be examined according to whether digitally mediated experiences support meaningful movement participation, competence development, social connection, and long-term physical activity orientation. Lupton (2015) showed that digitized health and PE raise important questions about how bodies, data, and schooling are assembled through technology. Rich and Lupton (2022) similarly argued that digital biopedagogies require attention to how health, bodies, and learning are reorganized through sociomaterial relations. Ryan and Deci (2020) emphasized that motivation and well-being depend on conditions that support autonomy, competence, and relatedness, which is especially important when PE shifts into online, AI-supported, or technology-enhanced environments. Ennis (2017) argued that PE should educate students for lifelong physical activity by strengthening motivation, meaning, and mindful engagement. These perspectives suggest that future research should move beyond measuring access, platform use, or technological adoption and instead examine whether digitally mediated PE supports movement competence, self-efficacy, student engagement, physical activity behavior, psychosocial development, data safety, and lifelong participation. This learning-and-development agenda is where digitally mediated PE can become more than a technical adaptation; it can become a reimagined pedagogical space for developing physically active, motivated, safe, and self-regulating learners.

Conclusions

This study positions digitally mediated physical education as an evolving pedagogical field rather than a temporary instructional adjustment or a purely technology-driven extension of traditional PE. Its value lies not simply in documenting the expansion of online learning, open distance learning, artificial intelligence, virtual reality, blended instruction, and educational technologies, but in showing that these developments collectively signal a deeper reconfiguration of how movement, learning, engagement, assessment, teacher preparation, and learner development are being imagined in digital environments. The central challenge moving forward is not whether technology will continue to enter physical education, but whether it will be used in ways that preserve the embodied, relational, inclusive, and developmental purposes of the discipline. Future scholarship must therefore move beyond describing digital tools and begin asking stronger pedagogical questions about how digitally mediated PE can cultivate motivation, competence, self-efficacy, physical activity participation, and lifelong movement orientation. In this sense, the future of the field depends on maintaining a careful balance between technological innovation and the human-centered educational mission of PE.

Limitations

This study has several limitations that should be considered when interpreting its findings. First, the analysis was limited to Scopus-indexed documents; therefore, relevant publications indexed exclusively in Web of Science, ERIC, PubMed, Google Scholar, regional databases, or non-indexed professional outlets may not have been captured.

Second, although the search strategy was designed to delimit a PE-centered corpus, the interdisciplinary nature of digitally mediated PE means that some adjacent studies from educational technology, sport science, public health, computer science, or computational learning fields may have entered the dataset. Third, the inclusion of conference papers and non-core PE sources may have shaped some bibliometric patterns, particularly in relation to source productivity, keyword prominence, bibliographic coupling, and co-citation structures. Although these sources were retained because digitally mediated PE is partly shaped by technological, computational, and health-oriented scholarship, they may have increased the visibility of artificial intelligence, digital systems, educational technology, and applied computational themes relative to more traditional PE pedagogy themes. Fourth, bibliometric indicators such as citation counts, keyword frequency, co-occurrence, bibliographic coupling, and co-citation provide structural evidence of scholarly patterns, but they do not replace full-text critical appraisal of methodological quality, theoretical depth, pedagogical effectiveness, or learner-development outcomes. Finally, recent publications, particularly those from 2024 and 2025, may be underrepresented in citation-based influence because they have had limited time to accumulate citations.

Future Research Directions

Future research should move beyond documenting the presence of digital technologies in Physical Education and examine how these technologies actually shape learning quality, movement competence, motivation, self-efficacy, engagement, assessment, and long-term physical activity participation. Greater attention is needed to the pedagogical and ethical use of artificial intelligence, virtual reality, wearable technologies, learning analytics, and personalized feedback systems, particularly in relation to inclusion, data privacy, student autonomy, and embodied learning. Future studies may also compare digitally mediated PE across educational levels, cultural contexts, and resource conditions to determine how digital access, teacher readiness, institutional support, and curriculum design influence learner development. More empirical and theory-driven research is also needed to clarify whether online, blended, hybrid, and AI-supported PE can support not only instructional continuity, but also meaningful, inclusive, and developmentally responsive movement education.

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-2026-0145-EX.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The bibliographic dataset was derived from records indexed in Scopus and analyzed using bibliometric software.

AI Transparency Statement

The author used ChatGPT 5.4+ by OpenAI during the preparation of this manuscript to assist with language refinement, organization, and drafting support. All intellectual decisions, interpretation of the literature, synthesis of ideas, and final approval of the manuscript remained the responsibility of the author.

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The author declares no conflict of interest.

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Еволюція навчання у цифрово-опосередкованому фізичному вихованні: бібліометричний та тематичний аналіз онлайн-, відкритого дистанційного та технологічно підтримуваного навчання (2015–2025)

Джозеф Лобо[1,2ABCDE]

[1]Державний університет Булакан
[2]Міжнародний університет ІНТІ

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

Реферат. Стаття: 14 с., 7 табл., 8 рис., 26 джерел.

Мета. Інтеграція фізичного виховання з цифровим навчанням, штучним інтелектом і гнучкими форматами організації освітнього процесу актуалізує питання збереження педагогічної цінності рухового навчання в технологічно опосередкованому освітньому середовищі. Метою дослідження було картографування світового наукового доробку з проблематики цифрово-опосередкованого фізичного виховання за 2015–2025 роки з акцентом на онлайн-, відкритому дистанційному та технологічно підтримуваному навчанні.

Матеріали та методи. Дослідження виконано з використанням бібліометричного дизайну та аналізу тематичної еволюції. Проаналізовано 1358 документів, індексованих у Scopus, із застосуванням програмних пакетів Bibliometrix/ Biblioshiny та VOSviewer.

Результати. Результати засвідчили стрімкий розвиток міждисциплінарного напряму досліджень, що формується на перетині педагогіки, освітніх технологій, штучного інтелекту, громадського здоров'я та комп'ютерних систем навчання. На концептуальному рівні науковий доробок був зосереджений навколо таких тем, як штучний інтелект, COVID-19, онлайн-навчання, вища освіта, змішане навчання, дистанційне навчання, віртуальна реальність, фізична активність, цифрові технології та освітні технології. Аналіз бібліографічного зв'язку та співцитування показав, що цей науковий напрям спирається як на усталені педагогічні традиції, так і на нові технологічні бази знань. Аналіз тематичної еволюції виявив перехід від раннього використання інформаційно-комунікаційних технологій і змішаного навчання до онлайн-фізичного виховання, зумовленого пандемією COVID-19, а в подальшому — до цифрових педагогічних підходів, заснованих на використанні штучного інтелекту, імерсивних технологій, орієнтації на діяльність учителя та студентоцентрованому навчанні.

Висновки. Цифрово-опосередковане фізичне виховання визначено як напрям розвитку теорії та практики навчання, що перебуває на етапі становлення й потребує подальшого педагогічного, етичного та теоретичного обґрунтування.

Ключові слова: цифрово-опосередковане фізичне виховання, онлайн-навчання, відкрите дистанційне навчання, штучний інтелект, бібліометричний аналіз, тематична еволюція.

Information about the Authors:

Lobo, Joseph: joseph.lobo@bulsu.edu.ph; 0000-0002-2553-467X; College of Sports Exercise and Recreation, Bulacan State University, Guinhawa, City of Malolos, 3000, Bulacan, Philippines; Graduate School, Bulacan State University, Guinhawa, City of Malolos, 3000, Bulacan, Philippines; INTI International University, Nilai, Malaysia.

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Review Article

Structural-Functional Model of Social Support for Athletes Across the Stages of Long-Term Athletic Development: A Bibliometric and Network Analysis (1981–2026)

Mariia Pryimak[1ABCDE], Lidiia Radchenko[1ABCDE], Volodymyr Tomashevskyy[1BDE], Olena Timasheva[2BDE] and Iryna Syvash[1BDE]

[1]National University of Ukraine on Physical Education and Sport
[2]Borys Grinchenko Kyiv Metropolitan University

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

Corresponding Author: Mariia Pryimak, e-mail: mpryimak@uni-sport.edu.ua
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Abstract

Background. Preserving athletes' mental well-being and social functioning under conditions of intensified training demands has become a critical challenge in contemporary elite sport. Annual training loads at the highest levels of performance may reach 1,500 hours, increasing vulnerability to burnout, social isolation, and identity-related difficulties. In response to the global transformation of elite sport in the 2020s, there is a growing need for integrated athlete support systems grounded in established theoretical frameworks of long-term athlete preparation.

Objectives. To develop a theoretically grounded structural-functional model of social support for athletes based on V. Platonov's long-term athlete preparation framework using bibliometric and network analysis.

Materials and Methods. Bibliometric metadata were retrieved from the Scopus database, yielding 550 scientific publications published between 1981 and March 2026. Science mapping was conducted using VOSviewer (version 1.6.20), applying keyword co-occurrence analysis and Louvain clustering. Following screening and normalization procedures, 134 keywords meeting the inclusion threshold ($n \geq 5$) were included in the network analysis. Cluster structures were subsequently interpreted in relation to V. Platonov's eight-stage model of long-term athlete preparation.

Results. The analysis identified eight thematic clusters reflecting the major domains of athlete social support across the athletic life course. The network structure indicated a progression from early-stage family- and school-based support toward institutional support mechanisms associated with dual career development, mental health, health maintenance, and career transition. The integrated athlete domain demonstrated the highest network centrality (TLS = 1146), highlighting the central conceptual role of athlete-centered support within the identified knowledge structure. Recent publication trends suggest increasing scholarly attention to athlete well-being, dual career pathways, and mental health as key priorities in contemporary sport science.

Conclusions. The proposed structural-functional model provides a conceptual framework for integrating psychosocial support into long-term athlete preparation systems. The findings suggest that social support should be considered a strategically important structural component of athlete development, with potential implications for burnout prevention, career sustainability, and post-sport reintegration. The model may serve as a practical reference for sport organizations and higher education institutions in designing stage-specific athlete support strategies.

Keywords: social support, athlete development, dual career, athletic identity, career transition, bibliometric analysis, structural-functional model.

Introduction

The global transformation of elite sport in the 2020s necessitates a substantial modernization of athlete support systems. Contemporary training is characterized by extreme intensification, with annual training loads at the highest levels of performance reaching 1,400–1,500 hours (Platonov, 2006). Professor Volodymyr Platonov's contributions to this field are foundational, as the long-term periodization system he developed provides methodological coherence for athlete preparation while accounting for the objective patterns of

psychophysiological adaptation to training loads (Platonov, 2021; Platonov, 2013; Lyakh et al., 2014).

However, the relevance of this study is further reinforced by the fact that athletic success today depends not only on physical condition, but also on the quality of social support, which serves as a buffer against stress and burnout (Luo et al., 2025; Saeed et al., 2025; Yiyi et al., 2025). The need to develop a model of social support integrated across the stages of long-term athletic development, as conceptualized by Volodymyr Platonov, arises from the necessity to overcome fragmentation in support provision and to preserve athletes' personal capital (Bulatova et al., 2025). Contemporary sport requires a paradigmatic shift from reactive assistance to proactive support for the athlete as a whole person throughout the entire life course (Pryimak, 2025a).

Between 1981 and 2026, the scientific discourse evolved from the fragmented examination of the "retirement crisis" to the development of holistic models of the athlete life course. A significant contribution to understanding this evolution was made by Khudolii and Ivashchenko (2026), who, through a bibliometric analysis of PETM, identified a sustained trend toward thematic diversification in sport science. Their findings documented a rapid increase in the prominence of research focused on health, inclusion, and functional outcomes, indicating that the scientific discourse has expanded beyond purely methodological and training-related dimensions (Khudolii & Ivashchenko, 2026).

A central position in contemporary conceptual frameworks is occupied by the Holistic Athletic Career (HAC) model proposed by Paul Wylleman (2019). This model postulates that athlete development unfolds simultaneously across sporting, psychological, academic, and financial domains, with deficits in any one domain inevitably constraining progress in the others (Wylleman, 2018, 2020). In contrast, Stambulova and Schinke (2025) conceptualize transition as a prolonged process of developing athletic retirement literacy, in which the cultivation of adaptive competencies during the peak of an athlete's career is considered essential (Stambulova & Schinke, 2025). Meanwhile, Kristoffer Henriksen et al. (2024) shift the focus toward the transition environment (TE), emphasizing that successful adaptation depends on the coordination of micro- and macro-level systems surrounding the athlete (Stambulova & Henriksen, 2025).

Statistical evidence supporting the mediating role of social support was provided by Luo et al. (2025), whose meta-analysis of 14,462 athletes identified a consistent negative association with depression ($r = -0.27$) and anxiety ($r = -0.22$). These findings align with the conclusions of Barbara Nuetzel (2023, 2025) and Eadie E. Simons and Matthew Bird (2022), who identified elite youth athletes as a particularly high-risk group under conditions of intensified training demands. In the Ukrainian context, Mariia Bulatova et al. (2025) found that 87.3% of specialists consider social support a strategic priority, while also identifying a systemic imbalance between the demands of sport and education as the principal barrier (Bulatova et al., 2025). These conclusions are further developed in the work of Mariia Pryimak (2025b, 2025c, 2025d), which substantiates a stage-specific approach to adaptation: at the early stages of Platonov's framework, family "emotional approval" plays a decisive role, whereas at the highest levels of performance, stress management and financial literacy become critical (Pryimak, 2024e; Pryimak, 2025f). In her most recent studies, the author proposes a holistic career management strategy as a mechanism for overcoming identity crises (Pryimak, 2025g).

Additional dimensions of resilience were explored by Chrétien et al. (2024), who identified a direct relationship between athlete resilience and the quality of the coach–athlete dyad, with trust emerging as a key determinant of well-being. A sociocultural perspective is added by the work of Yoon Jin Kim and Marcelle C. Dawson, who, through the lens of Goffman's stigma theory, examine the formation of coaching identity among former athletes (Kim & Dawson, 2022). Jane Thornton et al. (2023) and McClaskey et al. (2025) provide a detailed analysis of gender-specific factors, demonstrating that elite female athletes require more flexible institutional support systems. Pedagogical mechanisms for the development of social skills through game-based models, particularly Teaching Games for Understanding (TGfU), were examined by Uray Gustian et al. (2025), Valero-Valenzuela et al. (2020), and José L. Arias-Estero et al. (2020), highlighting their role in early socialization.

Important aspects of the dual career framework are highlighted in the works of Capranica et al. (2022), Linnér et al. (2026), and Di Rocco (2025), who demonstrate that institutional support within universities constitutes a fundamental mechanism for preventing premature career termination. This perspective is further complemented by the research of De Brandt et al. (2018), which examines the competencies required to successfully combine education with elite sport. The issue of mental health as a critical resource for athletic success is also addressed in the work of Ponomaryov et al. (2024).

Despite the substantial body of research and the foundational significance of V. Platonov's long-term athlete preparation system (2021), the scientific literature still lacks an integrated model that directly aligns specific types of support with the structural components of his framework. Most existing studies focus on a single critical transition point, without accounting for the dynamic transformation of athletes' needs across the entire life course.

The aim of this study is to develop and theoretically substantiate a structural and functional model of social support for athletes based on V. Platonov's contemporary system of long-term training periodization.

Research hypothesis. We hypothesize that the structure of athlete social support transforms synchronously with the evolution of training objectives within V. Platonov's framework, shifting from the dominance of emotional support at the micro level during the early stages to the predominance of institutional support at the macro level at the highest levels of performance.

Scientific novelty. For the first time, a structural-functional model comprising eight thematic clusters has been theoretically substantiated through bibliometric modeling of a co-occurrence network of 134 terms, with these clusters dynamically aligned with V. Platonov's eight-stage system of long-term athlete preparation.

Practical significance. The findings of this study may be used by sport organizations and higher education institutions to develop social support roadmaps, thereby contributing to the minimization of burnout risks and the successful professional reintegration of athletes.

Materials and Methods

Study Design

This study was conducted within a quantitative bibliometric research design employing the science mapping approach, integrated into a systems analysis of the athlete life course. This design enables the synthesis of large-scale bibliometric metadata to identify conceptual relationships and thematic patterns in the evolution of scientific perspectives on social support in sport. The methodological framework is grounded in approaches to constructing intellectual knowledge structures, as validated in contemporary scientometric research in the fields of physical education and sport science.

Data Source and Search Strategy

The empirical foundation of this study consisted of bibliographic metadata retrieved from the international scientometric database Scopus. The search was conducted in March 2026 using the advanced query functionality to ensure precision in sample selection. The search strategy was based on the application of Boolean operators and the proximity operator (W/3):

TITLE-ABS-KEY ((social W/3 (adapt* OR adjust* OR integrat* OR support OR identity OR personal*)) AND (athlet* OR sport*) AND (career OR lifecycle OR transition* OR retire* OR "dual career" OR "long-term athlete development" OR "periodization" OR "career longevity" OR "sports training" OR "life course"))

The chronological scope of the search covered the period from 1981 to March 2026. An additional data-cleaning step involved the application of an affiliation-based exclusion filter: AND (EXCLUDE (AFFILCOUNTRY, "russian federation")). The final dataset comprised 550 source records.

Eligibility Criteria and Screening

The selection of scientific publications was conducted in accordance with the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), ensuring transparency and reproducibility of the results. At the initial stage, a preliminary screening of titles and abstracts was performed to assess thematic relevance. The inclusion criterion for the network analysis was a minimum keyword occurrence frequency of $n \geq 5$, which allowed for the reduction of terminological noise. At the second stage, author name normalization and affiliation standardization procedures were applied. The final dataset used for constructing the co-occurrence maps comprised 134 nodes.

Bibliometric Mapping and Statistical Analysis

Statistical processing and network visualization were performed using VOSviewer software (version 1.6.20). The Louvain community detection algorithm was employed to identify thematic communities. The resolution parameter was calibrated to improve the interpretability of cluster structures in relation to the selected theoretical framework. The analytical procedure included:

Local optimization of modularity to maximize the density of internal connections within clusters.

Generation of eight differentiated thematic clusters reflecting the structure of social support across different stages of the athletic career.

Data Synthesis and Conceptual Modeling

The results of the bibliometric mapping were subjected to qualitative interpretation and systematically mapped onto V. Platonov's classical model of long-term athlete preparation (Platonov, 2021). This approach made it possible to align the dynamics of athletes' social support needs with the pedagogical objectives of each of the eight stages of the training process, ranging from Initial Preparation to Retirement from Elite Sport.

Analysis Metrics

The primary quantitative indicators included:

Occurrence frequency (Occurrences): the number of documents in which a given term appears.

Total Link Strength (TLS): the cumulative intensity of interactions between a specific node and all other elements within the network.

Study Limitations

The findings of this study are limited by the scope and depth of source indexing within the Scopus database. Given the time-lag effect in database indexing, data from the most recent period (2025–2026) may not be fully comprehensive; however, they remain indicative of the most current directions in the development of sport science.

Results

The results of the retrospective analysis made it possible to visualize the trajectory of scientific interest in athlete social support over the past 45 years (Figure 1). Quantitative indicators of publication activity provide objective evidence of a paradigmatic shift in sport science, whereby the transition from isolated theoretical inquiries to a substantial body of empirical research reflects the global demand for the humanization of athlete development systems.

The graphical analysis demonstrates a consistently low level of publication activity until 2010, followed by a sharp intensification of research on social support. The exponential growth observed in 2024–2025, with a peak of 90 publications per year, suggests that social support has become an increasingly prominent topic in contemporary athlete development research, while athletes' mental well-being has gained growing scholarly attention in the post-pandemic context.

To identify the conceptual core of the system, the weight and influence of the central concepts were assessed. The indicator (n = 134) represents the total number of unique terms comprising the conceptual lexicon of the model. Particular attention should be given to the close terminological relationship between the nodes "athlete" and "athletes." From a scientometric perspective, these terms function as conceptual twins that, through data

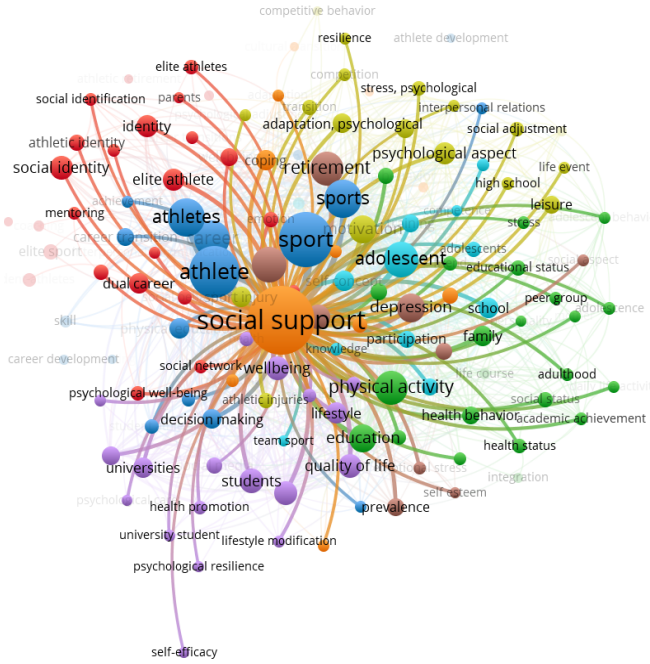

Fig. 1. Annual Trends in Scientific Publications (1981–2026)

normalization, effectively form a unified mega-node. The combined occurrence frequency of this dyad reached 160, while the integrated Total Link Strength attained an exceptionally high value (TLS = 1146). This finding positions the human factor as the central organizing element of the network, around which all psychosocial variables presented in Table 1 are structured.

Table 1. Analysis of the Weight and Influence of Central Network Nodes (n = 134)

Keyword	Cluster	Occurrences	Total Link Strength (TLS)
athlete + athletes	2	160	1146
athletic identity	2	38	85
career	8	53	424
mental health	5	52	361
social support	6	23	198
burnout	5	18	65
anxiety	5	26	213
depression	5	34	252

To provide a more detailed representation of the intellectual structure of social support, all 134 keywords were distributed across eight functional domains, which, following optimization of the resolution parameter (Resolution = 1.35), demonstrated clear alignment with the eight stages of V. Platonov's athlete preparation system. This classification made it possible to identify latent patterns of social interaction at each stage of the athletic career.

Table 2 presents the substantive composition of these clusters, with each element filtered according to a significance threshold of n ≥ 5, ensuring the robustness of the identified knowledge communities and their correspondence to the stages of long-term athlete preparation – from initial socialization (C1) to successful reintegration following retirement from sport (C8).

The modeling process revealed a clearly defined hierarchical architecture of athlete social support. The findings indicate that the microsystems of family and school

Table 2. Detailed Composition of Thematic Clusters in Athlete Social Support (n = 134)

Stage According to V. Platonov	Cluster No.	Number of Items	Keywords (Items)
I. Initial Preparation	1	22	Academic achievement, adolescence, adolescent behavior, child parent relation, education, educational status, family, friend, mother, parents, peer group, school, social interaction, social status.
II. Preliminary Basic Preparation	2	20	Athlete, athletes, athletic identity, coaching, coaches, identity, interpersonal communication, leadership, mentoring, social behavior, social environment, social identification, sport.
III. Specialized Basic Preparation	3	18	Adaptation, psychological adaptation, adaptive behavior, age factors, competition, competitive behavior, cultural transition, interpersonal relations, leisure activities, social capital, sports.
IV. Preparation for Peak Performance	4	16	Athletic performance, elite athlete, elite sport, achievement, motivation, performance, self-concept, self-esteem, team sport, training, return to sport.
V. Maximum Realization of Individual Potential	5	15	Anxiety, burnout, depression, emotional stress, mental health, psychological resilience, resilience, stress, psychological stress, coping, coping behavior.
VI. Maintenance of Peak Sporting Performance	6	16	Dual career, student-athlete, university student, college student, universities, learning, career choice, career development, physical education, skill, awareness.
VII. Gradual Performance Decline	7	14	Health status, health promotion, lifestyle, life style, quality of life, self-care, self-efficacy, athletic injuries, sport injury, psychological care, wellbeing.
VIII. Retirement from Elite Sport	8	13	Career, career transition, athletic retirement, retirement, transition, transitions, life satisfaction, life event, loneliness, social adaptation, social reintegration.

Table 3. Structural-Functional Model of Support Across the Stages of V. Platonov's Athlete Preparation Framework

Reparation Stage (V. Platonov's Framework)	Cluster	TLS	Psychosocial Risks and Barriers	Adaptation Resources and Coping Potential	Stakeholder Map	CAP Technologies and Support Vector	Expected Outcome
I. Initial Preparation	C1	245	Fear of failure, excessive parental pressure	Play-based motivation, enjoyment of movement	Parents, physical education teachers	Emotional foundation: Active Start programs, active games	Sport engagement
II. Preliminary Basic Preparation	C1/C2	310	Conflict between play and academic activities	Self-discipline, volitional development	Family, friends, school coaches	Developmental balance: Olympic education, youth sport school support	Initial athletic identity
III. Specialized Basic Preparation	C3	740	Pubertal crisis, risk of burnout	Role resilience, time management	Coaching staff, friends outside sport	Professional mentoring: career planning seminars	Stable athletic identity
IV. Preparation for Peak Performance	C4	820	High competitive stress, fear of deselection	Self-efficacy, prior coping experience	Sports physicians, psychologists, commissions	Psychological self-regulation: mental health screening	Psychological hardiness
V. Maximum Realization of Individual Potential	C4/C5	1146	Exclusive identity, media pressure	Cognitive flexibility, social capital	Professional community, managers	Buffer protection: specialized CAP support programs	Professional resilience and health
VI. Maintenance of Peak Sporting Performance	C5	680	Fear of age-related decline, performance deterioration	Strategic retirement planning	Mentors, higher education institutions, consultants	Institutional stability: Next Step programs, higher education pathways	Career flexibility and higher education attainment
VII. Gradual Performance Decline	C6/C7	560	Systemic sport–education imbalance	Academic adaptability, self-management	Universities, federations, student communities	Integration technologies: tutoring, flexible academic schedules	Dual career readiness (DC)
VIII. Retirement from Elite Sport	C8	424	Social maladaptation, loss of status	Athletic retirement literacy (ARL)	Veteran sport associations, family, HR professionals	Instrumental reintegration: employment transition programs	Social autonomy and successful reintegration

(Cluster 1) establish the foundational basis for adaptation during the Initial Preparation stage. As athletic expertise develops, the focus progressively shifts toward institutional dual career structures (Cluster 6) and mechanisms for managing psychophysiological reserves (Cluster 5).

Of particular importance is the identification of Cluster 7 (Health and Rehabilitation) and Cluster 8 (Career Transition), which supports the hypothesis that social support evolves from emotional affirmation at the beginning of the athletic pathway to professional reintegration at the conclusion of the sporting career. The presence of a strong mental health and resilience core (Clusters 5 and 7) supports the conceptual interpretation of social support as an important protective resource within athlete development systems under conditions of intensive training demands.

This structure provides the empirical foundation for the development of an integrated support model presented in Table 3.

The most significant outcome of this study is the mapping of eight thematic clusters onto Volodymyr Platonov's foundational eight-stage athlete preparation system. This transforms a static term map into a dynamic roadmap for athlete support. Within this model, social support is conceptualized as an evolving resource whose nature changes in response to increasing training loads and psychological pressures at each stage of professional development.

The proposed structural-functional model (Table 3) demonstrates that V. Platonov's framework may be meaningfully complemented by a social support dimension to strengthen athlete development pathways. Based on the conceptual mapping of network domains, the stages of peak performance appear to represent periods of heightened psychosocial vulnerability requiring intensified support mechanisms.

The findings further indicate that insufficient institutional support during the final stages (VI–VIII) may contribute to identity-related disruptions and transition crises. To address these challenges, the model incorporates athletic retirement literacy (ARL) programs and specialized Career Assistance Programs (CAP). Taken together, these results suggest that social support should be understood not as an auxiliary element, but as a structural component of contemporary athlete preparation systems that contributes to the preservation of human capital in sport.

Discussion

The findings of the bibliometric analysis suggest that, over the past 45 years, sport

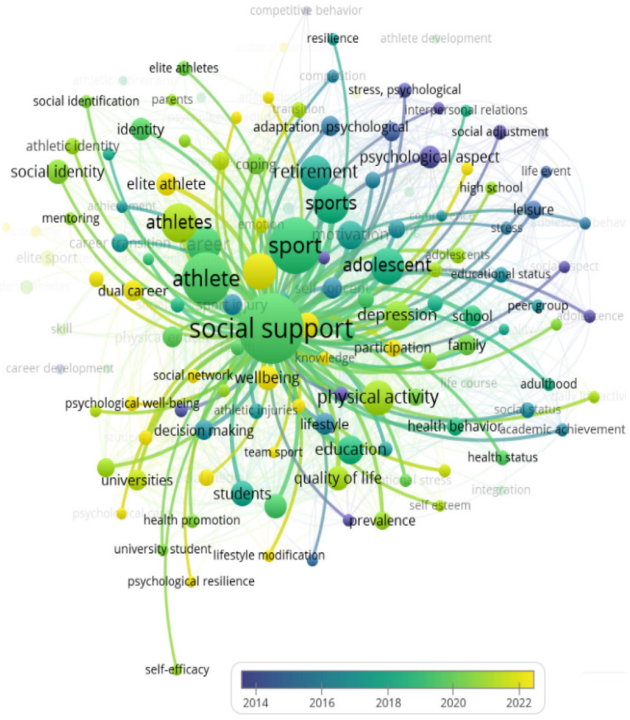

Fig. 2. Overlay visualization of the keyword co-occurrence network by average publication year

science has undergone a complex transformation from narrowly focused investigations of the "career termination crisis" (1980s–1990s) toward the development of integrated, holistic models of the athlete life course (2020–2026) (Luo et al., 2025; Stambulova & Schinke, 2025). The exponential growth in publication activity identified from 2015 onward reflects a broader global trend toward the humanization of sport, in which athlete well-being is increasingly recognized as an essential condition for sustainable professional performance.

The analysis of the chronological evolution of scientific interest (2014–2022) demonstrates a clear shift in research priorities (Figure 2). While the earlier terminological base (represented in dark blue) was primarily concentrated on general aspects of physical activity and adaptation, the most recent thematic vectors (yellow–green spectrum) are centered on concepts such as well-being, dual career, mental health, and university student.

This provides visual confirmation of the paradigm shift from the biologization of sport toward holistic support for the athlete as a whole person across all stages of the life course. This fully aligns with the conclusions of Khudolii and Ivashchenko (2026) regarding the thematic diversification of sport science toward inclusion, health, and functional psychological outcomes.

Our findings suggest that social support should no longer be viewed merely as an auxiliary resource, but rather as a strategically important component of contemporary athlete development systems. Analysis of the central network elements (n = 134) indicated that the integrated athlete domain (TLS = 1146) occupies a central conceptual position within the identified psychosocial knowledge structure, reflecting a shift in priorities from "performance at any cost" toward the preservation of human capital in elite sport (Pryimak, 2025a).

The distribution of the terminological base across eight thematic clusters enabled the identification of specific support vectors that have previously been addressed only fragmentarily in the literature:

1. Foundational Block (Clusters 1–3): Cluster 1 (Socialization) clearly delineates the foundation of socialization, in which parental support serves as the principal factor in athlete retention during the early stages. In contrast to Wylleman (2019), our findings emphasize that during Stages I–II of Platonov's framework, support functions as an "emotional shield" protecting the child from premature specialization (Wylleman, 2019; Lee et al., 2018). Cluster 2 (Foundational Development) demonstrates the critical role of the coach. However, the elevated TLS value for the term athletic identity (85) (see Table 1) indicates the risk of identity foreclosure, which, according to Kim and Dawson (2022), may become a barrier to successful post-sport adaptation.

2. Psychological Safety Core (Clusters 4, 5, and 7): A central contribution of our model is the network-based identification of these clusters as a core safety-related domain within the conceptual framework. The concept of social support emerges as a central psychosocial construct within the broader literature on training-related stress and athlete mental well-being. The meta-analysis by Luo et al. (2025) (n = 14,462) demonstrates that, for elite athletes at the Maximum Realization stage (Stages IV–V in Platonov's framework), support from close relationships exerts a stronger protective effect (r = −0.27) than team cohesion. Previous evidence suggests that the absence of such support networks may increase vulnerability to burnout, whose TLS value (65) indicates its notable prevalence among young athletes. Our interpretation aligns with previous evidence suggesting an association between social support and athlete engagement (Ye & Liu, 2016).

3. Institutional and Applied Context (Clusters 6 and 8): These findings gain particular significance when compared with applied research conducted in Ukraine. Survey data from 150 specialists (2025) revealed a paradox: 87.3% of respondents recognize social adaptation as critical, yet actual funding and athlete awareness remain low (Bulatova et al., 2025). The principal challenges in Ukraine include the sport–education imbalance (54.5%) and psychological overload (40.0%), which directly correspond to the clusters identified in our analysis – Cluster 6 (Dual Career) and Cluster 5 (Mental Health). Unlike European standards, Ukrainian practice often remains fragmented and ad hoc (Di Rocco et al., 2025), underscoring the need for a transition toward an institutionalized support model as early as Stages VI–VII in Platonov's framework.

Analysis of recent years (2024–2026) indicates the growing role of digital support. The use of mobile applications for monitoring athletes' condition is emerging as a new tool that ensures continuity of support during injury recovery or remote training camps (Gertz et al., 2026). In addition, the effectiveness of the model depends on mental health literacy. A limited ability to identify one's own psychosocial needs during the Preparation for Peak Performance stage (Stage IV) may be associated with increased vulnerability to

anxiety, as reflected in the relatively high Total Link Strength value observed for the term anxiety (TLS = 213).

The most relevant contemporary vector is Cluster 8 (Transition). Our model proposes a reconceptualization of Stage VIII in Platonov's framework – from a period of "decline" to a phase of active social reconstruction. The concept of athletic retirement literacy (ARL) becomes central in this context (Stambulova & Schinke, 2025). Gender differences also warrant particular attention (Thornton et al., 2024). Female athletes demonstrate distinct trajectories of maladaptation: the high prevalence of reproductive health challenges (19%) and the risk of early osteoarthritis necessitate the inclusion of medico-social modules within the overall model. Women also exhibit higher levels of anxiety (RR = 1.42) (McCluskey et al., 2025).

Thus, the application of Resolution = 1.35 enabled the development of a dynamic social support roadmap, in which each of the eight stages of V. Platonov's athlete preparation framework corresponds to a specific mechanism of social protection aimed at preserving human capital in elite sport.

Conclusions

The developed structural-functional model of athlete social support constitutes an integrated scientific and methodological framework grounded in the objective findings of bibliometric analysis and embedded within V. Platonov's foundational system of long-term athlete preparation periodization. The present study suggests that the nature of psychosocial support undergoes a systematic and nonlinear transformation in parallel with the evolution of training objectives. The transition from the emotional microenvironment of the family during the early stages to the institutional macro-level of higher education institutions and specialized career assistance programs at the highest stages of athletic performance emerges as a critical condition for preserving the athlete's personal capital.

The structural-functional model supports the strategic significance of social support as an important component of athlete development systems, with potential relevance for addressing risks related to depressive symptoms, anxiety, and emotional exhaustion. This allows for a reconceptualization of social resources – not as merely auxiliary factors, but as an integral structural component of athletic performance and professional longevity.

The particular scientific value of the proposed model lies in its capacity to provide mechanisms for the proactive reconstruction of athlete identity prior to career termination. The development of athletic retirement literacy and the implementation of individualized social support roadmaps within higher education institutions and sport organizations offer a means of overcoming the fragmentation of existing support systems. Such an approach may facilitate the social reintegration of athletes into society and support smoother career transitions.

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Ethics Approval

Ethics committee approval was not required for this publication, as the study is theoretical-conceptual and scientometric in nature. The research methodology was based exclusively on the systematization and analysis of open bibliographic datasets and publicly available sources, with no involvement of human or animal participants, and no collection, analysis, or dissemination of confidential personal data.

Data Availability Statement

The bibliometric data analyzed in this study were retrieved from the Scopus database and are available through institutional access to Scopus. The processed datasets generated during the current study are available from the corresponding author upon reasonable request. However, the data may be made available from the corresponding author upon reasonable request and subject to approval by the relevant institutional bodies.

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Conflicts of Interest

The authors declare no financial or personal conflicts of interest that could have influenced the objectivity of the findings or the interpretation of the study results.

AI Transparency Statement

Artificial intelligence tools were not used for data collection, statistical analysis, or interpretation of results. During manuscript preparation, artificial intelligence tools were partially used for language editing of the text. Full responsibility for the content, conclusions, and accuracy of the work rests with the authors.

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Структурно-функціональна модель соціальної підтримки атлетів на етапах багаторічної підготовки: бібліометричний та мережевий аналіз (1981–2026)

Марія Приймак[1,2ABCDE], Лідія Радченко[1ABCDE], Володимир Томашевський[1BDE], Олена Тімашева[2BDE], Ірина Сиваш[1BDE]

[1]Національний університет фізичного виховання і спорту України
[2]Київський столичний університет імені Бориса Грінченка

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

Реферат. Стаття: 10 с., 3 табл., 2 рис., 39 джерел.

Вступ. Збереження ментального благополуччя та соціального функціонування атлетів в умовах інтенсифікованих тренувальних навантажень є актуальним викликом сучасного спорту вищих досягнень. На етапах найвищої спортивної майстерності річний обсяг тренувальної роботи може сягати 1500 годин, що підвищує вразливість до вигорання, соціальної ізоляції та труднощів, пов'язаних із спортивною ідентичністю. Глобальна трансформація спорту вищих досягнень у 2020-х роках актуалізує потребу в інтегрованих системах соціального супроводу, заснованих на теоретично обґрунтованих моделях багаторічної підготовки спортсменів.

Мета дослідження. Теоретично обґрунтувати структурно-функціональну модель соціальної підтримки атлетів на основі системи багаторічної підготовки спортсменів В. Платонова шляхом бібліометричного та мережевого аналізу.

Матеріали і методи. Емпіричну основу дослідження становили бібліометричні метадані, отримані з наукометричної бази Scopus. До аналізу включено 550 наукових публікацій, опублікованих у період з 1981 року по березень 2026 року.

Бібліометричне картографування здійснювалося із застосуванням програмного забезпечення VOSviewer (версія 1.6.20) з використанням аналізу співвузстрічальності ключових слів та алгоритму кластеризації Лувена. Після процедур скринінгу, нормалізації та застосування критерію включення (n ≥ 5) до мережевого аналізу включено 134 ключові слова. Отримані кластерні структури інтерпретовано у співвіднесенні з восьмиетапною системою багаторічної підготовки спортсменів В. Платонова.

Результати. У результаті аналізу ідентифіковано вісім тематичних кластерів, що відображають ключові домени соціальної підтримки атлетів упродовж спортивного життєвого шляху. Структура мережі вказує на поступовий перехід від сімейно- та шкільно-орієнтованих форм підтримки на ранніх етапах до інституційних механізмів підтримки, пов'язаних із дуальною кар'єрою, ментальним здоров'ям, збереженням здоров'я та кар'єрним переходом. Найвищу центральність у мережі продемонстрував інтегрований домен athlete (TLS = 1146), що підкреслює центральну концептуальну роль атлетоцентричного підходу в ідентифікованій структурі знань. Аналіз публікаційної динаміки також засвідчив зростання наукової уваги до проблем ментального благополуччя, дуальної кар'єри та соціальної підтримки у сучасній спортивній науці.

Висновки. Запропонована структурно-функціональна модель формує концептуальну основу для інтеграції психосоціального супроводу в системи багаторічної підготовки спортсменів. Отримані результати свідчать, що соціальна підтримка може розглядатися як стратегічно важливий структурний компонент розвитку атлета, з потенційним значенням для профілактики вигорання, підтримки кар'єрної стійкості та соціальної реінтеграції після завершення спортивної кар'єри. Модель може бути використана фізкультурно-спортивними організаціями та закладами вищої освіти для розроблення етапно-специфічних стратегій соціального супроводу атлетів.

Ключові слова: соціальна підтримка, розвиток атлета, дуальна кар'єра, спортивна ідентичність, кар'єрний перехід, бібліометричний аналіз, структурно-функціональна модель.

Information About the Authors:

Pryimak Mariia: mpryimak@uni-sport.edu.ua; https://orcid.org/0000-0003-3249-9902; Department on History and Theory of Olympic Sport, Educational and Scientific Olympic Institute, National University of Ukraine on Physical Education and Sport, Fizkultury St, 1, Kyiv, 03150, Ukraine.

Radchenko Lidiia: lradchenko@uni-sport.edu.ua; https://orcid.org/0000-0002-5149-2952; Department on History and Theory of Olympic Sport, Educational and Scientific Olympic Institute, National University of Ukraine on Physical Education and Sport, Fizkultury St, 1, Kyiv, 03150, Ukraine.

Tomashevskyy Volodymyr: vtomashevskyi@uni-sport.edu.ua; https://orcid.org/0000-0003-2256-2656; Department on History and Theory of Olympic Sport, Educational and Scientific Olympic Institute, National University of Ukraine on Physical Education and Sport, Fizkultury St, 1, Kyiv, 03150, Ukraine.

Timasheva Olena: o.yarmoliuk@kubg.edu.ua; https://orcid.org/0000-0002-1786-4759; Head of department of physical aducation and pedagogy of sport, Boris Grinchenko Kyiv Metropolitan University, Bulvarno-Kudriavska St, 18/2, Kyiv, 04053, Ukraine.

Syvash Iryna: isyvash@uni-sport.edu.ua, https://orcid.org/0000-0001-8548-3133; Department on History and Theory of Olympic Sport, Educational and Scientific Olympic Institute, National University of Ukraine on Physical Education and Sport, Fizkultury St, 1, Kyiv, 03150, Ukraine.

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Review Article

Modern Karate Technology Landscape: Bibliometric Mapping and Literature Network Visualization Based on Scopus Database 2000-2025

Fajar Awang Irawan[1ABCDE], Dewangga Yudhistira[2ABCDE], Samsuryadi[3ABCDE], Derry Alamsyah[3,4ABCDE] and Nutcharee Senakham[5CDE]

[1]Universitas Negeri Semarang
[2]Universitas Negeri Surabaya
[3]Universitas Sriwijaya
[4]Universitas Multi Data Palembang
[5]Srinakharinwirot University

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

Corresponding Author: Dewangga Yudhistira, e-mail: dewanggayudhistira@unesa.ac.id
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Abstract

Objectives. The current landscape of karate technology is beginning to mature, marked by an abundance of recent studies. Previous analyses have primarily focused on original investigations, and mapping research trends in karate through bibliometric analysis has not received adequate attention. Therefore, this study aimed to conduct a bibliometric analysis of research trends in karate technology through the Scopus database for the period 2000–2025.

Materials and Methods. Data were collected using specific Boolean keywords in the Scopus database. A total of 122 RIS-format documents were retrieved and filtered using the Mendeley application, then visualized using the VOSviewer and Biblioshiny applications.

Results. (1) Literature development, where productivity increased during 2021–2025, while journal citations tended to fluctuate. (2) Journal performance, where the most productive journals were in applied sciences, engineering, and several sports-related fields. (3) Author productivity, where the most active researchers published 10–13 articles, with the highest citation counts ranging from 109 to 134. (4) Geographic distribution and collaboration patterns, where Poland and Indonesia were the leading contributors to SCP and MCP, although overall international collaboration was not optimal. (5) Popular keyword trends, where the dominant cluster focused on artificial intelligence, deep learning, and sensors, comprising 40 keywords, while the use of virtual reality and augmented reality has also become increasingly common.

Conclusions. Although some aspects have improved, further research and technological development are needed, along with increased demand in this area and stronger international collaboration. Modern karate requires both the implementation and continuous improvement of technology to optimize learning and athletic performance.

Keywords: scientometrics, karate bibliometrics, karate technology, literature network visualization.

Introduction

Karate is a Japanese martial art that has developed around the world. This art is known as an empty-handed martial art that depends on the hands and feet as weapons in combat (Yudhistira & Tomoliyus, 2020). Traditionally, karate has existed as a martial art that focuses on philosophical values, spirituality, and mental toughness, not just physical aspects and methods (Cynarski, 2019). Karate methods consist of movements (kata) and fighting (kumite), but before learning these two aspects, basic movements (kihon) should be practiced. Kihon serves as a foundation for a karateka to improve in kata and kumite (Dewangga et al., 2025). Over the years, karate has become a competitive sport to achieve success.

The transformation of Karate into an Olympic sport at the 2020 Tokyo Olympics has drastically shifted the paradigm, transforming the preservation of traditional

values into a science-based and measurable achievement program. In modern karate, success at the top is not solely determined by talent and consistent training. External factors, such as infrastructure management, sports science support, and digital technology, are crucial to achieving peak performance on the tatami. These results are consistent with the argument of Bompa and Buzichelli that internal and external support in sport are crucial for optimizing performance (Bompa & Buzzichelli, 2020).

Digital transformation has brought advanced devices to the training and competition arenas (Sungkowo et al., 2024). In other sports, the use of sensors and big data analysis has become the gold standard for technological advancement in sports science (Sungkowo et al., 2024, 2025). In karate, this potential is beginning to be explored through several technologies, such as video analysis and match review. The technologies are to facilitate decision-making on points and fouls, the emergence of high-quality karate apparel and equipment brands, as well as virtual reality-based training tools to hone punch and kick reaction skills (Witte et al., 2022)

As technological advancements offer significant advantages in the area, substantial gaps remain. The application and development of technology in karate is still far from optimal, both in terms of study depth and implementation in training settings. Regularly, studies on technology in karate stop at prototype design and have not advanced to the area of periodization and real-time automated training programs. Therefore, technology tends to be viewed as simply an add-on rather than a pressing necessity in training management systems.

There are cultural challenges, as some practitioners believe that digitalization diminishes the spiritual values of karate. This creates uncertainty about how technology can be integrated with karate philosophy without losing the essence of the martial art, potentially hindering widespread adoption. Another issue is the lack of literature to comprehensively map the extent of digital transformation in modern karate. Without a clear map, academics and practitioners struggle to determine how technology will change in karate in the future.

Technological transformation is driven by two key mechanisms: (1) practical efforts to shift from intuition-based technical assessments to objective data such as match statistics, and (2) a shift from tools like stopwatches to wearables and machine learning capable of processing data in real time. Through these mechanisms, technology is not merely an addition of accessories, but an effort to redesign training methods to help athletes achieve peak performance.

The ever-increasing complexity of study requires a method to distill massive amounts of information into meaningful patterns. Bibliometric analysis is a solution for quantitatively mapping the scientific landscape. Moreover, bibliometrics is a type of scientific method that aims to identify study trends related to the number of publications, authors, and popular countries on a particular topic (Akhiruyanto & Yudhistira, 2024). This method is very useful for identifying study gaps through structured pattern mapping, enabling the process to be easier for analyses to map topics for further study (Hafidz et al., 2024).

Previous studies on the bibliometric analysis of karate have been conducted. For example, Gabriela et al. mapped publications trends, relationships among topics, collaborations between countries, and identified the most dominant study clusters (Gabriela et al., 2023). Similarly, Kek et al. conducted a bibliometric analysis, and found that leading countries, particularly the United States, produced the highest number of publications on karate-related injuries (Kek et al., 2023). A study by Leonardo et al. conducted a review analysis of 450 original articles, with 67% published in the last 10 years. The most frequently cited references in these articles were in the fields of biodynamics and performance with a focus on sports science (Mazzei et al., 2022). European authors published the most works on karate, and the most frequent publications were on injuries in karate (Mazzei et al., 2022).

A total of three scientific papers on karate bibliometrics exist, leaving a scarcity of studies on karate bibliometrics. In response to these studies, the bibliometric analysis conducted is still general and focuses more on mapping the number of publications and study collaborations (Gabriela et al., 2023). Following the discussion, the bibliometric analysis in karate still focuses on injury studies (Kek et al., 2023; Mazzei et al., 2022). The diversity of references, journals, and authors produces an abundance of knowledge, but there are gaps in the areas of management, history, social sciences, and current karate training methods (Mazzei et al., 2022).

Bibliometric analysis on mapping technological developments in karate has not received special attention. This mapping is very important to determine study trends, as well as to provide follow-up and direction for future studies related to sports technology in karate. Therefore, this study aims to "conduct a bibliometric analysis of digital transformation in karate based on the Scopus database from 2000 to 2025". The focus of study questions (RQ) includes (1) literature development, (2) journal performance, (3) author productivity, (4) geographic distribution and collaboration networks, and (5) trends in popular study topics. Through a systematic bibliometric analysis of karate study trends, the present analysis is expected to provide progress-based evidence on how karate functions as an educational and scientific field. Furthermore, the process is expected to provide information to karateka trainers and practitioners in understanding and applying technology in karate as a medium to advance higher achievements. The operational limits of karate technology are presented in more detail in Table 1.

Table 1. Operational Limitations of Karate Technology

Technology Pillar	Main Focus	Variable
Digital system	Administrative and managerial efficiency, software-based training simulations	Augmented reality, virtual reality, e-learning, big data, information systems
Biomechanical study	Assessment of physical condition, technique (kihon, kata, kumite), and injuries using digital measurement tools	Inertial sensors, computer vision, kinematics, electromyography, accelerometers
General Sports Science	A combination of psychological and physiological principles, training methods that support physical performance, and technological aids	Performance analysis, exercise monitoring, instrument development, and behavioral responses

Materials and Methods

This study was a bibliometric analysis that aimed to map and analyze published trends by presenting quantitative data. The data presented patterns, networks, keywords, citation data, and author collaboration trends, helping to identify thematic evolutions in previous studies (Donthu et al., 2021). This method had great potential in the disciplines of education, training, and exercise in the context of sport (Oktavani et al., 2026). Specifically, the present study aimed to analyze the bibliometrics of digital transformation in karate using the Scopus database.

Data Collection Strategy

The Scopus database was selected due to its extensive coverage across various disciplines, including health, humanities, and education, as well as the advanced analytical features for mapping articles using bibliometric analysis (Oktavani et al., 2026). The data search process started on April 8, 2026, leading to a final dataset of 122 articles in RIS format. The criteria used for the final dataset were shown in Table 2.

Data Screening Procedure

Data screening was conducted independently by three expert karate reviewers, all doctoral academics. The three reviewers possessed sufficient practical and theoretical experience, ensuring the relevance as well as methodological demand of the data during the selection process. Moreover, the use of independent reviewers improved objectivity, strengthened methodological transparency, and minimized bias in data screening (Oktavani et al., 2026). The initial screening process started with a search for relevant titles and abstracts focused on karate topics related to the application of training, analysis, and technological developments in karate. Full texts were then reviewed, which served as inclusion and exclusion criteria. Any disagreements between the three experts were resolved through structured discussions aimed at reaching a mutual agreement on the inclusion and exclusion criteria. As a form of transparency, all inclusion and exclusion decisions were documented throughout the selection process. The experts followed predetermined criteria regarding publication type, time, language, methodology, and topic relevance. This data selection procedure provided information that maintained internal validity by following a structured, rigorous, and transparent bibliometric analysis (Oktavani et al., 2026).

Data Extraction Procedure

Data were retrieved from scopus.com, which contained bibliographic information such as name, author, title, year, journal, affiliation, country, keywords, abstract, and number of citations. Duplicate records were identified using the Scopus website and manually checked using the Mendeley desktop application to avoid word as well as spelling disambiguations. Moreover, metadata was compiled for quantitative analysis and network patterns to improve the analysis. Data analysis preparation was assisted by the VOSviewer and Biblioshny applications.

Bibliometric Indicators

The bibliometric analysis focused on quantitative results regarding literature development, journal performance, author productivity, geographic distribution, topic trends, and collaboration networks. The outcomes of this analysis were shown more visibly in Table 3.

Data Visualization

Study data visualization was conducted using VOSviewer and Biblioshny applications (Borgohain et al.,

Table 2. Criteria for data collection through the Scopus database

No	Item	Description	Rationalization
1.	Database source	Scopus	The database had high credibility, broad coverage in the sports field, and was multidisciplinary.
2.	Search field	Title, Abstract, and Keywords	To collect data relevant to the study topic.
3.	Method type	Quantitative, Development	To present collaborative networks, patterns, and trends objectively through numerical data.
4.	Language	English	As an international language, it facilitated global data retrieval.
5.	Boolean	• "karate" AND "inertial sensor" OR "IMU" OR "accelerometer." • "Karate" AND "computer" OR "kinematics" OR "biometrics" OR "data mining." • "Karate" AND "exergaming" OR "virtual reality" OR "augmented reality" OR "simulation."	Integrating the main keyword "Karate" with various technology terminologies to find extensive and comprehensive data.
6.	Publication Year	2000-2025	Described the evolution of karate technology from its early digital beginnings to modern developments.
7.	Document Type	Original article	
8.	Data Export	RIS	To ensure data quality, it experienced a rigorous review process.

Table 3. Indicators and Objectives of Bibliometric Analysis

Category	Indicator	Focus of Analysis
Literature development	• Study productivity 2000-2025 • Average citations per year	Measuring publication volume and citation impact
Journal performance	• List of most popular journals • List of the most impactful journals	Identifying relevant and influential publication sources on karate topics
Author productivity	• List of the most productive authors • List of most impactful authors	Mapping dominant individual study contributions and citation rates
Geographic distribution and collaboration networks	• List of countries of correspondence • List of collaboration patterns	Analyzing study distribution and countries that were centers for karate technology development, as well as patterns of international study collaboration
Popular keyword trends	• Popular keyword patterns	Identifying popular keyword patterns to justify developing technologies

2022; Chen et al., 2022). VOSviewer was used specifically for co-occurrence analysis to identify topic trends and technological focuses in karate studies. In addition, the application was used for co-authorship analysis to visualize collaborative networks among institutions, authors, and countries in building global study partnerships. Biblioshny was used for literature productivity analysis, including the presentation of annual publication trends and average citations per year. Additionally, the application was applied in source and author performance analysis, including the identification of popular and high-impact journals, as well as the contributions of dominant studies in the field. Biblioshny was also used for geographic distribution analysis to map scientific production and identify countries that served as major centers of technological development in karate studies.

Data Validity and Limitations

Data validity was maintained through a systematic method to find objective and replicable results.

- Internal validity was conducted using a search instrument developed using Boolean keywords (AND, OR), integrating the primary keyword "karate" with several relevant terms such as artificial intelligence, internet of things (IoT), and inertia sensors. This ensured that the searched data covered the full scope of digitalization in karate.
- External validity, through the use of the Scopus database, ensured credibility due to its rigorous scope and review standards for each article included in the database.
- Data consistency was ensured through independent screening procedures to minimize subjectivity and increase study transparency. Expert consensus was used, where any discrepancies in inclusion and exclusion criteria were resolved through structured discussions and consensus. Moreover, technical reliability using the VOSviewer and Biblioshiny applications ensured consistent as well as accurate data processing.
- Limitations: The researchers acknowledge that "citation latency" in the 2024–2025 data is an inherent limitation of Scopus-based bibliometric research, which may influence the interpretation of the urgency of the latest technological research. Therefore, these trends should be interpreted with caution and not viewed as an absolute measure of a technology's effectiveness in practice.

Protocol Registration

Protocol registration is not mandatory in a bibliometric study. As protocol registration is commonly used in systematic reviews or intervention studies to improve transparency (Oktavani et al., 2026), it is not a standard requirement in bibliometric studies. However, the screening strategy and analysis framework are predetermined and clearly reported to ensure methodological transparency in accordance with established bibliometric study guidelines (Donthu et al., 2021).

Results

RQ1: Literature Development

Table 4. Study productivity 2000-2025

Period of the year	Number of articles	Percentage
2000-2010	2	1.6%
2011-2015	10	8.2%
2016-2020	35	28.7%
2021-2025	75	61.5%
Total	122	100%

Table 4 showed that publication growth in 2000-2010 was still very limited at 1.6%. In addition, the initial growth phase in 2011-2015 increased moderately to 8.2%, the publication volume expansion phase improved sharply to 28.7%, and the digital acceleration phase in 2021-2025 witnessed a peak in publications with a contribution of 61.5%. However, volume efficiency is inversely proportional to citations (Table 5), which indicates citation latency—that is, publications from 2024–2025 have not yet reached the mature citation phase within the scientific community

Table 5 showed that 2007 recorded the highest average citation impact, with 54.00 citations per document, followed by 2011 with 42.33 and 2004 with 31.00, indicating the strong influence of publications from these periods. The growth trend from 2015-2020 showed an average of 27.75

Table 5. Average citations per year

Year	Mean Total Citations per article	N (total article)	Mean total Citations per year	Citable year
2025	0.54	13	0.54	1
2024	0.73	11	0.36	2
2023	6.89	9	2.30	3
2022	10.38	8	2.59	4
2021	12.00	8	2.40	5
2020	7.10	10	1.18	6
2019	21.00	6	3.00	7
2018	5.36	11	0.67	8
2017	17.40	10	1.93	9
2016	11.67	3	1.17	10
2015	27.75	4	2.52	11
2014	8.75	4	0.73	12
2013	14.67	6	1.13	13
2012	11.50	2	1.13	13
2011	42.33	3	2.82	15
2010	7.50	2	0.47	16
2009	0.0	0	0.00	0.0
2008	29.00	2	1.61	18
2007	54.00	1	2.84	19
2006	0.0	0	0.00	0.0
2005	0.0	0	0.00	0.0
2004	31.00	1	1.41	22
2003	0.0	0	0.0	0.0
2002	0.0	0	0.0	0.0
2001	0.0	0	0.0	0.0
2000	0.0	0	0.0	0.0

citations per document. By 2019, the average citation per year reached 3.00, despite the total citations per article being 21.00. The latest dynamics in 2021 were 12.00 citations per document, 2024 had 0.73, and in 2025, 0.54 citations were achieved. These figures were low, particularly in 2000, 2003, 2006, and 2009, where the citations were 0.

RQ2: Journal Performance

Table 6. List of 10 popular journals

No	Journal Name	Total Articles
1.	Sensors	4
2.	Applied sciences (Switzerland)	3
3.	Journal of Sports Sciences	3
4.	Journal of electromyography and kinesiology	3
5.	Sport engineering	2
6.	International journal of computer science in sport	2
7.	Journal of strength and conditioning study	2
8.	Plos one	2
9.	Journal of physical education and sport	2
10.	IEEE Access	2

Table 6 showed that Sensors was a popular journal, producing 4 articles, followed by Applied Sciences (Switzerland), Journal of Sports Sciences, and Journal of Electromyography and Kinesiology, producing 3 articles. Following the discussion, other journals had 2 documented articles, as shown in the table.

Table 7. List of the 10 most impactful journals

No	Journal Name	Total Citations
1	Journal of electromyography and kinesiology	188
2	Journal of Sport Sciences	155
3	Plos one	82
4	Sports engineering	64
5	Sensors	59
6	Journal of strength and conditioning study	59
7	Biomedical signal processing and control	54
8	Journal of science and medicine in sport	58
9	IEEE access	38
10	Archives of Budo	34

Table 7 showed that the electromyography and kinesiology journal, with 188 citations, and the sports science journal, with 155 citations, were the journals with the most citations. Meanwhile, the other journals had an average of 34 to 82 citations. The dominance of "Sensors and Applied Sciences" (Table 5) confirms a sociotechnical shift in karate research from the realm of pure sports toward engineering in pursuit of global visibility. However, popular engineering journals, such as the "Journal of Electromyography and Kinesiology", have become scientific authorities, indicating that biomechanics remains the standard for sports science research in karate.

RQ3: Author Productivity

Table 8. List of the 10 most productive authors

No	Author Name	Total Article	Articles Fractionalized
1.	Hachaj	13	7.83
2.	Ogiela	10	4.33
3.	Witte	7	1.85
4.	Petri	6	2.05
5.	Quinzi	6	1.14
6.	Sbriccoli	5	1.35
7.	Setiawan	4	0.85
8.	Koptyra	4	1.25
9.	Masik	4	0.82
10.	Emmeracher	4	0.82

Table 8 showed that Hachaj was the most prolific author with 13 articles, followed by Ogiela in with 10, indicating individual central role in advancing study in this field. Other authors, such as Witte, Petri, and Quinzi, each contributed 6 articles. Several other studies, including Sbriccoli, who had 5 articles, and Setiawan, Koptyra, Masik, as well as Emmeracher contributed 4 articles. Productivity does not guarantee research impact; for example, while Hachaj leads in the number of publications with 13 articles, Sfroza holds

the lead in impact with 134 citations. The difference between productivity (Table 8) and impact (Table 9) underscores that technology research is still largely driven by individual researchers and has not yet achieved a broad collective consensus.

Table 9. List of the 10 most impactful authors

No	Name	Total citations	h-index	g-index	M-index
1.	Sforza	134	6	11	0.429
2.	Zago	119	5	5	0.357
3.	Sbriccoli	112	5	5	0.556
4.	Quinzi	109	4	4	0.286
5.	Witte	76	3	3	0.214
6.	Hachaj	70	3	3	0.231
7.	Petri	68	5	5	0.385
8.	Vencesbrito	67	1	1	0.062
9.	Dierick	67	1	1	0.062
10.	Sayers	67	1	1	0.062

Table 9 showed that Sforza was ranked first with a total of 134 citations, an h-index of 6, and a g-index of 11 (Sforza et al., 2001). Zago obtained 119 citations with an h-index of 5 (M Zago et al., 2015, 2017; Matteo Zago, Giuriola, et al., 2016; Matteo Zago, Piovan, et al., 2016)balance control represents a key performance determinant. With the hypothesis that high-level athletes display advanced balance abilities, the purpose of the current study was to quantitatively investigate the motor strategies adopted by elite and non-elite karateka to maintain balance control in competition. The execution of traditional karate techniques (kihon, and Sbriccoli obtained 112 citations. Interestingly, Sbriccoli had the highest m-index of 0.556, reflecting a consistent acceleration of study impact throughout his scientific career (Sbriccoli et al., 2010). Quinzi observed the impact of 109 citations (Fiorilli et al., 2020; Quinzi et al., 2013, 2014, 2015, 2016, 2018; Sbriccoli et al., 2010)muscle fibre conduction velocity (MFCV, Witte had 76 citations (Witte et al., 2022), Hachaj produced 70 citations (Hachaj, 2017; Hachaj et al., 2018, 2013), and Petri achieved 68 citations (Pastel et al., 2023; Petri et al., 2019) it is still unclear to what extent VR training tools can be applied for motor learning of complex movements. Previous VR studies primarily relate to realize performances rather than learning motor skills. Therefore, the current study compared VR with video training realizing the acquisition of karate technique, the Soto Uke moving forward in Zenkutsu Dachi, without being accompanied by a trainer or partner. Further analyses showed whether a less lavished forearm compared to a whole-body visualization in VR is necessary to acquire movements' basics sufficiently. Four groups were tested: 2 groups conducted VR training (VR-WB: whole-body visualization, and VR-FA having only visualized the forearms. Following the discussion, Vencesbrito, Dierick, and Sayers had 67 citations (Gavagan & Sayers, 2017; Pozo et al., 2011; A. VencesBrito et al., 2019; A. M. VencesBrito et al., 2011)and (ii. Although the number of citations was the same for all three, the h-index and g-index were low, namely 1, showing a large impact in one article.

RQ4: Geographic Distribution and Collaboration Network

Table 10. List of 10 countries of correspondence

No	Countries	N	%	SCP	MCP	% MCP
1.	Poland	16	13.1%	14	2	12.5%
2.	Indonesia	14	11.5%	12	2	14.3%
3.	Italy	13	10.7%	10	3	23.1%
4.	Germany	11	9.0%	9	2	18.2%
5.	Japan	9	7.4%	8	1	11.1%
6.	Brazil	8	6.6%	6	2	25.0%
7.	Spain	6	4.9%	4	2	33.3%
8.	Portugal	5	4.1%	4	1	20.0%
9.	Russia	4	3.3%	4	0	0.0%
10.	Serbia	4	3.3%	3	1	25.0%

Table 10 showed that Poland ranked first with 13.1% (16) articles of single-country publications (SCP), but still had a multiple-country publication (MCP) engagement of 12%. Indonesia ranked second with 11.5% (14) articles, with 12 SCP publications and a MCP percentage of 14.3%. Germany followed with 10.7%, approximately 13 articles, and 9.0%, about 11 articles. Japan, as the country of origin of karate, ranked fifth with 9 articles, approximately 7.4%. Spain showed the highest MCP collaboration at 33.3%, followed by Israel with 25.0% and Serbia with 25.0%. Meanwhile, Russia showed an MCP of 0.0%, signifying that technological study is more often conducted independently in the country.

Table 11. Popular collaboration patterns

No	Category	Collaborator Name	Total collaboration
1.	Cluster 1/Red	Bandow, brunnet, burger, danneberg, droste, emmermacher, masik, pastel, petri, ritter, witte, zhang	12
2.	Cluster 2/Dark Blue	Balashov, bocharov, bublikov, khasanshin, labintsev	5
3.	Cluster 3/Yellow	Camomilla, di mario, felici, quinzi, sbriccoli	5
4.	Cluster 4/Purple	Ciprandi, galvani, sforza, zago	4
5.	Cluster 5/Light Blue	Hachaj, koptyra, ogiela, piekarczyk	4
6.	Cluster 6/Orange	Kim, terada, tsuchida, tsukamoto	4
7.	Cluster 7/Brown	Franchini, goethel, robalino	3
8.	Cluster 8/Light Purple	Borysiuk, blaszczyszyn, kaczmarski	3
9.	Cluster 9/Pink	Ferreira, martins, piemontez	3
10.	Cluster 10/Green	Echeverria. santos	2

Table 11 showed that the largest collaborative hub was red cluster 1, with 12 collaborators, as the network density showed strong study integration. Meanwhile, subsequent clusters ranged from 2 to 5 collaborators, which could not be considered optimal in terms of collaborative study networks

Table 12. Popular keyword patterns

No	Category	Keyword Pattern	Total
1.	Cluster 1/Red	Accelerometers, accelerometry, algorithm, algorithms, artificial intelligence, classification, classification of information, community detection, community detection algorithm, complex networks, computer vision, convolutional neural network, computer vision, convolutional neural network, deep learning, description languages, dynamic time warping, human motion analysis, image processing, image recognition, information systems, karate, kinetic, kinematic, kinematic analysis, kinematics, kumite, learning algorithms, learning systems, machine learning, motion analysis, motion capture, multilayer neural network, physical activity, population dynamic, punch, reliability, sensor signal averaging, training process, wearable sensors wearable technology	40
2.	Cluster 2/Green	Arm, athlete, athletes, athletic performance, electromyography, hip, human experiment, joint characteristics and functions, priority journal, range of motion articular, skeletal muscle, skill	18
3.	Cluster 3/Blue	Adolescent, adult, biomechanical phenomena, biomechanics, body mass, comparative study, knee functional, martial art, martial arts, motor performance, motor skills, physiology, principal component analysis, sport, velocity,	17
4.	Cluster 4/Yellow	Combat sport, combat sports, e-learning, karate kumite, performance, personnel training, quality control, reaction time, response behavior, three-dimensional computer, virtual reality, virtual reality training, visualization	13
5.	Cluster 5/Purple	Acceleration, ankle, body equilibrium, controlled study, lower extremity, lower limb, middle-aged, pathophysiology, postural balance	10

since the clusters remained fragmented in individual studies, as shown in Figure 1.

RQ5: Popular keyword trends

Table 12 showed that Cluster 1 (red) was dominated by digitalization and artificial intelligence keywords, totaling 40. Cluster 2 (green) was dominated by athlete performance and biomechanics keywords, totaling 18. In addition, Cluster 3 (blue) was dominated by physiology and basic movement keywords, totaling 17. Cluster 4 (yellow) was dominated by technology simulation and combat response keywords, totaling 13. Moreover, Cluster 5 (purple) was dominated by body balance and pathophysiology keywords, totaling 10, as shown in Figure 2.

Discussion

This study maps the transition of karate from a traditional pedagogical sport to a science- and technology-driven sport. The researchers frame this shift not merely as an increase in the use of technology, but as a process in which traditional karate values begin to interact within measurable biomechanical, physical, and psychological parameters. This framework explains why the shift in key terms from motion tracking in the 2000s to artificial intelligence in the 2020s is not merely a trend, but a systemic response to the need for objectivity in decision-making during training and competition.

RQ1: Development of literature

The results showed a 61.5% increase in publications between 2021 and 2025. This confirms that the transformation of karate into an Olympic sport at Tokyo 2020 has shifted the paradigm from preserving traditional values to measurable, science-based achievements. This is not only a result of karate's status as an Olympic sport but also a reflection of the maturity of the research infrastructure. This situation is further supported by the increased availability of inertial measurement units (IMUs), enabling researchers from developing countries to analyze the biomechanical aspects of karate without the need for large laboratories. Although study productivity on technology in karate had increased significantly, the average citation rate in the final year of 2024-2025 remained relatively low, at only 11-13 citations. As a result, annual study productivity did not guarantee impactful publications, as showed by high citation counts.

Publication productivity was an important benchmark for assessing the performance of studies (Fischer et al., 2012). Scientific publications in any field were a source of information for societal advancement (Wahid et al., 2021). Relating to the discussion, publications aim to create and transform new knowledge as well as stimulate innovation (Wahid et al., 2021). In an academic context, publications and citations influenced individual career development and recruitment (Wahid et al., 2021). Study productivity was primarily influenced by time, academic rank, and collaboration, but had less impact by position as well as mentorship (Wahid et al., 2021). In an institution, the environment, situation, funding, and electronic infrastructure significantly influenced publication productivity (Wahid et al., 2021).

Based on the description above, publication productivity was not directly proportional to publication impact, which was characterized by the number of articles cited by other studies. In this case, the present study was needed, or similar studies that would need to be conducted. Several categories were available that influenced the increase in average citations each year. First, factors related to the article , including novelty, paper quality, popularity, interest of studies, characteristics of the discipline, methodology, study design, and documents. Other factors comprised results, discussion,

use of images, characteristics of the title, abstract, and keywords, characteristics of references, page length, article age, initial citations, and citation rate, as well as accessibility (Tahamtan et al., 2016). Second, factors about the journal, including the prestige of the journal, journal language, scope, and publication form (Tahamtan et al., 2016). Third, factors about the authors, including the number of authors, author reputation, previous citations, author academic rank, gender, race, age, productivity, organizational features, and grant funding received (Tahamtan et al., 2016).

The increase in publications was also influenced by the fact that publication indexing has tended to be more inclusive of open-access journals over the past decade. Expanded accessibility has acted as a catalyst for researchers in developing countries to improve their publication performance, yet citation latency has emerged as a factor. The data indicates a drastic increase in publication volume from 2021 to 2025, yet the average citation count has declined. This indicates literature inflation, where the speed of publication is not matched by sufficient time for evaluation, assimilation, and citation of the work. Citation latency reflects a delay in practical adaptation; that is, published technology often takes more than one or two years to be adopted in real-world applications, resulting in lower citation rates in the early years.

According to the results and citations above, productivity as well as citations per year were indeed influenced by many factors. However, when the focus was on technological developments in karate, the most important influencing factors were as follows. (1) The transition from traditional karate to modern karate required holistic dissemination, particularly for trainers. (2) The rise of academics who focused on karate was still not optimal. (3) The academic background was essentially from the field of sports, showing that the innovation to develop technology was not optimal. For example, collaboration with academics in the field of computer science or educational technology was needed.

RQ2: Journal performance

The results showed that the Sensor journal was the most popular with 4 articles, followed by Applied Sciences, Journal of Sports Sciences, and Journal of Electromyography and Kinesiology. This outcome showed that studies on karate technology were increasingly shifting from sports journals to engineering-based journals and applied sciences. Therefore, karate was observed as an extremely complex biomechanical and sensory study object. The journal with the highest impact was characterized by the number of citations, where the Journal of Electromyography and Kinesiology ranked first with 188 citations. This reinforced the global trend of technology validation through physical activity data being more popular than just the use of digital devices. Another journal, such as the Journal of Sport Sciences as the second highest impact. There was a particular concern that journals focused on sports became impactful to other studies besides those relating to engineering. Third place was the Journal Plos One with 82 citations that covered a wide scope, including sports studies. However, the 10 influential journals were still dominated by journals related to the engineering field.

The complexity of journal selection was influenced by national and university policies, study funding factors, as well as journal ranking systems, all of which were dynamic and constantly changing (Rowley et al., 2022). Experience publishing in specific journals, personal competencies, and career objectives influenced journal selection (Rowley et al., 2022). Other studies also provided different perspectives, such as good relationships with journal staff, publication reliability, and organizational willingness to sponsor publication in a particular journal, or other reasons for inviting submissions to a particular journal (Thompson, 2007). Following the discussion, the impact of the journal was influenced by open-access journals. For example, articles published twice a year were more expected to be cited in 4–10 months and nearly three times more possibly to be cited 10–16 months after publication compared to non-open access journals (Mckiernan et al., 2016).

Journal selection is often determined by indexing. Journals such as "Sensors" or "Applied Sciences" dominate due to their open-access publication profiles, thereby providing a solution for readers. However, researchers must be more critical of the shift from sports journals to engineering journals, which reflect the complexity of the subject matter and high impact factors, yet often come with excessively high publication costs. This creates a new dichotomy: sports research related to engineering that is expensive to publish, compared to sports research published in pure sports journals with lower publication costs.

Based on the description above, journal performance from a karate technology study perspective was related to study funding, experience, and journal open access. The performance was also according to the development of karate study related to less well-known technologies, which was different from other sports, such as games, namely football, volleyball, and basketball. Individual martial arts sports were still less interested in being explored. Meanwhile, the relatively limited optimal development in martial arts, particularly karate, had become an accessible and appealing field for integration with technology, facilitating the publication in reputable international journals. This process was directly proportional, and when the productivity of the journal in publishing articles was not high, citations would also be less optimal in terms of citation impact. However, certain topics related to technology in karate were interesting and had relevant pragmatic value in other sports technology, allowing the process to be dynamic. There was a possibility that these topics would be widely referenced.

RQ3: Author productivity

The results showed that, among the 10 most productive authors, Hachaj (13 articles) and Ogliela (10 articles) had the highest production and became central figures. This showed the effort and ambition to publish works related to karate technology. Despite being the most productive authors, the results of influential authors were not directly proportional. Authors with the most citations were Sfroza (134), Zagi (119), Sbriccoli (112), Quinzi (109), and others. Hachaj was not included in the top 5 influential authors, and Ogliela was excluded from the top 10. Therefore, the number of publications did not necessarily signify the number of citations.

There is a disconnect between productivity and impact: for instance, the highly productive author Hachaj is not the most cited researcher, while Sforza, with fewer publications,

is the most cited researcher. This suggests that technological research in karate still relies heavily on individual innovation. Existing studies often stand alone without forming a mutually supportive research ecosystem. One solution is interdisciplinary collaboration between computer scientists and karate experts to ensure that technology development does not stop at prototype design but continues into the long-term commercialization phase.

Studies showed that topic significantly influenced citation rates, with only a limited number if areas in sports science, such as injury and exercise physiology, receiving highly citation impact (Gholampour et al., 2022). Highly cited articles were often published in high-impact journals ranked in the top quartile and were the result of collaborations across institutions, studies, and countries (Gholampour et al., 2022). This action was also dynamic, as not all articles published in high-impact journals were highly cited (Chapman et al., 2026). Other studies had shown that international collaboration patterns had a higher potential citation impact than domestic publications (Wang et al., 2015).

Based on the description above, publication productivity was influenced by both internal and external support factors, including the presence of lecturers or academics with doctoral degrees or professorial ranks, who provided additional resources and facilitate study publication in academic journals. However, the impact of authorship on ongoing studies might be due to the need for relevant analyses previously published by authors. In karate study, particularly in relation to technology, citation practices remained suboptimal, as most analyses had primarily focused on physical training aspects that did not require technology. A high level of study collaboration between countries had an optimal impact on citation performance for articles discussing karate technology.

RQ4: Geographic Distribution and Collaboration Network

The results showed that Poland and Indonesia were among the most productive countries in terms of contributions to single-country publications (SCPs) and multi-country publications (MCPs). Other countries that followed included Italy, Germany, Japan, Brazil, Spain, Portugal, Russia, and Serbia. Poland and Indonesia showed strong ambitions of domestic academics to advance karate sports science through digital transformation. Japan was not among the top three for MCPs, despite karate originating from the country. This was probably due to the continued focus on SCP publications. Another interesting result was that Russia had not published MCP publications, which needed to be improved in its growing study efforts. Therefore, the overall collaboration network in the field of karate technology remained fragmented in a small group of collaborators. There was no consensus on a single technology platform, leading many studies to prefer SCP publications to developing MCP prototypes. Without large-scale collaborative research initiatives, karate technology will remain stuck in a state of fragmentation, meaning that the innovations produced will be difficult to replicate and implement on a global scale.

The action was shown by the largest collaboration hub in cluster 1, showed in red, with only 12 associations. As the value represented the largest cluster, it was not considered quantitatively optimal. Subsequent clusters only had between 2 and 5 collaborators, showing the strong correlation between MCP and collaboration patterns. This process allowed the present analysis to identify gaps in collaboration trends in technology studies that needed improvement, as shown in Figure 1.

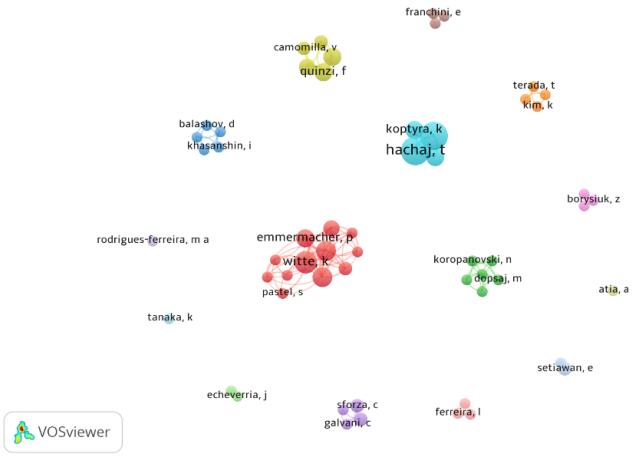

Fig. 1. Popular collaboration patterns

RQ5: Trends in Popular Keyword Patterns

The keyword pattern trend with cluster 1 in red showed a digitalization and artificial intelligence form with 40 keywords. The outcomes showed that current karate depended on subjective intuition, deep learning, and data mining. In cluster 4 (yellow), responsive training methods incorporated virtual reality applications and exergaming to support learning and achievement. When examined across different periods, the focus of literacy and studies in this field has changed significantly. Between 2000 and 2010, studies primarily focused on how to track movement using optical-based methods. From 2011-2015, investigations shifted toward kinematic and kinetic analysis of punching and kicking through the application of an electrogoniometer. During 2016-2020, developments included the introduction of the iKaraate application, the use of inertial measurement unit (IMU) sensors, and the early exploration of virtual reality for responsive training. More recently, from 2021-2025, studies have increasingly integrated artificial intelligence, deep learning, augmented reality, and systems such as Kumitron for performance monitoring and evaluation. The rise of artificial intelligence and deep learning marks a new phase in the automation of sports coaching. Underlying this transformation is the urgent need for monitoring capabilities that can handle the complexity of karate movements. Deep learning mechanisms make it easier for coaches to perform the laborious task of movement analysis, allowing them to focus on tactical aspects rather than just technique. This outcome showed the development of study trends that were starting to increase, as shown in Figure 2.

Conclusions

It is concluded that karate is evolving into a technology-driven sport, propelled by key drivers such as (1) technological needs; the surge in publications from 61.5% between 2021 and 2025 reflects researchers' pragmatic response to the complexity of karate data,

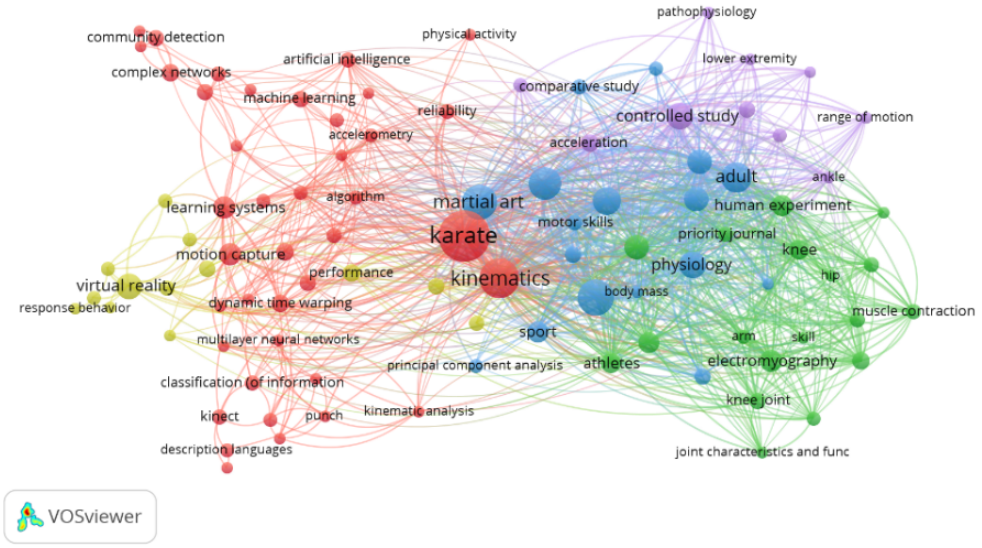

Fig. 2. Popular keyword patterns

which cannot be analyzed manually. The dominance of keywords such as artificial intelligence and deep learning underscores that technology serves as a tool for coaches. Additionally, the development of virtual reality, augmented reality, and exergaming as training tools for karateka. (2) methodological fragmentation: although productivity has increased, citation rates have fluctuated, proving that the quantity of publications does not correlate directly with research impact. Although Poland and Indonesia show high contributions to SCP and MCP, research remains confined to small groups. Suboptimal collaboration patterns result in technology research remaining uncertain, which explains why innovations are difficult to commercialize. (3) A shift in scientific authority; the dominance of engineering journals such as "Applied Sciences" and "Sensors", compared to sports science journals like the "Journal of Sports Sciences", indicates that the legitimacy of karate technology is now validated through precise biomechanical data and physical condition metrics. Researchers with high productivity—10–13 articles and 109–134 citations—have become the center of gravity, indicating a shift in authority from pedagogy toward applied science.

This study provided an analytical overview of how technology had started to develop in the implementation of karate. Although karate was occasionally viewed as a traditional sport in relation to the body and movement, technological support played a crucial role in achieving more optimal performance. Related to performance, modern karate greatly requires technology for measurement, justification, talent scouting, performance analysis, and training program development. Academically, this study contributes to how future analyses can be optimized related to the development of technology-based applications, international collaboration, and increased study productivity. The analysis also contributes to how future studies can implement applications that have been developed in the scope of karate organizations and clubs to provide knowledge and be able to use technology in training rooms. From the perspective of a practitioner, it is important to understand that the implementation of technology in karate is essential to support physical and technical performance.

Ethical Considerations

This study uses secondary data in the form of a literature review; therefore, ethical approval is not required.

Conflicts of Interest

All authors declare that they have no conflicts of interest.

Data Availability Statement

Research data are available from the corresponding author upon reasonable request. The research data were obtained from Scopus in the form of RIS records selected on April 8, 2026, using the strategy described in the research methods section.

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AI Transparency Statement

This study uses AI solely for grammar correction. The author did not use AI to write this article.

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Сучасний технологічний ландшафт карате: бібліометричне картографування та візуалізація мережі наукової літератури за даними бази Scopus (2000–2025)

Фаджар Аванг Іраван[1ABCDE], Девангга Юдхістіра[2ABCDE], Самсур'яді[3ABCDE], Деррі Аламсьях[3,4ABCDE], Нутчарі Сенакхам[5CDE]

[1]Державний університет Семаранга
[2]Державний університет Сурабаї
[3]Університет Шрівіджая
[4]Університет Multi Data Palembang
[5]Університет Срінакхарінвірот

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

Реферат. Стаття: 12 с., 12 табл., 2 рис., 46 джерел.

Мета. Сучасний напрям технологій у карате починає активно розвиватися, що підтверджується значною кількістю нещодавніх досліджень. Попередні аналізи переважно були зосереджені на окремих оригінальних дослідженнях, тоді як картування тенденцій досліджень у галузі технологій карате за допомогою бібліометричного аналізу не отримало належної уваги. Тому метою цього дослідження було проведення бібліометричного аналізу тенденцій досліджень технологій у карате на основі бази даних Scopus за період 2000–2025 років.

Матеріали та методи. Дані були зібрані за допомогою спеціально сформованих пошукових запитів із використанням логічних операторів Boolean у базі даних Scopus. Загалом було відібрано та відфільтровано 122 документи у форматі RIS із використанням програми Mendeley, після чого їх візуалізацію виконано за допомогою програм VOSviewer і Biblioshiny.

Результати. (1) Розвиток публікаційної активності: продуктивність досліджень зросла у 2021–2025 роках, тоді як цитованість журналів мала тенденцію до коливань. (2) Ефективність журналів: найпродуктивнішими були журнали у галузях прикладних наук, інженерії, а також низка спортивних журналів. (3) Продуктивність авторів: найактивніші дослідники опублікували 10–13 статей, а найбільша кількість цитувань їхніх праць становила від 109 до 134. (4) Географічний розподіл і моделі співпраці: Польща та Індонезія були провідними країнами за кількістю однокраїнних (SCP) і міжнародних (MCP) публікацій, хоча загальний рівень міжнародної співпраці залишався недостатнім. (5) Тенденції ключових слів: домінуючий кластер був зосереджений на штучному інтелекті, глибокому навчанні та сенсорах і охоплював 40 ключових слів, тоді як використання технологій віртуальної та доповненої реальності також набуває дедалі більшого поширення.

Висновки. Незважаючи на позитивні зміни в окремих аспектах, існує потреба у подальших дослідженнях і технологічних розробках, зростанні попиту в цій галузі та посиленні міжнародної співпраці. Сучасне карате потребує впровадження та безперервного вдосконалення технологій для оптимізації процесу навчання й підвищення спортивної результативності.

Ключові слова: наукометрія, бібліометрія карате, технології карате, візуалізація мережі наукової літератури.

Information About the Authors:

Irawan, Fajar Awang: fajarawang@mail.unnes.ac.id; https://orcid.org/0000-0002-0508-267X; Faculty of Sport Sciences, Universitas Negeri Semarang, Semarang, Indonesia.

Yudhistira, Dewangga: dewanggayudhistira@unesa.ac.id; https://orcid.org/0000-0002-4194-1283; Faculty of Sport sciences and Health, Universitas Negeri Surabaya, Surabaya, Indonesia.

Samsuryadi: samsuryadi@unsri.ac.id; https://orcid.org/0000-0001-9761-476X; Computer Science Doctoral Program, Universitas Sriwijaya, Palembang, Indonesia.

Alamsyah, Derry: derry@mdp.ac.id; https://orcid.org/0000-0003-4598-9919; Computer Science Doctoral Program, Universitas Sriwijaya, Palembang (Indonesia). Faculty of Computer Science and Engineering, Universitas Multi Data Palembang, Palembang, Indonesia.

Senakham, Nutcharee: senakhamnutcharee@gmail.com; https://orcid.org/0000-0002-7561-1864; Faculty of Physical Education, Sports and Health, Srinakharinwirot University, Nakhon Nayok, Thailand.

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Review Article

Technical Engagement in Small-Sided Games: Effects of Task Constraints in Football — A Systematic Review

Samir Essafi[1ABCDE], Younes Brouki[1ABCDE], Hatim Ben Seddik[2ABCDE], Hiba Rimy[1ABCDE], Chaimae Khali[1ABCDE], Mohamed Barkaoui[1ABCDE], Aziz Eloirdi[1ABCDE], El Mokhtar EL Ouali[1ABCDE] and Aziz Chokri[1ABCDE]

[1]Hassan I University
[2]Abdelmalek Essaâdi University

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

Corresponding Author: Samir Essafi, e-mail: essafisamir114@gmail.com
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Abstract

Introduction. In football training, small-sided games (SSGs) are frequently used as an integrated approach to simultaneously develop the technical, tactical, physical, and cognitive dimensions of performance. However, the extent to which specific task constraints influence technical engagement remains inconsistently synthesized.

Objectives. This systematic review aimed to examine how different SSG task constraints affect technical engagement in football players within an integrated training framework.

Materials and Methods. A systematic search of electronic databases was conducted following established review guidelines. A total of 35 studies investigating the effects of SSG format, pitch size, rule modifications, age, biological maturity, and integrated effects on technical engagement were included. Methodological quality was assessed, and the findings were synthesized according to thematic categories.

Results. The findings indicated that smaller formats and reduced team sizes increased technical involvement, while pitch dimensions and scoring rules modulated passing patterns, shooting frequency, and ball possession. Touch limitations accelerated ball circulation but often increased technical errors, particularly in younger players. Age, technical level, and biological maturity significantly influenced technical efficiency. Mental fatigue and inadequate recovery were consistently associated with reduced passing accuracy, poorer ball control, and increased errors.

Discussions. These findings are consistent with prior research highlighting the role of task constraints in shaping performance. The evidence supported the view that technical engagement in SSGs emerges from the dynamic interplay of structural, developmental, and psychophysiological factors.

Conclusions. SSGs constitute an effective integrated training modality for enhancing technical engagement, provided that task design is developmentally aligned and contextually structured.

Keywords: small-sided games, technical engagement, integrated training, task constraints, football.

Introduction

Football is a dynamic and complex team sport in which performance emerges from the continuous interaction between technical execution, tactical organization, and physiological demands (Little & Williams, 2006; Parlebas, 2020). Given the complexity of football, traditional training methods initially targeted physical, technical, and tactical components separately, often emphasizing ball-free exercises to develop aerobic and anaerobic capacities (Helgerud et al., 2001; Radziminski et al., 2013). Although effective for physiological development, this approach was time-intensive and insufficient for enhancing context-specific technical and tactical skills (Michailidis, 2013). Considering that technical and tactical proficiency are decisive for offensive performance and competitive success (Francesco et al., 2015, 2016), the multidimensional demands of modern football have led to the emergence of integrated training, which simultaneously develops physical capacities alongside technical and tactical competencies.

Integrated training is considered effective approach for player development, as performance improvements are maximized when training conditions mirror the demands of competition (Clemente, 2016). Within this framework, small-sided games (SSGs) enable coaches to concurrently stimulate technical and tactical skills, while enhancing physiological capacities (Chootsungnoen et al., 2025b; Muhyi et al., 2025; Owen et al., 2011). A key pedagogical advantage of SSGs lies in their capacity to promote "repetition without repetition," meaning that players are repeatedly exposed to representative task conditions that enhance perception–action coupling without relying on mechanical and decontextualized technical drills typical of analytical training approaches (Tan et al., 2012).

SSGs are now widely integrated into training programs and can be adapted according to coaching objectives by manipulating rules, player numbers, pitch dimensions, and other contextual variables to regulate task intensity and learning focus (Hill-Haas et al., 2011; Michailidis, 2013). However, modifications in task constraints are expected to produce different effects on players' technical engagement and therefore require careful design and control. Although their impact on physiological responses (Aguiar et al., 2012; Clemente et al., 2014; Hill-Haas et al., 2011), tactical engagement (Essafi et al., 2026; Ometto et al., 2018), and multidimensional outcomes (Bujalance-Moreno et al., 2019; Sarmento, Clemente, Harper, et al., 2018) has been widely reviewed, further clarification is needed regarding how coaches can deliberately manipulate these constraints to enhance technical engagement. Technical engagement refers to the degree of involvement of a player in technical actions within the game, reflecting the frequency, diversity, and contextual relevance of technical behaviors. Variability in findings across similar task manipulations reinforces the need for a clearer synthesis of evidence.

The specific effects of SSG task manipulations on technical engagement indicators remain insufficiently systematized despite the expanding body of literature. The use of SSGs for developing technical skills has been previously examined; however, a structured synthesis of objective indicators of technical engagement across different task constraints is still lacking (Clemente & Sarmento, 2020; Francesco Sgrò et al., 2018). A clearer and more structured understanding of how task design shapes players' technical involvement would provide practitioners with more precise guidance for optimizing integrated football training.

The purpose of this systematic review is to explore how different small-sided game (SSG) task constraints—such as game format, pitch size, rule modifications, and contextual factors—affect technical engagement in football players. By synthesizing outcomes across task designs, it seeks to clarify how SSG configurations influence technical engagement and to provide a more structured and practice-oriented framework for optimizing integrated training in football.

Materials and Methods

Study design and eligibility criteria

The present systematic review was conducted in strict accordance with the PRISMA guidelines, which provide a standardized framework to ensure transparency, methodological rigor, and reproducibility throughout the processes of study identification, selection, and evidence synthesis (Moher et al., 2010; Page, M. J., McKenzie, J. E., Bossuyt, P. M., et al., 2021; Page, M. J., Moher, D., Bossuyt, P. M., et al., 2021).

Study eligibility was determined through the PICO framework (Population, Intervention, Comparator, Outcomes). The population included football players of any age category, gender, and competitive level. The intervention consisted of training interventions based on small-sided games (SSGs) implemented within an integrated training approach. Comparators involved different manipulations of SSG task constraints. The outcomes of interest focused on indicators of technical engagement.

Studies were included if they: (a) focused solely on football; (b) were published in English; (c) consisted of peer-reviewed articles available in full-text format; (d) were carried out in competitive or performance-oriented contexts; (e) implemented SSG-based training interventions; and (f) reported quantifiable technical performance outcomes. Studies were excluded when they: (a) were conducted in purely educational or recreational settings; (b) were not available in English; (c) did not assess technical performance variables; (d) examined only physical or physiological outcomes without reporting technical indicators; (e) lacked an empirical scientific design (e.g., opinion papers or descriptive reports); (f) did not present original data; or (g) were systematic reviews or meta-analyses.

Search strategy

A systematic search was conducted across three electronic databases—Scopus, PubMed, and Web of Science—and was limited to studies published between 2015 and 2025, in order to capture recent advances in methodological practices, analytical techniques, and training models relevant to SSG research. Search strategies were tailored to each database and constructed using combinations of keywords and Boolean operators. The core search string included terms related to small-sided games, football, integrated training, task constraints, and technical engagement, as follows: ("soccer" OR "football") AND ("small-sided games" OR "SSG") AND ("integrated training") AND ("task constraints" OR "task manipulation") AND ("technical performance" OR "technical engagement" OR "technical actions" OR "technical skills").

All retrieved records were imported into Zotero reference management software for systematic organization and deduplication. The screening process adhered to PRISMA guidelines. Following duplicate removal, titles and abstracts were independently evaluated by two reviewers to eliminate studies failing to satisfy the predefined eligibility criteria. Articles deemed potentially eligible were subsequently assessed in full text to confirm their inclusion. Disagreements between reviewers were addressed through deliberation until a consensus was reached.

Figure 1 presents the PRISMA flow diagram summarizing the entire selection process, from initial record identification through screening and exclusion to final study inclusion.

Methodological quality

To evaluate the methodological quality and risk of bias of the retained studies, a validated 16-item checklist tailored

specifically to Small-Sided Games (SSG) research was applied (Sarmento, Clemente, Araújo, et al., 2018; Sarmento, Clemente, Harper, et al., 2018). This instrument enables a structured appraisal of both methodological rigor and reporting transparency across the selected articles. The checklist covers several key domains: study purpose stated clearly (item 1), relevance of background literature (item 2), appropriateness of the study design (item 3), sample included (items 4 and 5), informed consent procedure (item 6), outcome measures (item 7 and 8), method description (item 9), significance of results (item 10), analysis (item 11), practical importance (item 12), description of drop-outs (item 13), conclusions (item 14), practical implications (item 15), and limitations (item 16).

Items were scored on a binary scale (0 = not fulfilled; 1 = fulfilled), with a "not applicable" (NA) option reserved for informed consent and dropout-related criteria when irrelevant to the study design. A composite quality score was then calculated as the proportion of fulfilled criteria relative to applicable items. On this basis, studies were subsequently classified into three quality tiers: low quality (≤50%), good quality (51–75%), or excellent quality (>75%).

Data Extraction

Data extraction was carried out using a standardized form to maintain consistency across studies. For each article, general characteristics were recorded (author, year, sample size, participants' age, and competitive level). In addition, key methodological and intervention details were collected, including study objectives, SSG format, pitch dimensions, work duration, applied rules, technical variables analyzed, and main findings.

Results

Study Identification and Selection

The initial database search yielded 442 records. All references were imported into Zotero, where 98 duplicates were automatically identified and removed. The remaining studies then underwent title and abstract screening, resulting in the exclusion of 211 articles deemed inconsistent with the overarching objectives of the review. A total of 98 full-text papers were subsequently excluded after detailed assessment against the predefined inclusion criteria. A total of 35 studies ultimately met all eligibility requirements and were retained for final synthesis. These studies comprised a total sample of 1,088 participants and examined technical engagement outcomes under different Small-Sided Game formats within an integrated training context. The PRISMA flow diagram (Figure 1) provides a comprehensive visual summary of the identification, screening, and inclusion stages.

Data Synthesis

Technical engagement within SSG-based integrated training contexts was predominantly explored through task constraint manipulation. The findings derived from the selected studies were subsequently organized into thematic categories to ensure a clear and coherent synthesis.

Specifically, results were structured according to: (1) the effects of different SSG formats (n = 10); (2) the impact

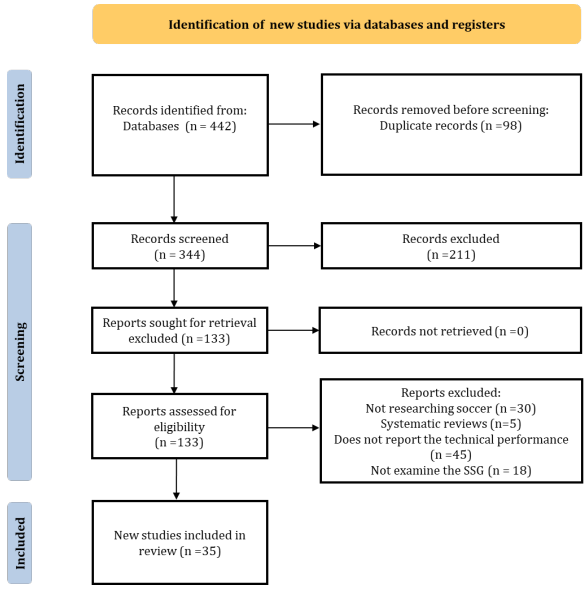

Fig. 1. PRISMA flow diagram summarizing the screening and selection process

of pitch size and spatial configurations (n = 8); (3) the influence of specific task-rule modifications (n = 7); (4) effects associated with players' age, biological maturity and technical level (n = 5); and (5) integrated effects arising from the manipulation of other constraints. (n = 5).

This categorization allowed for a systematic examination of how task constraints shape technical outcomes in football SSGs.

Methodological Quality

Methodological quality was evaluated using a checklist specifically designed for SSG research (Sarmento, Clemente, Araújo, et al., 2018). Overall, the studies exhibited a high level of methodological rigor, with all being rated within the "excellent" quality category. Nevertheless, none reached a perfect score of 100%, and the lowest observed score was 75%. The most frequently identified limitations concerned insufficient reporting of study constraints and a lack of clear justification for sample size calculations. Despite the generally strong methodological quality, improving transparency in these areas would enhance the robustness of future research in this field.

Discussion

This systematic review sought to determine how different Small-Sided Game (SSG) task constraints influence technical engagement in football players within the context of integrated training. Unlike prior reviews that frequently examined technical actions in isolation, this study adopts an integrated approach by focusing on technical engagement across multiple task constraints, including pitch size, player numbers, rules, and contextual factors. The synthesis of the included studies demonstrates that variations in SSG formats consistently produce distinct changes in technical engagement, supported by a growing body of research and

Table 1. Technical engagement across different game formats

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Oh & Joo, 2018)	27 players, U12 "Age not specified"	Assess the effect of format variations on technical engagement	8 v. 8 11 v. 11	62 x 51 (198 m^2) 80 x 54 (196 m^2)	1 x 25'	At kick-off, no shoot directly was allowed; at goal kick, the ball could not be passed over the halfway line; and GKs were not permitted to kick the ball into the opposing half.	Passes Ball contacts Passes in attacking area Forward passes build-up passing Passing in the final third One touch passes Dribbles Shot, mid-, and long-distance passes Crosses Cutbacks Shooting actions goals scored Duels	The smaller game format was associated with a notable rise in the frequency of ball contacts, total passes, zone-specific passing actions and their corresponding success rates, short- and mid-range passes, attempts on goal, shots within the penalty area, and successful dribbling actions.
(Torrents et al., 2016)	44 players, 23.1 ± 0.7 y.o (Amateur; n = 22) and 25.6 ± 4.9 y.o (Pro; n = 22)	Investigate the effects of format modifications on technical engagement	4 v. 3 + G.K 4 v. 5 + G.K 4 v. 7 + G.K	40 x 30 (171 m^2,133 m^2, 109 m^2)	1 x 3'	Regular rules were applied. The score was reset to zero whenever a two-goal margin was reached by either team.	Withdraw Pass Anticipate Drive Run to the ball Control Delay Dribble Support Clear Press Wait Feint Balance Shoot Unmark Deflect Protect Dissuade Intercept	A higher number of opponents was linked to a higher occurrence of defensive actions (notably ball control) and a reduction in waiting behaviors. As the number of opponents increased, players in possession performed fewer passes and less driving actions.

Table 1 (continued)

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Sanchez-Sanchez et al., 2017)	22 players, 17.2 ± 0.9 y.o	To examine how the use of internal and external floaters affects players' technical engagement.	4 v. 4 4 v. 4 + 2 4 v. 4 + 2 + 2 4 v. 4 + G.K 4 v. 4 +2+ G.K 4v.4+2+2+G.K	40 x 30 (150 m^2; 120 m^2;120 m^2)	4 x 4'/2'	Each SSG involved four neutral players (two internal, two external), providing possession support from both within and outside the playing area, with no offside rule enforced.	Game pause Dribbling Pass Collective success	Compared to formats involving neutral players, 4v4 SSGs (both with and without the inclusion of a goalkeeper) showed a higher number of dribbling actions. Moreover, collective success was significantly greater in 4v4 SSGs without a goalkeeper (both with and without neutral players) than in formats including a goalkeeper.
(Bergmann et al., 2022)	85 players, U7 (n = 42) U9 (n = 43)	Compare technical actions across different game formats	5 v. 5 + G.K 7 v. 7 + G.K 3 v. 3	28 x 20 (56 m^2) 45 x 35 (125.5 m^2)	4 x 5' 1 x 20'	3v.3 on mini-goals (no GK) 5v.5 on 1.65 × 5 m goals (with GK) 7v7: regular rules	Total actions, passes, dribbles, goals, and duels	In under-7, 3v3 increased all technical actions compared with 7v7. In under-9, 5v5 increased most technical actions, while 7v7 increased unsuccessful 1v1 situations. Smaller formats increased total technical actions compared with 7v7 in both age groups.
(Clemente et al., 2018)	12 players 7.6 ± 0.5 y.o	Analyse variations in individual technical actions and their variability between SSG formats	3 v. 3 6 v. 6	20 x 15 (50 m^2) 30 x 22 (55 m^2)	3 x 3'/2'	regular rules with small goal (2 × 1 m)	Ball recoveries Ball losses Balls received Attacking balls Neutral balls Successful shots Unsuccessful shots	The 3v3 format substantially increased the individual frequency of technical actions—including ball receptions, recoveries, neutral possessions, turnovers, and unsuccessful shots—compared to the 6v6 condition.
(Alcântara et al., 2021)	11 players 13.0 ± 0.8 y.o	Assess the effect of variations in player number on technical engagement.	3 v. 3 + GK 5 v. 5 + GK	37 x 24 (148 m^2) 48 x 31 (148.8 m^2)	(4 or 2 or 1) x (5 or 10 or 20) / (150 to 300 s)	Influence of the Regimen; Goalkeepers	Successful passes Ball involvement Balls contact Unsuccessful passes Shots on target Unsuccessful shots Goals scored	Compared to 5v5, the 3v3 format generated more successful passes, ball involvement, ball contacts, shots on target and goals.

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Table 1 (continued)

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Wang et al., 2024)	24 players 16.6 ± 0.5 y.o	Compare technical performance between 2v2 and 4v4 and examine association with aerobic capacity (YYIRT)	2 v. 2 4 v. 4	25 x 15 (94 m^2) 35 x 17 (92 m^2)	4 x 2'/ 2' 4 x 4'/ 2'	No offside small goal	Lost ball Successful passes Unsuccessful passes	2v2 increased successful passes, unsuccessful passes, and ball losses compared with 4v4. YYIRT was positively correlated with unsuccessful passes and ball losses in 2v2.
(Yılmaz & Soylu, 2024)	24 players 21.0 ± 1.5 y.o	Evaluate the influence of SSG formats on technical responses	2 v. 2 2 v. 2 +GK 4 v. 4 4 v. 4 +GK	27 × 15 (101m^2) 27 × 15 (101m^2) 32 × 25 (100m^2) 32 × 25 (100m^2)	4 x 2'/ 2' 4 x 4'/ 2'	Scoring method: Goalkeeper; Small goals; Ball possession	Ball losses Successful passes Unsuccessful passes Interceptions	Possession games increased successful passes in both 2v2 and 4v4 compared with mini-goal and goalkeeper formats. In 2v2, possession games also increased interceptions compared with mini-goal and goalkeeper formats.
(Clemente et al., 2019)	16 players 10.1± 0.3 y.o	Compare technical action variability and differences between formats	3 v. 3 6 v. 6	15 x 20 (50 m^2) 30 x 22 (55 m^2)	3 x 3' /2' 3 x 6' /2'	Standard SSG rules	Shots (S) Attacking balls/passes (AB) Received balls (RB) Conquered balls (CB) Lost balls (LB)	3v3 largely increased, conquered balls, lost balls, received balls and shots compared with 6v6. 6v6 showed very large decreases in technical actions per minute compared with 3v3.
(Chootsungnoen et al., 2025a)	20 players 21.4 ± 1.82 y.o	Examine the effects of floater number on technical engagement	4 v. 4 4 v. 4 + 1 4 v. 4 + 2	32 x 25 (100 m^2)	4 x 4'/4'	Addition of 1 or 2 neutral floaters	Interceptions Total passes Successful passes Dribbling	4v4+2 increased total and successful passes compared with 4v4. 4v4+1 showed intermediate technical responses. However, no clear differences were observed in dribbling and interceptions across all small-sided game groups.

Table 2. Technical engagement across spatial configurations and pitch sizes

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Coutinho et al., 2020)	10 players, 13.7 ± 0.5 y.o	To examine how different pitch boundary markings affect technical engagement in SSGs.	5 v. 5 + G.K	30 x 25 (75 m^2)	3 x 6'/ 3'	Three distinct types of external pitch markings were employed: (1) fully continuous lines, (2) dashed lines and (3) markings limited to the corners only	Goals Dribbles Passes Shots on target	In comparison with corner-only markers, the presence of pitch lines was linked to an increase in offensive technical actions, while simultaneously resulting in a lower frequency of passes.
(Folgado et al., 2019)	20 players, 14.1 ± 0.5 y.o	To evaluate how manipulating pitch length and width affects technical engagement in SSGs.	4 v. 4 + G.K	40 x 30 (150 m^2) 30 x 40 (150 m^2)	3 x 6'/ 3'	The offside rule was not enforced.	Passes Dribbles Lost balls Goals Shoots	The 30 x 40 m pitch configuration was linked to a higher individual shooting frequency, whereas the 40 x 30 m format yielded an elevated frequency of completed passes per player.
(Olthof et al., 2018)	148 players, 12.5 ± 0.5 y.o (n = 36), 14.4 ± 0.5 y.o (n = 43), 16.6 ± 3.2 y.o (n = 28), 17.9 ± 1.0 y.o (n = 43)	To examine how alterations in pitch size affect players' technical engagement in SSGs.	4 v. 4 + G.K 4 v. 4 + G.K	40 x 30 (120 m^2) 68 x 47 (320 m^2)	1 x 4'	In the smaller pitch dimension, the offside rule was not enforced.	Goals/shots Set pieces Transitions Ball possessions	The larger pitch was associated with longer ball possession phases and a reduced number of transitions.
(Jara et al., 2018)	13 players, 16.6 ± 0.9 y.o	To examine how alterations in pitch size affect goalkeeper-specific technical engagement in SSGs.	5 v. 5 + G.K	32 x 23 (74 m^2) 50 x 35 (175 m^2) 62 x 44 (273 m^2)	3 x 8'/5'	No corners were awarded.	Goal kick Control with the foot Fly Direct and indirect free kick Clear-out 1-on-1 Open palm technique Pass by hand and foot Screen Deflection Clear-out by the defence Parry Save	The frequencies of duels and blocks were increased on the larger pitch, In contrast, the smaller pitch was associated with an increased number of passes executed using both the hands and the feet.

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Table 2 (continued)

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Martone et al., 2017)	33 players, 10.0 ± 0.5 y.o (n = 17), 13.2 ± 0.3 y.o (n = 16)	To examine how differences in relative playing space allocated per player affect technical engagement in SSGs.	3 v. 3 3 v. 3 4 v. 4 4 v. 4 5 v. 5 5 v. 5	20 x 20 (67 m^2) 30 x 30 (150 m^2) 20 x 20 (50 m^2) 30 x 30 (113 m^2) 20 x 20 (40 m^2) 30 x 30 (90 m^2)	3 x 4'/3'	No goalkeeper was included; goals were considered valid exclusively when all members of the attacking team had advanced into the opponent's half of the pitch.	Ball involvements Dribbles Passing actions Target passes Headers Defensive tackles Shots on goal Crosses	Older players performed more dribbles, crosses, and tackles when relative space was smaller. In larger relative space, higher overall involvement with the ball was observed. Younger players showed a more variable (scattered) pattern of technical actions across space conditions.
(Joo et al., 2016)	32 players, 12.0 ± 0.4 y.o	Examine how variations in pitch dimensions influence technical engagement.	7 v. 7 + G.K 7 v. 7 + G.K 11 v. 11	68 x 47 (228 m^2) 75 x 47 (252 m^2) 75 x 47 (176 m^2)	1 x 30'	Regular rules	All passes Continuous passes Side passes Forward passes Back passes Short; Mid and Long-distance passes Blocked balls	The 7v7+GK format on the larger pitch produced a significant increase in total passes and forward passes.
(Nunes et al., 2021)	52 players, U11: (n = 16), age: 10.0 ± 0.7 y.o, U15: (n = 18), age: 14.0 ± 1.3 y.o U23: (n = 18), age:21 ± 1.60 y.o	Investigate effects of playing area size on technical responses	4 v. 4	20 x 15 (37.5m^2) 25 x 20 (62.5 m^2) 30 x 25 (93.75 m^2)	4 x 4'/4'	The format excluded both goalkeepers and any type of goal or target structure.	Maximum passing speed Dominant foot passes, and non-dominant foot passes.	No overall significant differences in technical actions. U11 performed more passes in larger areas, while U23 performed more passes in smaller areas. Minimal effects observed in U15.
(Qiao et al., 2025)	36 players 16.5 ± 0.5 y.o	To examine how pitch size and scoring method interact to affect technical engagement in SSGs.	3 v. 3	18.4 x 24.5 (75 m^2) 21.2 x 28.3 (100m^2) 23.3 x 31.0 (120m^2)	3 x 4'/2'	Two formats: ball possession vs small goals	Passes Receptions dribbles shots	Larger pitches promoted greater passing success. Small-goal formats and smaller pitches encouraged more frequent dribbling but reduced passing success and overall technical variety. Higher physiological intensity was moderately associated with decreased shooting effectiveness.

Table 3. Technical Engagement across different task-rule modifications

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Machado, Ribeiro, et al., 2019)	20 players, 13.5 ± 1.2 y.o (n = 10), 16.3 ± 0.5 y.o (n = 10)	Assess how rule changes and variations in game configurations influence technical engagement.	3 v. 3 + G.K 4 v. 4 + G.K	36 x 27 (162 m^2) 47.72 x 29.54 (176 m^2)	1 x 10'	Six SSG formats were used: three progression-to-target games and three ball possession games.	Ball touches Ball possessions Passes Players involved Shots	In youth players, reduced SSG formats made ball retention more challenging. The 3v3 condition improved offensive effectiveness in progression-based games, while possession-maintenance tasks resulted in extended passing sequences and higher player involvement.
(Rago et al., 2018)	8 players, 20.1 ± 1.0 y.o (Amateurs)	Evaluate how different playing surfaces (sand versus artificial turf) influence technical engagement.	4 v. 4 + GK	37 x 28 m (130 m^2)	3 x 6'/3'	No offside rule	Goals Dribbling Passes or crosses Tackles Shots Headers Involvements with the ball Chest trap	In comparison with sand, a higher number of successful actions was recorded on artificial turf. Conversely, actions involving lifting the ball occurred more frequently on sand than on artificial turf.
(Batista et al., 2019)	16 players, 23.9 ± 5.4 y.o (semi-pro)	Assess how coach instructions influence technical engagement.	7 v. 7 + G.K	62 x 50 (221 m^2)	1 x 5'	Standard rules were applied. Teams were either given no tactical instructions or specific guidance related to defensive and offensive strategies.	Ball recoveries Number of passes per ball possession	Defensive instructions led to more ball recoveries and reduced space occupation, whereas offensive instructions, relative to the no-instruction control condition, produced more passes and greater spatial coverage.
(Pulling et al., 2016)	8 players, 12.1 ± 0.5 y.o	To assess how different scoring formats (2-goal, 4-goal, 2-goal with goalposts, and 4-goal with one infield corner goal) affect technical engagement in SSGs.	4 v. 4	45.72 x 36.58 (209 m^2)	2 x 5'/3'	The study used four scoring formats: (1) a 2-goal game, (2) a 4-goal game, (3) a 2-goal game with goalposts, and (4) a 4-goal game featuring one infield goal positioned at each corner. Throw-ins were not permitted during play.	Goal Shot Dribbling Turning 1 vs. 1 (duels) One-two Overlap Penetrating pass Successful pass Pass forwards Pass backwards Pass sideways Unsuccessful pass	The 2-goal condition generated more successful penetrating, forward and backward passes, while the 4-goal format produced more sideways passes and turns. Shots and goals were most frequent in the 4-goal game with one corner-positioned infield goal.

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Table 3 (continued)

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Castellano et al., 2016)	24 players, 19.1 ± 1.2 y.o	Evaluate how different scoring formats (small goals, presence of goalkeepers, and use of floaters) influence technical engagement.	7 v. 7 + G.K 7 v. 7 7 v. 7 + G.K + 2 (outside neutral players)	40 x 25 (71 m^2)	1 x 6'	No offside rule The 7 vs. 7 format without a goalkeeper was played using small goals.	Offensive sequences (Duration) total possession percentage	Game formats integrating small goals and neutral players were associated with prolonged ball possession sequences relative to the format employing solely a goalkeeper.
(Soylu et al., 2024)	20 players, 17.3 ± 1.4 y.o	To examine how coach encouragement (CE) affects players' technical performance in SSGs.	2 v. 2 3 v. 3 4 v. 4	15 x 27 (100 m^2) 20 x 30 (100 m^2) 25 x 32 (100 m^2)	4 x 2'/ 2' 4 x 3'/ 2' 4 x 4'/ 2'	Two conditions: with coach encouragement (CE+) vs without encouragement (CE−)	Successful passes, successful shots	CE+ increased successful passes and shots compared to CE− (moderate to very large effects). CE− showed lower technical performance.
(Rosten et al., 2025)	12 players, 17.9 ± 0.8 y.o	To investigate how different touch restrictions influence ball-touch temporal intervals and technical engagement	4 v. 4 + GK	20 x 30 (75m^2)	3 x 4'/4'	Three conditions: max 2 touches; max 3 touches; free play (no touch restriction)	Temporal interval between 1st and 2nd touch, total passes, receptions	Touch restrictions generated more passes than unrestricted conditions, while unrestricted play produced more receptions. Across all touch rule conditions, the shortest interval between first and second touches was observed in the offensive zone.

Table 4. Technical engagement across age, technical level, and biological maturity

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Machado, Barreira, et al., 2019)	48 players, 13.1 ± 1.5 y.o (n = 24), 16.9 ± 0.1 y.o (n = 24)	Evaluate how age and tactical skill level influence technical engagement.	3 v. 3 + 3 + G.K 4 v. 4 + G.K	47.72 x 29.54 (157 m^2) 47.72 x 29.54 (176 m^2)	1 x 10'	No offside rule was enforced	Ball possession Shooting actions Players involved Passing actions Ball contacts	Players with higher skill levels demonstrated increased offensive activity and effectiveness.

Table 4 (continued)

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(Rowat et al., 2017)	27 players, 17.4 ± 0.9 y.o	To assess how physical performance and technical skills combine to influence overall technical engagement in SSGs.	5 v. 5	30 x 25 (75 m^2)	4 x 5'/ 3'	Small goals were used No GK	A technical game scoring system was used to evaluate player performance across ten indicators: first touch, awareness, overall control, aerial control, short and long passing, dribbling, turning, shooting, accuracy, two-footed ability, and attitude.	Dribbling executed in combination with a pass was the strongest indicator of a player's technical level during SSGs. Overall technical performance showed no significant association with physical performance.
(Coutinho et al., 2022)	114 players, U9=20 (7.9± 0.9 y.o) U11= 20 (9.5 ± 0.9 y.o) U13= 21 (11.6± 0.8 y.o) U15= 18 (13.9± 0.6 y.o) U17= 19 (16.2± 0.7 y.o) U19= 16 (17.9± 0.4 y.o)	To assess how limiting the number of ball touches affects performance across different age groups in SSGs.	G.K+ 4 v. 4 +G.K	40 x 30 (150 m^2)	3 x 4'/2'	Three conditions : free play (FP); max 2 touches (2T); max 1 touch (1T)	Technical variables included successful and unsuccessful passes, successful dribbles, shots on target, and goals scored.	Restricting ball touches (2-touch and 1-touch conditions) led to small-to-moderate improvements in successful passes across U9, U15, and U17 players, while generally also resulting in an increase in unsuccessful actions; younger groups (U9–U13) coped better with 2T than 1T, while older groups showed better adaptation to stricter touch limits.
(King et al., 2025)	53 players 13.4 ± 0.9 y.o	To assess how team size and bio-banding (maturity grouping) affect technical engagement in SSGs.	4 v. 4 5 v. 5 6 v. 6	40.3 x 28 (141.05 m^2) 44.1 x 32 (141,12 m^2) 47 x 36 (141m^2)	72 SSGs total × 5'/5'	No goalkeepers were used. Players were not allowed to score unless they were in the opponent's half.	Touches, releases, possessions, time on the ball.	Technical action frequency declined with increasing team size, while more biologically mature players performed more technical actions in 4v4 than 6v6 formats. Less mature players in mismatched groups showed greater technical variability, especially in 4v4. Overall, smaller formats enhanced technical involvement, particularly under maturity-matched conditions.
(Cherni et al., 2025)	36 players Pre-PHV (n = 12) 14.7±0.4 y.o Circa-PHV (n = 12) 14.4±0.9 y.o Post-PHV (n = 12) 14.2±0.7 y.o	Evaluate how biological maturity status influences technical engagement across different SSG formats.	3 v. 3 4 v. 4	36 x 27 (162m^2) 40 x 29 (193 m^2) 40 x 30 (150 m^2) 44 x 33 (181,5m^2)	2 x 4'/1'	Standard SSG rules	Successful passes (%SP), interceptions, duels, ball-loss, ball possession	Pre-PHV: higher interceptions in large SSGs; post-PHV: higher %SP; 4-a-side increased ball-loss and decreased duels/%SP; large pitches increased ball possession and interceptions; regular pitches increased accelerations and decelerations.

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Table 5. Technical engagement across integrated effects

Author / year	Sample	Objective	SSGs format	Pitch size (m)	Work	Rules	Analyzed variables	Results
(McLean et al., 2016)	12 players 21 ± 3 y.o	Assess how the duration of recovery between SSG bouts influences technical engagement.	3 v. 3	15 x 20 (50m²)	6 x 2'/30" 6 x 2'/120"	The game format excluded both goals and goalkeepers, and no form of coach encouragement was administered throughout the sessions.	Successful passes Unsuccessful passes Interceptions Ball possession Tackles Balls lost	Only successful tackles increased and team possession time decreased in REC-120; all other technical variables unchanged. Recovery duration had minimal impact on technical execution.
(Christopher et al., 2016)	12 players, 15.8 ± 0.6 y.o	To examine how different work-to-rest ratios affect players' technical engagement in SSGs.	6 v. 6 + G.K	50 x 32 (133 m²)	1 x 8' 2 x 4'/1' 4 x 2'/1'	No offside	Ball Control & Possession: Individual possessions Regains Passes (Successful passes; Unsuccessful passes) Shots (Shots on target; Goals)	In the continuous regimen, players scored significantly fewer goals, while no meaningful differences were observed in the other technical actions.
(Badin et al., 2016)	20 players 17.8 ± 1.0 y.o	Evaluate how mental fatigue influences technical engagement during SSGs.	5 v. 5	20 x 30 (60m²)	2 x 7'/1'	standard SSG rules without GK	Involvements, Possessions, Passes, Control Error, Tackles	Mental fatigue reduced the quality of technical actions, including passing, receptions…
(Trecroci et al., 2020)	9 players 17.6 ± 0.5 y.o	To examine how mental fatigue affects technical engagement during SSGs.	4 v. 4 + 1	32 x 40 (160 m²)	2 x 7'/1'	No offside rule	Passing accuracy, shot accuracy, Control, tackles	Mental fatigue likely reduced passing and shot accuracy, increased control errors and negative passes, and decreased tackle success and ball possession.
(Selmi et al., 2021)	20 players 25.1 ± 1.0 y.o	Assess how well-being measures and Total Quality of Recovery shape players' technical engagement.	5 v. 5	35 x 25 (87,5m²)	4 x 4'/3'	standard rules	Successful pass Lost ball Possession Interception Tackle	Greater fatigue and DOMS levels corresponded to fewer successful interceptions, passes, tackles, and more lost passes. Likewise, lower TQR scores were associated with reduced technical performance.

diverse participant samples. These results equip coaches with actionable guidance to optimize SSG design and planning targeting specific technical engagement while accounting for players' developmental stages and game contexts.

Most included studies were rated as excellent in methodological quality, which enhances confidence in the validity of the findings reported. Nonetheless, some recurrent limitations were observed, particularly the lack of justification for sample sizes and the limited acknowledgment of study constraints, suggesting that even validated quality assessment tools may not capture all methodological nuances.

For clarity and coherence, the discussion is organized around the main thematic areas that emerged from the reviewed literature, including game format, pitch size, task-rule modifications, age and maturity, and integrated influences on technical engagement.

Effects of game format on technical engagement

Manipulating SSG format, particularly through adjustments in player numbers, clearly modifies the frequency and nature of technical involvement. Across age groups and competitive levels, reduced formats consistently increased individual technical actions per player, suggesting that fewer players per team enhance interaction density, ball exposure, and repetition opportunities.

In youth categories, smaller formats appear especially advantageous for promoting technical engagement. Greater frequencies of ball touches, total and successful passes across pitch zones, shots, and successful dribbles were observed in 8v8 compared with 11v11 among U12 players (Oh & Joo, 2018). Similarly, 3v3 substantially increased total technical actions compared with 7v7 in U7 players, while 5v5 elicited more technical actions than 7v7 in U9 (Bergmann et al., 2022). Increased frequencies of received balls, conquered balls, lost balls, and shots were also reported in 3v3 compared with 6v6 in young players (Clemente et al., 2018), with very large reductions in technical actions per minute observed when shifting from 3v3 to 6v6 (Clemente et al., 2019). Overall, the findings indicate that reduced formats in early developmental stages maximize direct involvement and technical repetitions.

Comparable patterns were identified in adolescent and adult players. Greater successful passes, ball contacts, ball involvement, goals, and shots on target were recorded in 3v3 relative to 5v5 (Alcântara et al., 2021). Highly reduced formats such as 2v2 generated more successful and unsuccessful passes, as well as more ball losses, compared with 4v4, reflecting increased technical demand and risk exposure (Wang et al., 2024). Moreover, possession-based scoring conditions increased successful passes in both 2v2 and 4v4 compared with mini-goal and goalkeeper formats, indicating that scoring structure interacts with player number to shape technical output (Yılmaz & Soylu, 2024).

Conversely, increasing the number of opponents appears to constrain offensive technical expression. A progressive reduction in passes and ball-driving actions, accompanied by an increase in defensive control behaviors, was observed as opposition increased from 4v3 to 4v7 + GK (Torrents et al., 2016). This pattern suggests that greater defensive density restricts available time and space for offensive execution. In symmetrical 4v4 formats, higher dribbling frequency and greater collective success were observed compared with configurations including neutral players or goalkeepers (Sanchez-Sanchez et al., 2017). However, introducing two neutral floaters (4v4+2) increased total and successful passes compared with standard 4v4, while dribbling and interceptions remained unchanged, indicating that numerical superiority facilitates ball circulation rather than individual penetration (Chootsungnoen et al., 2025a).

Overall, reduced formats (e.g., 2v2, 3v3, 4v4) consistently amplify individual technical involvement, whereas larger formats or increased opposition density decrease per-player technical frequency while potentially raising contextual and tactical complexity. The inclusion of floaters or possession-oriented constraints tends to promote passing behaviors, whereas strictly balanced formats without external support stimulate greater individual actions such as dribbling.

From a practical perspective, manipulating game format constitutes a primary methodological lever for targeting specific technical adaptations. Highly reduced formats may be preferable when the objective is to maximize ball contacts, shooting opportunities, and active involvement, whereas slightly expanded formats may better approximate competitive structures and collective organization demands.

Effects of spatial configuration and pitch size on technical engagement

Manipulating spatial constraints—either through pitch dimensions, relative space per player, or external markings—demonstrably alters technical expression in SSGs. However, unlike game format, the effects of spatial configuration appear more context-dependent, varying according to age group, relative area per player, and scoring structure.

Adjustments in pitch shape (length versus width) modify the type of technical skills performed. Increasing pitch width (30 × 40 m) led to more shots per player, whereas increasing pitch length (40 × 30 m) favored a higher number of completed passes per player, indicating that spatial orientation influences offensive tendencies (Folgado et al., 2019). Similarly, larger pitch dimensions promoted longer periods of ball possession and fewer transitions, suggesting greater stability in build-up play (Olthof et al., 2018). In line with these findings, expanding pitch size increased overall and forward passes in 7v7 + GK formats, reinforcing the idea that greater longitudinal space facilitates ball circulation and progression (Joo et al., 2016). Moreover, larger pitches enhanced passing success in 3v3 formats, whereas smaller areas reduced passing effectiveness and technical diversity (Qiao et al., 2025).

Conversely, reduced playing areas appear to stimulate more direct and individual technical behaviors. Smaller pitches increased dribbling frequency and reduced passing success, particularly in small-goal formats (Qiao et al., 2025). In older youth players, smaller relative space per player elicited more dribbles, crosses, and tackles, suggesting that spatial restriction intensifies individual duels and technical confrontation (Martone et al., 2017). Additionally, reduced pitch dimensions were associated with a greater number of passes performed by goalkeepers—both by hand and by foot— indicating greater involvement in ball circulation under spatial compression (Jara et al., 2018).

Nonetheless, the relationship between area size and technical output is not uniform across developmental stages. Larger areas increased passing frequency in U11 players, whereas U23 players performed more passes in smaller areas, and minimal effects were observed in U15, highlighting age-dependent adaptations to spatial constraints (Nunes et al., 2021). Furthermore, modifications in external pitch markings influenced offensive indicators, with complete lines generating more offensive technical actions compared with corner markers, although passing frequency decreased under line conditions (Coutinho et al., 2020).

Collectively, these findings indicate that increasing pitch dimensions tends to promote passing behaviors, ball possession, and structured circulation, whereas reducing space intensifies individual actions such as dribbling, tackling, and goalkeeper involvement. However, the magnitude and direction of these effects depend on relative space per player, age category, and scoring structure. From a practical perspective, spatial manipulation constitutes a refined methodological tool: larger areas may be preferable when the objective is to develop passing networks and positional play, whereas smaller areas may be strategically used to enhance technical confrontation, rapid decision-making, and individual execution under pressure.

Effects of task-rule modifications on technical engagement

Beyond structural constraints such as format and pitch size, specific task-rule manipulations substantially reshape technical expression during SSGs. Modifications related to scoring systems, instructional cues, environmental conditions, encouragement, and touch limitations appear to act as fine-tuning mechanisms that orient players toward particular technical engaement.

Altering the objective of the task (e.g., maintaining possession vs. progressing toward target) influences both offensive efficacy and involvement patterns. Greater offensive effectiveness in progression games was observed in 3v3 configurations, whereas possession-focused conditions generated longer passing sequences and increased player involvement; however, younger players experienced greater difficulty maintaining possession in smaller configurations (Machado, Ribeiro, et al., 2019). These findings indicate that the nature of the task goal directly modulates passing dynamics and shooting frequency.

Scoring structure also exerts a marked effect on technical outputs. Two-goal formats promoted more successful forward, backward, and penetrating passes, while four-goal configurations increased sideways passes and turning actions; additionally, shots and goals were most frequent when a goal was positioned infield at each corner (Pulling et al., 2016). Similarly, incorporating small goals and neutral players extended the duration of offensive sequences and increased overall possession compared with formats using only a goalkeeper (Castellano et al., 2016). These results suggest that diversifying scoring references modifies spatial orientation and passing patterns.

Environmental and contextual manipulations further affect execution quality. A greater number of successful technical actions was achieved on artificial turf compared with sand, whereas actions requiring ball elevation occurred more frequently on sand, reflecting surface-induced technical adaptations (Rago et al., 2018). Instructional interventions also modulate performance: defensive instructions increased ball recoveries and reduced occupied space, whereas offensive instructions increased the number of passes and expanded spatial occupation relative to no-instruction conditions (Batista et al., 2019). In addition, coach encouragement enhanced successful passes and shots compared with non-encouragement conditions, with moderate to very large effects (Soylu et al., 2024).

Finally, imposing touch restrictions modifies interaction tempo and passing behavior. Limiting players to two or three touches increased the total number of passes compared with unrestricted play, whereas free play resulted in more receptions; moreover, the shortest interval between first and second touches consistently occurred in the offensive zone regardless of the rule condition (Rosten et al., 2025). This indicates that constraining ball contact frequency accelerates circulation but may alter individual control opportunities.

Overall, task-rule manipulations operate as targeted pedagogical levers capable of directing technical engagement toward specific outcomes. While possession-oriented rules and touch restrictions tend to stimulate passing frequency and circulation speed, diversified scoring systems and instructional cues modify spatial occupation, offensive penetration, and shooting opportunities. For practitioners, these findings highlight that subtle regulatory adjustments can strategically refine technical demands without altering the broader structural framework of the SSG.

Effects of age, technical level, and biological maturation on technical engagement

Inter-individual differences related to age, technical expertise, and biological maturation appear to substantially mediate technical engagement during SSGs. Rather than acting as simple background characteristics, these developmental factors interact dynamically with task constraints to shape the frequency, quality, and efficiency of technical actions.

Higher technical proficiency is consistently associated with greater offensive involvement and effectiveness. Players with superior skill levels demonstrated increased participation in attacking actions and enhanced execution efficiency across different SSG formats (Machado, Barreira, et al., 2019). Moreover, composite assessments of technical proficiency indicate that dribbling combined with passing actions constitutes a strong discriminator of overall technical level, whereas physical performance shows no significant association with global technical proficiency during SSGs (Rowat et al., 2017). This reinforces the notion that technical expression in constrained games is more closely linked to perceptual–motor expertise than to purely physical capacities.

Chronological age seems to influence players' responses to rule modifications. Specifically, limiting ball contacts through two- and one-touch constraints led to small-to-moderate improvements in passing success across multiple age categories, but also elevated unsuccessful technical actions overall; younger players (U9–U13) adapted more effectively to two-touch conditions than to stricter one-touch constraints, whereas older players demonstrated greater adaptability to more restrictive formats (Coutinho et

al., 2022). These findings suggest that cognitive processing speed, decision-making maturity, and accumulated training experience likely underpin age-related differences in coping with temporal constraints.

Biological maturation further influences technical involvement and efficiency. More mature players executed more technical actions in smaller SSG formats (4v4 compared with 6v6), and technical involvement generally declined as team size increased; additionally, in maturity-mismatched games, less biologically mature players demonstrated a higher degree of variability in their technical actions, particularly in smaller formats (King et al., 2025). Complementary evidence indicates that post-PHV players achieved higher percentages of successful passes, whereas pre-PHV players recorded more interceptions in larger SSGs; 4-a-side formats increased ball losses and reduced duel frequency and passing success, while larger pitches promoted greater ball possession and interception rates (Cherni et al., 2025).

Collectively, these findings indicate that technical engagement in SSGs is not uniformly distributed across developmental stages. Instead, age, expertise, and maturation status systematically modulate how players respond to format size, pitch dimensions, and rule constraints. From an applied perspective, these findings reinforce the pedagogical value of developmentally aligned SSG design—such as bio-banding, adapted touch limitations, and format selection—to optimize technical engagement while accounting for individual growth trajectories.

Integrated effects on technical engagement

Technical engagement in SSGs emerges from the interaction between task design and players' physiological and psychological states. Manipulations related to recovery duration, work-to-rest ratio, mental fatigue, and well-being indices demonstrate differentiated effects on execution quality.

Altering recovery time between bouts appears to have limited influence on most technical variables. Extending recovery increased successful tackles and reduced team possession time, while other indicators remained stable, suggesting a minimal overall impact of acute recovery manipulation (McLean et al., 2016). Likewise, different work-to-rest configurations produced few changes in technical skills, except for fewer goals during continuous play, indicating that scoring efficiency may be more sensitive to accumulated fatigue than passing or possession metrics (Christopher et al., 2016).

In contrast, mental fatigue consistently impairs technical precision. Reduced passing and shooting accuracy, increased control errors, and lower tackle success were observed under cognitively fatigued conditions (Badin et al., 2016; Trecroci et al., 2020). Similarly, higher perceived fatigue, greater muscle soreness, and lower recovery quality were associated with fewer successful technical actions and more ball losses (Selmi et al., 2021).

Collectively, these integrated findings suggest that while structural manipulations such as recovery intervals or bout configuration may exert modest effects on technical indicators, psychophysiological state—particularly mental fatigue and perceived recovery—represents a more decisive determinant of technical accuracy and efficiency. From an applied perspective, optimizing recovery strategies and monitoring well-being indices may therefore be essential to preserve technical quality during SSG-based training interventions.

Limitations, practical implications, and future research directions

Several limitations must be considered. Marked heterogeneity existed across studies regarding SSG formats, pitch dimensions, rule constraints, workload structures, and technical performance indicators, limiting direct comparability. Sample sizes were often modest and restricted to specific age categories or competitive levels, which may reduce external validity. In addition, the operational definitions of technical engagement varied considerably across investigations. Restricting the search to English-language publications may have introduced language bias, potentially excluding relevant studies published in other languages. Contextual variables such as prior training load and seasonal timing were not consistently controlled and may have influenced technical outcomes.

Technical engagement in SSGs, as a core component of integrated training, is strongly modulated by task constraints. Smaller formats and reduced team sizes generally increase technical involvement, while pitch configuration and scoring rules shape passing dynamics and shooting behavior. Touch limitations can accelerate ball circulation but may elevate error rates, particularly in younger players. Furthermore, mental fatigue and inadequate recovery negatively affect technical precision, highlighting the need to monitor cognitive load and well-being during training. Coaches should therefore structure SSGs coherently within an integrated training framework, aligning task design with players' developmental stage, technical level, and targeted performance objectives.

Future studies should seek greater standardization of technical performance metrics to improve comparability. Larger and more diverse samples, including female players and multiple competitive standards, would enhance generalizability. Longitudinal research is needed to determine the long-term impact of specific SSG manipulations on technical engagement. Additionally, integrating perceptual–cognitive assessments and objective fatigue measures may clarify the mechanisms underpinning technical adaptation within constrained game environments.

Conclusion

This systematic review aimed to investigate how different Small-Sided Game (SSG) task constraints influence technical engagement in football players within the framework of integrated training. The findings indicate that technical expression is not an isolated outcome, but rather emerges from the dynamic interaction between structural constraints (e.g., format, pitch size, rules), individual characteristics (e.g., age, technical level, biological maturity), and psychophysiological factors (e.g., fatigue and recovery status). Within an integrated training perspective, SSGs represent an effective methodological tool to simultaneously stimulate technical, tactical, physical, and cognitive

components of performance. Smaller formats and adapted rule constraints tend to increase technical involvement, whereas contextual and recovery-related factors can substantially influence execution quality and precision. Overall, the evidence supports the strategic use of SSGs as an integrated training modality, provided that task design is developmentally aligned and methodologically structured to optimize technical outcomes while preserving the ecological validity of game-based practice.

Ethics Approval

Ethical approval was not required for this study, as it is a systematic review relying solely on previously published and publicly accessible data.

Informed Consent

Not applicable.

Data Availability Statement

All data analyzed in this study were obtained from previously published sources cited in the reference list. No new datasets were created.

AI Transparency Statement

AI-assisted tools were used exclusively for language refinement. The authors retain full responsibility for the content and its scientific accuracy.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Технічна залученість в іграх у малих складах: вплив обмежень завдання у футболі — систематичний огляд

Самір Ессафі[1ABCDE], Юнес Брукі[1ABCDE], Хатім Бен Седдік[2ABCDE], Хіба Рімі[1ABCDE], Шайма Халі[1ABCDE], Мохамед Баркауї[1ABCDE], Азіз Елуїрді[1ABCDE], Ель Мохтар Ель Уалі[1ABCDE], Азіз Шокрі[1ABCDE]

[1]Університет Хасана I

[2]Університет Абдельмалека Ессааді

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

Реферат. Стаття: 19 с., 5 табл., 1 рис., 59 джерел.

Вступ. У підготовці футболістів ігри в малих складах (Small-Sided Games, SSGs) широко використовуються як інтегрований засіб одночасного розвитку технічних, тактичних, фізичних і когнітивних компонентів спортивної діяльності. Проте ступінь впливу окремих обмежень завдання (task constraints) на технічну залученість досі не має узагальненого й послідовного висвітлення.

Мета. Цей систематичний огляд мав на меті дослідити, як різні обмеження завдання в іграх у малих складах впливають на технічну залученість футболістів у межах інтегрованої системи тренування.

Матеріали і методи. Систематичний пошук в електронних базах даних було проведено відповідно до загальноприйнятих рекомендацій щодо підготовки систематичних оглядів. До аналізу включено 35 досліджень, у яких вивчали вплив формату SSG, розмірів ігрового майданчика, модифікацій правил, віку, біологічної зрілості та їхнього комплексного впливу на технічну залученість. Методологічну якість досліджень було оцінено, а отримані результати узагальнено за тематичними категоріями.

Результати. Встановлено, що менші формати гри та зменшена кількість гравців сприяли підвищенню технічної залученості, тоді як розміри ігрового майданчика та правила зарахування очок впливали на характер передач, частоту ударів по воротах і володіння м›ячем. Обмеження кількості дотиків прискорювало циркуляцію м›яча, проте нерідко призводило до збільшення кількості технічних помилок, особливо у молодших гравців. Вік, технічна підготовленість і рівень біологічної зрілості істотно впливали на технічну ефективність. Психічна втома та недостатнє відновлення стабільно асоціювалися зі зниженням точності передач, погіршенням контролю м›яча та збільшенням кількості помилок.

Обговорення. Отримані результати узгоджуються з попередніми дослідженнями, які підкреслюють роль обмежень завдання у формуванні спортивної діяльності. Наявні дані підтверджують, що технічна залученість в іграх у малих складах формується внаслідок динамічної взаємодії структурних, онтогенетичних і психофізіологічних чинників.

Висновки. Ігри в малих складах є ефективним інтегрованим засобом тренування для підвищення технічної залученості за умови, що дизайн завдання відповідає закономірностям вікового розвитку спортсменів і враховує особливості тренувального контексту.

Ключові слова: ігри в малих складах, технічна залученість, інтегроване тренування, обмеження завдання, футбол.

Information about the Authors

Essafi, Samir: essafisamir114@gmail.com; https://orcid.org/0009-0001-6294-0538; Sports Science Research Team, Institute of Sports Science, Hassan 1st University, Settat, Morocco.

Brouki, Younes: younes.brouki@gmail.com; https://orcid.org/0000-0002-7906-989X; Sports Science Research Team, Institute of Sports Sciences, Hassan 1st University of Settat, Morocco.

Ben Seddik, Hatim: hatimbenseddik17@gmail.com; https://orcid.org/0009-0004-5176-9933; Humanities and education research laboratory, Higher Normal School, Abdelmalek Essaâdi University, Tetouan, Morocco.

Hiba, Rimy: Rimy.hiba.doc@uhp.ac.ma; https://orcid.org/0009-0007-3458-6176; Sports Science Research Team, Institute of Sports Sciences, Hassan 1st University, Settat, Morocco.

Khali, Chaimae: Chaimaekhali17@gmail.com; https://orcid.org/0009-0003-5790-6516; Sports Science Research Team, Institute of Sports Sciences, Hassan 1st University, Settat, Morocco.

Barkaoui, Mohamed: mohamed.barkaoui@uhp.ac.ma; https://orcid.org/0000-0002-5209-1499; Sports Science Research Team, Institute of Sports Science, Hassan 1st University, Settat, Morocco.

Eloirdi, Aziz: aziz.eloirdi@uhp.ac.ma; https://orcid.org/0000-0003-1061-7787; Sports Science Research Team, Institute of Sports Science, Hassan 1st University, Settat, Morocco.

El Ouali, El Mokhtar: elmokhtar.elouali@uhp.ac.ma; https://orcid.org/0000-0003-1235-9486; Sports Science Research Team, Institute of Sports Science, Hassan 1st University, Settat, Morocco.

Chokri, Aziz: aziz.chokri@uhp.ac.ma; https://orcid.org/0000-0001-8357-3880; Sports Science Research Team, Institute of Sports Science, Hassan 1st University, Settat, Morocco.

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Trainers' Perceptions of Initial Physical Education Teacher Training within Moroccan CRMEFs: Preliminary Development and Exploratory Validation of an Evaluation Grid

Hamza Marzak[1ABDE], Mouhcine El Qryefy[1CDE], Hanan El Faylali[1CDE] and Youssef El Madhi[1,2ABDE]

[1]University Ibn Tofail
[2]CRMEF Rabat–Salé–Kénitra

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

Corresponding Author: Hamza Marzak, e-mail: hamza.marzak@uit.ac.ma
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Abstract

Objectives. This study aimed to examine teacher trainers' perceptions of initial Physical Education and Sport teacher training within Moroccan Regional Centers for Education and Training Professions and to provide preliminary evidence of the exploratory validity and internal consistency of a multidimensional evaluation grid.

Materials and Methods. A quantitative cross-sectional design was adopted. The sample included 125 Physical Education and Sport teacher trainers from five Moroccan CRMEFs. An initial pool of 38 items was developed based on institutional standards, the expected graduate profile, and the literature on teacher education and professionalization. After expert review, the instrument was reduced to 30 items. Principal component analysis with Varimax rotation was used as an exploratory procedure to examine the internal structure of the grid, while Cronbach's alpha was calculated to assess its internal consistency.

Results. The exploratory analysis suggested a four-factor structure corresponding to the theoretical dimensions of the instrument: training program organization, pedagogical training practices, supervision and pedagogical support, and internship–CRMEF field articulation. After item purification, the final version included 26 items. Internal consistency was acceptable across all four dimensions. The final 26-item version showed acceptable preliminary psychometric indicators, particularly regarding its exploratory factorial structure and internal consistency. Descriptive results showed moderate perceived levels across all dimensions, with relatively higher scores for training organization and pedagogical support and lower scores for internship and CRMEF–field articulation. ANOVA results indicated no statistically significant differences between CRMEFs, with very small effect sizes.

Conclusion. The findings suggest relatively homogeneous perceptions among teacher trainers across the participating CRMEFs. However, the study does not assess the objective effectiveness of teacher training or professional outcomes. Rather, it provides preliminary exploratory evidence for an evaluation grid and highlights perceived weaknesses in the articulation between institutional training and field-based internship. Further studies using larger samples, confirmatory factor analysis, and multi-stakeholder data are needed.

Keywords: initial training, PES trainee teachers, construct validity, reliability, professional practices.

Introduction

Physical Education (PE), as a compulsory subject across most schools at both primary and secondary levels, has recently gained increased importance (Syaukani, et al,. 2023). Initial teacher education is now recognized as one of the major levers for reforming educational systems, identified as a cornerstone of the new social contract for education (UNESCO, 2021; OECD, 2020). It is crucial not only for the acquisition of foundational competencies but, more importantly, for preparing future teachers to cope with the complexity of the profession. In this regard, internships and practicum experiences play a central role: they allow trainee teachers to develop a reflective and critical stance, contributing to the shaping of their professional identity. In Physical Education, such training provides them with the scientific and pedagogical knowledge essential for their teaching career (Almonacid-Fierroetal et al., 2021). Research

consistently emphasizes that professionalization cannot be reduced to the mere accumulation of theoretical knowledge; rather, it results from a dynamic process of situated learning and continuous regulation between theory and practice (Lave & Wenger, 1991; Korthagen & Kessels, 1999). According to Darling-Hammond (2017), the objective is to develop effective practices capable of addressing the real challenges of the classroom.

In this context, Physical Education and Sports (PES) occupies a distinctive position. As an action-centered discipline, it confronts novice teachers with the need to master "core practices" within a dynamic and often unpredictable environment (McDonald et al., 2013). Teachers must simultaneously manage motor learning, safety issues, student heterogeneity, and frequently significant material constraints. The quality of pedagogical intervention therefore depends critically on the training program's ability to integrate academic knowledge with field-based demands—a coherence that is often difficult to achieve (Hammerness, 2006). In Morocco, the training provided by the Regional Centers for Education and Training Professions (CRMEF) aims to foster this professionalization process. However, a gap persists between the intentions of the curriculum and the reality of practicum experiences. This discrepancy is even more critical in Physical Education (PE), where material and institutional conditions may hinder the transfer of acquired knowledge and skills into practice.

The mismatch between institutional prescriptions and classroom realities is not without consequences. For trainee teachers, the impact is immediate and often burdensome. From the very first weeks of training, they face a mental workload that goes beyond purely academic demands. In Morocco, research confirms this sense of distress: future teachers exhibit concerning levels of stress and burnout well before their official appointment (Bouhaba et al., 2021, 2022). In practice, this translates into a persistent feeling of inadequacy—the impression of never fully meeting expectations, the difficulty of balancing coursework at the CRMEF with the urgency of classroom demands, and the feeling of being evaluated without having the real means to adjust. Of course, this experience is not uniform. As analyzed by Bouhaba et al. (2022), certain personal or organizational factors may exacerbate the situation, particularly when support lacks structure. In PE, where everything is visible—safety management, group control, performance—the ambiguity that sometimes surrounds the roles of each actor (trainer, mentor, trainee) can further fuel anxiety. Ignoring these perceptions would be a mistake. According to Abdelmounaim et al. (2022), taking trainee teachers' lived experiences into account is an essential step toward understanding the roots of these tensions and preventing them from becoming an accepted norm within teacher education.

Despite the recognized importance of initial teacher education, a gap persists between training objectives and actual teaching practices (Korthagen & Kessels, 1999; Darling-Hammond, 2017). This misalignment reflects both difficulties in translating competencies into practice and a lack of validated tools to rigorously assess training processes. Evaluating initial teacher education cannot be reduced to a simple counting of instructional hours or a verification of theoretical curricula. The issue is far more concrete: does the program genuinely equip future teachers to face the realities of the profession? Unfortunately, the Moroccan context suffers from a methodological gap in this regard, particularly in Physical Education (PE). In the absence of more suitable tools, generic evaluation grids are often used, which fail to capture the specific nature of motor activities or the subtleties of modern mentoring practices (Ben-Amram & Davidovitch, 2024). Yet, the scientific requirement is clear: to be meaningful, any evaluation instrument must first demonstrate its reliability and content validity (Carmines & Zeller, 1979; Fabrigar et al., 1999).

This challenge, however, is not insurmountable. Recent research conducted with Moroccan teachers has shown that it is entirely possible to design measurement instruments that are both robust and culturally appropriate (Abdelmounaim et al., 2022). Achieving this requires grounding the process in real-world practice by giving voice not only to teacher educators but also to mentor teachers—key field actors whose crucial role too often remains unclear (Baco et al., 2023). This study focuses specifically on teacher trainers' perceptions of initial Physical Education and Sport (PES) teacher training within CRMEF institutions in Morocco, using a multidimensional evaluation grid developed for exploratory purposes. This approach is not intended to measure the objective effectiveness of training, but rather to provide training stakeholders with an initial, structured, and contextually relevant tool for identifying perceived strengths and areas for improvement.

Education plays a fundamental role in the development of societies and constitutes a key lever for national progress (Poonsri, 2008). It represents a structured process of acquiring and transmitting knowledge, skills, and values through teaching, training, and research (Arifin, 2017). Universally recognized as the cornerstone of progress and social development, education relies largely on the commitment and quality of the teaching workforce, whose role is decisive in fulfilling this essential mission (Oulaydi et al., 2024). The quality of teaching depends to a great extent on the various forms of teachers' knowledge, including specific subject-matter knowledge, pedagogical content knowledge, and psycho-pedagogical knowledge, all considered essential for effective educational practice (Kunter et al., 2013; Oulaydi et al., 2025). In this regard, the quality of the educational system largely depends on the quality of teacher education, as teachers are central actors in the educational process. Furthermore, preparing pre-service teachers to adapt to educational systems during their training programs can help them cope more effectively with the challenges they may face during the early years of their careers (Filiz & Durnali, 2019).

Physical Education (PE), as an integral component of the educational system, contributes to students' overall development—physically and motorically, as well as cognitively, affectively, and socially (Kelmendi & Dedi, 2024). It also promotes the development of critical thinking, reasoning, and social skills through engagement in physical activities (Kelmendi & Dedi, 2024). Therefore, the training of PE teachers is of particular importance, given the specific knowledge and competencies mobilized within this discipline. In this context, classroom management represents a significant challenge for Physical Education teachers. Physical education teachers, like all educators, are

frequently confronted with students' problematic behaviors. However, many of them report difficulties in creating a learning environment that not only supports effective learning but also promotes cooperation and self-regulation among students (Buchanan & Hinton, 2018).

The teaching profession requires the mobilization of multiple resources—cognitive, affective, and motor—to cope with complex and diverse pedagogical situations (Zahir, 2019). However, students entering initial teacher education programs bring with them pre-existing beliefs about the profession, constructed throughout their academic and social trajectories (Tsangaridou, 2006). These representations influence their approaches to teaching and must therefore be taken into account in teacher education programs. The work of Rayou and Ria (2009) highlights that entry into the teaching profession requires training grounded in authentic, field-based situations. According to these authors, professional learning relies on the trainee's ability to analyze and manage critical situations by developing contextualized responses. They also emphasize the importance of dialogic support that fosters the verbalization of action and reflective practice. Thus, alternation should not be conceived as a simple juxtaposition of theory and practice, but rather as a dynamic process of reflective articulation between the two training environments (Rayou & Ria, 2009). From this perspective, training programs that incorporate field placements constitute a central component of educational systems. In Morocco, trainee teachers engage in various practical activities within schools. However, some studies point out that the contribution of host institutions to trainees' professional development sometimes remains limited, raising questions about the coherence of the training–field articulation (Bouabdallah, 2021).

In Morocco, teacher education is provided by the Regional Centers for Education and Training Professions (CRMEF). Candidates admitted through a competitive examination receive qualifying, professionally oriented training focused on the practice of teaching through real-life professional situations in schools (high schools, middle schools, and primary schools) (Zahir, 2019). This training is based on the "Practice–Theory–Practice" paradigm, organized through a modular system and centered on the competency-based approach and educational research. The perceived quality of initial teacher education is an important indicator for understanding how teacher training systems are evaluated by training actors and how they may support trainee teachers' professional preparation. Furthermore, the evolving role of the teacher in guiding teaching and learning processes, with an emphasis on placing the learner at the center, requires the implementation of contemporary teaching methods and strategies that align with the rapid transformations in the educational system (El Qryefy et al., 2024b).

More specifically, the training of Physical Education (PE) teachers within the CRMEF is structured around four complementary modules: planning of learning, management of learning, assessment of learning, and an additional module focusing on the technical, tactical, and regulatory aspects of physical and sports activities (Zahir, 2019). Together, these components aim at the progressive development of the professional competencies required for effective teaching practice. In this context, examining the perceived quality of initial teacher training emerges as a central issue. Examining the alignment between training objectives, support mechanisms, and the practices actually implemented makes it possible to evaluate the level of professionalization achieved and to identify areas for improving the initial teacher education system in Physical Education (PE) in Morocco. To our knowledge, there is currently no specific tool designed to systematically and structurally examine teacher trainers' perceptions of the quality of initial training of Physical Education and Sport (PES) trainee teachers within the CRMEF in Morocco. From this perspective, the present study is of particular importance, as it aims to develop and explore the validity of an evaluation grid for examining the perceived quality of this training from the perspective of teacher trainers. This grid is structured around four complementary dimensions: the organization of the training program, pedagogical training practices, supervision and pedagogical support, and the articulation between the CRMEF and the field internship.

The objectives of this study are to examine teacher trainers' perceptions of initial Physical Education and Sport (PES) teacher training across different CRMEFs using a structured evaluation grid. First, the study aims to explore the construct structure of the instrument through exploratory factor analysis (EFA). It also seeks to assess the internal consistency of the instrument and to examine the relevance and clarity of its items in relation to the theoretical framework of initial teacher education. Finally, the study aims to investigate inter- and intra-CRMEF differences in teacher trainers' perceptions of training across the four dimensions of the evaluation grid.

Materials and Methods

This research adopts a quantitative cross-sectional approach aimed at examining teacher trainers' perceptions of initial Physical Education and Sport (PES) teacher training. First, a preliminary study was conducted to develop and explore the psychometric properties of an evaluation grid for this training program. This study is based on exploratory factor analysis and reliability assessment, with the aim of examining the preliminary structural coherence and internal consistency of the proposed instrument.

It is important to note that the present study does not assess the objective effectiveness of initial teacher training or the actual professional performance of trainee teachers. The data reflect teacher trainers' perceptions of the organization, pedagogical practices, supervision, and internship articulation within the training system. Therefore, the findings should be interpreted as perceived indicators of training quality rather than direct evidence of professional training effectiveness.

Measurement Instrument

Initial Development of the Evaluation Grid

This tool aims to examine, in a comprehensive and multidimensional way, teacher trainers' perceptions of initial teacher education, particularly in Physical Education and Sport (PES), within the CRMEF. The instrument allows for the examination of teacher trainers' perceptions regarding:

- The organization and coherence of the training system in terms of structure, planning, and alignment with institutional standards.
- The pedagogical practices of the training, including teaching methods, proposed learning situations, and the use of pedagogical and digital tools.
- The supervision and mentoring of trainees, including monitoring, feedback, and support for professional development.
- The articulation between training at the CRMEF and field-based practicum, as well as coordination with host institutions.

The development of the grid began with an initial pool of 38 items, designed based on:

- Institutional standards for initial PE teacher training at the CRMEF,
- The expected graduate profile of trainee teachers, and
- A review of the scientific literature on initial teacher education, teacher professionalization, and evaluation of training programs (Darling-Hammond, 2017; Zeichner, 2016).

Content Validation of the Grid

The content validity of the initial version of the evaluation grid was examined using a panel of six experts, composed of CRMEF teacher educators, Physical Education (PE) inspectors, and university researchers specialized in teacher education. This approach follows established methodological recommendations for content validation in the development of measurement instruments in educational sciences (Lynn, 1986; Boateng et al., 2018). Each expert was asked to evaluate the items according to several criteria, including relevance, clarity of wording, and representativeness with respect to the targeted theoretical dimensions. Feedback from the experts allowed the identification of items with redundancies, conceptual ambiguities, or insufficient operational precision. At the end of this expert review, 8 items were removed, resulting in a revised version of the grid comprising 30 items. Furthermore, some formulations were reworded and adjusted to improve readability, internal coherence, and overall clarity of the instrument. The item reduction process leading to the final version of the grid is presented in Table 1.

Participants

The study was conducted with 125 Physical Education and Sport (PES) teacher educators working in five Regional Centers for Education and Training Professions (CRMEF) in Morocco. These educators were selected due to their proven experience in supervising trainee teachers and their direct involvement in initial teacher education. During the teaching practicum, they observed the pedagogical practices of trainee teachers in real classroom settings. Their contribution helped enrich the analysis of teaching practices in initial teacher education, taking into account institutional requirements as well as the realities of school contexts. The sample consisted of 45 women and 80 men, with a mean age of 43.52 years (SD = 1.09; min = 27; max = 62).

Data Collection Procedure

The revised 30-item version of the observation grid was administered to teacher trainers using a five-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree"). Participants had prior knowledge of the study and took part voluntarily. The main objective of this data collection phase was to assess the feasibility of the instrument, verify the clarity and comprehensibility of the items, and produce descriptive and inferential results in order to examine teacher trainers' perceptions of initial Physical Education and Sport (PES) teacher training within the CRMEFs. After the exploratory factor analysis and item purification process, the final retained version of the grid consisted of 26 items.

Statistical Analyses

Data were entered, coded, and analyzed using SPSS software, version 26. The reliability of the scale was assessed using Cronbach's alpha coefficient to examine the internal consistency of the items and their homogeneity within each dimension of the grid. The factorial structure of the grid was examined through exploratory factor analysis (EFA) in order to explore its internal structure and assess the appropriateness of item grouping within the underlying factors. Descriptive analyses, including means and standard deviations, were conducted to describe teacher trainers' perceptions across the evaluated dimensions. In addition,

Table 1. Item Reduction Process (Instrument Development)

Process Step	Objective	Method	Number of Items
Initial item pool development	Cover all theoretical dimensions of initial PE teacher education	Analysis of institutional standards, literature review, authors' expertise	38
Evaluation of item relevance	Verify the alignment of items with the targeted dimensions	Expert judgment (relevance, clarity, representativeness)	38
Removal of redundant or imprecise items	Improve conceptual coherence and readability of the grid	Qualitative analysis of expert feedback	8 removed
Item adjustment and rewording	Strengthen the operational precision of retained items	Linguistic and conceptual revision	30
Revised version administered to participants	Obtain a coherent instrument for empirical testing	Research team consensus after expert review	30
Final retained version after PCA purification	Retain items with acceptable factorial structure	Removal of items with low loadings or cross-loadings	26

a one-way analysis of variance (ANOVA) was performed to examine differences in perceived training quality across the five CRMEFs included in the study.

Results

In this section of the results, the findings related first to construct validity and the reliability of the evaluation grid are presented, in order to examine its psychometric properties. In addition, descriptive and inferential statistical analyses were conducted to examine teacher trainers' perceptions of initial Physical Education and Sport (PES) teacher training across the different dimensions of the grid.

Results of the Validation of the Evaluation Grid

Exploratory Factor Analysis

An exploratory factor analysis (EFA) was conducted to examine the initial structural coherence of the evaluation grid. First, the data adequacy indices for factor analysis were verified. The corresponding results are presented in Table 2.

Table 2. Data Adequacy Indices for Factor Analysis

Index	Value
KMO Index	0.69
Bartlett's Test (χ^2, p)	χ^2=879.463 , p < 0.001

The results presented in Table 2 show that the Kaiser–Meyer–Olkin (KMO) coefficient is above 0.60, a threshold considered acceptable according to the recommendations of Cohen et al. (2013). This value indicates that the sample size is adequate for conducting a factor analysis. Furthermore, Bartlett's test of sphericity (χ^2) is statistically significant ($p < 0.001$), allowing us to reject the null hypothesis that the correlation matrix is an identity matrix (El Qryefy et al., 2024a). Taken together, these results confirm the appropriateness and feasibility of the data for performing an exploratory factor analysis.

A principal component analysis (PCA) with Varimax orthogonal rotation was conducted to examine the internal structure of the evaluation grid. Factor selection was based on the Kaiser criterion, retaining components with eigenvalues greater than 1. According to the criteria established by Hair et al. (2010), a factor loading above 0.50 for each item is considered significant and validates the relevance of the questionnaire. Items with factor loadings equal to or greater than 0.50 were therefore deemed acceptable and retained. Conversely, items with factor loadings below 0.30 were automatically removed by SPSS due to their low contribution to the identified factors.

Table 3. Variance Explained by the Extracted Factors

Factors	Explained Variance (%)
Factor 1	26.8
Factor 2	18.5
Factor 3	12.1
Factor 4	9.3
Cumulative Variance	66.7

The results presented in Table 3 indicate that the principal component analysis (PCA) extracted four factors, consistent with the number of dimensions initially retained during the construction of the teacher practices evaluation grid. These four factors explain a total cumulative variance of 66.7%, reflecting a satisfactory level of information retention. This percentage is considered acceptable and adequate for this type of factor analysis, in accordance with the methodological recommendations of Gorsuch (2013), who suggests that an explained variance rate above 60% is generally sufficient in research within the social and human sciences.

Table 4. Factors Extracted by Principal Component Analysis (PCA) (N = 125)

Items	Factors			
	F1	F2	F3	F4
Item 24	0.915			
Item 20	0.882			
Item 6	0.819			
Item 11	0.801			
Item 3	0.769			
Item 19	0.754			
Item 27	0.747			
Item 12	0.728			0.311
Item 17		0.863		
Item 30		0.823		
Item 22		0.778		
Item 16		0.735	0.350	
Item 4		0.718		
Item 9		0.698		
Item 14		0.636		
Item 18			0.843	
Item 25			0.791	
Item 5			0.772	
Item 13			0.731	
Item 15		0.437	0.633	
Item 21			0.598	0.410
Item 8			0.524	
Item 2		0.367	0.461	
Item 10				0.782
Item 28				0.759
Item 7				0.721
Item 23				0.638
Item 1				0.573
Item 26				0.546
Item 29	0.346			0.489

The results presented in Table 4 show that the majority of items exhibit high factor loadings on their theoretically expected factor, confirming the coherence of the factorial structure of the evaluation grid. However, items 12 and 15

showed high loadings (> 0.50) on factors other than those theoretically expected, suggesting a mismatch between the observed results and the factor to which they were theoretically associated. Furthermore, items 2 and 29 showed factor loadings below the threshold of 0.50, indicating an insufficient contribution to the dimensions to which they were associated. Following the recommendations of Hair et al. (2010), these four items were removed in order to improve the stability and theoretical coherence of the factorial structure. Their removal within the grid purification process also contributed to strengthening the overall psychometric properties of the instrument.

Following this purification procedure via principal component analysis (PCA), the final version of the scale consists of 26 items, coherently distributed across the retained dimensions:

- Factor 1: Organization of the program (7 items).
- Factor 2: Pedagogical training practices (7 items).
- Factor 3: Supervision and pedagogical support (6 items).
- Factor 4: Internship and CRMEF–field articulation (6 items).

The final 26-item version showed acceptable preliminary psychometric indicators, particularly regarding exploratory factorial structure and internal consistency. However, this validation should be considered preliminary, as confirmatory factor analysis, test–retest reliability, convergent validity, and discriminant validity were not examined.

Reliability of the Grid

The internal consistency of the grid was assessed using Cronbach's alpha coefficients, calculated for each identified dimension as well as for the entire instrument, which comprises 26 items after the purification phase conducted through PCA. This procedure aims to verify the degree of item homogeneity and their ability to reliably measure the underlying theoretical constructs. The results, presented in Table 5, demonstrate the level of internal reliability for each dimension as well as the overall robustness of the evaluation tool.

Table 5. Reliability of the Evaluation Grid

Dimension	Number of Items	Cronbach's Alpha
Organization of the Training Program	7	0.85
Pedagogical Training Practices	7	0.81
Supervision and Pedagogical Support	6	0.73
Internship and CRMEF–Field Articulation	6	0.76
Overall Grid	26	0.79

Note. CRMEF = Regional Center for Education and Training Professions (Centre Régional des Métiers de l'Éducation et de la Formation)

As shown in the results presented in Table 5, all dimensions of the observation grid, as well as the instrument as a whole, demonstrate satisfactory levels of reliability. The internal consistency coefficients for each dimension exceed the recommended threshold of 0.70 (Nunnally, 1994), indicating good item homogeneity and acceptable reliability of the measurement tool. These results support the internal consistency of the adopted structure and suggest that the grid may be used as an initial tool for examining teacher trainers' perceptions of initial PES teacher training. However, its use should remain cautious until further psychometric validation is conducted.

Teacher Trainers' Perceptions of Initial PES Teacher Training in Moroccan CRMEFs

Normality of Each Dimension of the Evaluation Grid

The results presented in Table 6 show that teacher trainers' perceptions regarding the different dimensions of the initial teacher training evaluation grid are generally moderate. The dimension "Organization of the Training Program" records the highest mean score (M = 3.13; SD = 0.81), indicating a relatively positive assessment of the structuring and planning of the initial training program. Similarly, the dimension "Supervision and Pedagogical Support" also obtains a relatively high score (M = 3.09; SD = 0.84), suggesting that teacher trainers perceived the mentoring and support provided during training relatively positively. In contrast, the dimension "Pedagogical Training Practices" (M = 2.97; SD = 0.81) and especially "Internship and CRMEF–Field Articulation" (M = 2.79; SD = 0.71) show the lowest mean scores. These results reveal perceived shortcomings, particularly regarding training practices and the coordination between theoretical training within the CRMEF and field-based experiences. These aspects therefore represent priority areas for institutional improvement, particularly in strengthening the perceived coherence between initial training and field-based professional preparation.

Regarding data distribution, it can be considered normal when skewness and kurtosis values remain between -2 and +2, according to the recommendations of Kline (2023). The skewness coefficients range from -0.345 to -0.580, while the kurtosis coefficients range from -0.289 to -0.701. These values indicate that the distributions of the different dimensions of the scale are normal. Thus, based on these methodological recommendations, the results obtained in this study meet the conditions of approximate normality, which statistically justifies the use of parametric tests for subsequent inferential analyses.

Table 6. Overall Means and Normality Assessment of the Dimensions of the Evaluation Grid

Dimensions	Mean	SD	Skewness	Kurtosis
Organization of the Training Program	3.1291	0.81772	-0.345	-0.289
Pedagogical Training Practices	2.9742	0.80856	-0.343	-0.701
Supervision and Pedagogical Support	3.0920	0.84387	-0.580	-0.497
Internship and CRMEF–Field Articulation	2.7968	0.71791	-0.352	-0.579

Descriptive Analysis Results of the Mean Scores of the Dimensions of the Grid across the Five CRMEFs

Table 7 presents the descriptive statistics of the four dimensions of the evaluation grid of the initial training of Physical Education and Sports (PES) trainee teachers, as assessed by teacher trainers working in five Regional Centers

for Education and Training Professions (CRMEF) in Morocco. The results show that teacher trainers' perceptions of initial training are generally moderate across all the CRMEFs studied, with relatively limited differences between centers. Regarding the dimension "Organization of the Training Program," the means range from 2.90 to 3.33. CRMEF3 records the highest mean score (M = 3.33; SD = 0.67), reflecting a relatively positive perception of the organization and structuring of the training program. In contrast, CRMEF4 shows the lowest mean score (M = 2.90; SD = 0.86), indicating a more reserved perception of this dimension among teacher trainers. For the dimension "Pedagogical Training Practices," the results reveal relatively close mean values across the different centers, ranging from 2.89 to 3.13. CRMEF5 obtains the highest mean (M = 3.13; SD = 0.80), while CRMEF2 shows the lowest mean (M = 2.89; SD = 0.85). This similarity in scores suggests that pedagogical practices implemented across the CRMEFs are perceived in a relatively homogeneous way by teacher trainers.

Regarding the dimension "Supervision and Pedagogical Support," the observed means range from 2.98 to 3.24. CRMEF5 shows the highest mean score (M = 3.24; SD = 0.88), indicating a more positive perception of pedagogical support and mentoring provided during initial training. In contrast, CRMEF1 records the lowest mean (M = 2.98; SD = 0.80). Finally, the dimension "Internship and CRMEF–Field Articulation" records the lowest scores among all four dimensions, with means ranging from 2.74 to 2.91. CRMEF5 shows the highest mean (M = 2.91; SD = 0.65), while CRMEF2 presents the lowest (M = 2.74; SD = 0.65). Overall, the relatively similar standard deviations indicate a moderate dispersion of responses among teacher trainers across the different centers. The 95% confidence intervals also indicate acceptable stability of the estimated means. In general, the dimensions related to program organization and pedagogical support show relatively higher mean scores compared to the "Internship and CRMEF–Field Articulation" dimension, which records the lowest scores across the CRMEFs.

Analysis of Inter- and Intra-CRMEF Differences in Perceived Initial Training Quality of Physical Education and Sport Teachers

Levene's test (Table 8) was conducted to verify the assumption of homogeneity of variances prior to performing the one-way analysis of variance (ANOVA). This condition represents one of the key statistical assumptions required for the application of parametric comparative tests (Field, 2018). The results show that the significance values associated with Levene's test are above the critical threshold of 0.05 for all studied dimensions: "Organization of the Training Program" (p = 0.465), "Pedagogical Training Practices" (p = 0.887), "Supervision and Pedagogical Support" (p = 0.930), and "Internship and CRMEF–Field Articulation" (p = 0.262).

These findings indicate that there are no statistically significant differences between the variances of the groups corresponding to the different Moroccan CRMEFs. Consequently, the assumption of homoscedasticity is

Table 7. Descriptive Statistics of the Evaluation Grid Dimensions across the Five CRMEFs

Dimensions	CRMEF	N	Mean	Standard Deviation	Standard Error	95% CI (Lower Bound)	95% CI (Upper Bound)
Organization of the Training Program	CRMEF1	27	3.0370	0.82408	0.15859	2.7110	3.3630
	CRMEF2	21	3.1293	0.88399	0.19290	2.7269	3.5316
	CRMEF3	30	3.3333	0.67146	0.12259	3.0826	3.5841
	CRMEF4	27	2.9048	0.86080	0.16566	2.5642	3.2453
	CRMEF5	20	3.2500	0.86323	0.19302	2.8460	3.6540
Pedagogical Training Practices	CRMEF1	27	2.9365	0.83142	0.16001	2.6076	3.2654
	CRMEF2	21	2.8980	0.85731	0.18708	2.5077	3.2882
	CRMEF3	30	2.9924	0.74528	0.13607	2.7141	3.2707
	CRMEF4	27	2.9365	0.85928	0.16537	2.5966	3.2764
	CRMEF5	20	3.1286	0.80799	0.18067	2.7504	3.5067
Supervision and Pedagogical Support	CRMEF1	27	2.9877	0.80454	0.15483	2.6694	3.3059
	CRMEF2	21	3.1508	0.88961	0.19413	2.7458	3.5557
	CRMEF3	30	3.0444	0.86318	0.15759	2.7221	3.3668
	CRMEF4	27	3.0926	0.83760	0.16120	2.7613	3.4239
	CRMEF5	20	3.2417	0.88601	0.19812	2.8270	3.6563
Internship and CRMEF–Field Articulation	CRMEF1	27	2.8148	0.81954	0.15772	2.4906	3.1390
	CRMEF2	21	2.7381	0.65738	0.14345	2.4389	3.0373
	CRMEF3	30	2.7756	0.67250	0.12278	2.5244	3.0267
	CRMEF4	27	2.7654	0.79024	0.15208	2.4528	3.0780
	CRMEF5	20	2.9083	0.65220	0.14584	2.6031	3.2136

Note. CRMEF = Regional Center for Education and Training Professions

satisfied for all four dimensions of the evaluation grid. Furthermore, the low values of the Levene statistic reflect a relative homogeneity in the dispersion of responses provided by teacher trainers across the different centers. This statistical homogeneity strengthens the reliability of subsequent comparisons performed using ANOVA. Thus, the methodological conditions required for conducting one-way analysis of variance are met, allowing the ANOVA results to be interpreted under appropriate statistical conditions.

Table 8. Levene's Test of Homogeneity of Variances for the Dimensions of Evaluation Grid

Dimensions	Levene Statistic	df1	df2	Significance
Organization of the Training Program	0.903	4	120	0.465
Pedagogical Training Practices	0.285	4	120	0.887
Supervision and Pedagogical Support	0.215	4	120	0.930
Internship and CRMEF–Field Articulation	1.331	4	120	0.262

Table 9 presents the results of a one-way analysis of variance (ANOVA) conducted to examine the existence of possible statistically significant differences between the different Moroccan CRMEFs regarding the dimensions of the evaluation grid of the initial training of Physical Education and Sports (PES) trainee teachers. In addition to the statistical analysis, effect size coefficients (η^2) were calculated in order to assess the practical significance of the observed differences between groups. The results show that all significance values associated with the different dimensions are higher than the 0.05 threshold. Thus, no statistically significant differences were found between the five CRMEFs for the dimension "Organization of the Training Program" ($F = 1.177$; $p = 0.324$), for "Pedagogical Training Practices" ($F = 0.256$; $p = 0.906$), for "Supervision and Pedagogical Support" ($F = 0.303$; $p = 0.876$), nor for "Internship and CRMEF–Field Articulation" ($F = 0.175$; $p = 0.951$).

The absence of statistically significant differences between CRMEFs should be interpreted cautiously. These results indicate that teacher trainers' perceptions were relatively similar across the five participating centers, but they do not demonstrate that the objective quality or effectiveness of training is equivalent across all Moroccan CRMEFs. The observed differences between the mean scores of the centers remained small and did not allow for the conclusion that statistically significant differences existed between the studied institutions.

Moreover, the analysis of effect size coefficients (η^2) revealed very small values for all studied dimensions. According to Cohen's (1988) criteria, an η^2 value below 0.01 corresponds to a very small effect, around 0.06 to a medium effect, and above 0.14 to a large effect. The dimension "Organization of the Training Program" presented the highest effect size coefficient ($\eta^2 = 0.038$), although it still indicated a small effect. This means that only 3.8% of the variance observed in this dimension was explained by belonging to different CRMEFs. The other dimensions showed very small effect sizes: "Pedagogical Training Practices" ($\eta^2 = 0.008$), "Supervision and Pedagogical Support" ($\eta^2 = 0.010$), and "Internship and CRMEF–Field Articulation" ($\eta^2 = 0.006$). These results suggest that the effect of the "CRMEF" factor on teacher trainers' perceptions was practically limited.

Furthermore, the low F-values indicate that inter-group variability was lower than intra-group variability. This suggests that individual differences among teacher trainers within the same center may be greater than the overall differences between CRMEFs. Therefore, the findings should be understood as evidence of perceived homogeneity within the present sample, rather than as proof of equivalent training effectiveness across institutions. This relative similarity in perceptions may be partly explained by the existence of common national frameworks, standardized training programs, and similar institutional guidelines governing initial teacher training at the national level.

Discussion

The present study aimed to examine teacher trainers' perceptions of initial Physical Education and Sport (PES) teacher training within Moroccan Regional Centers for Education and Training Professions (CRMEFs), while

Table 9. One-Way ANOVA of the Dimensions of Evaluation Grid

Dimensions	Source of Variation	Sum of Squares	df	Mean Square	F	Sig.	η^2
Organization of the Training Program	Between Groups	3.131	4	0.783			
	Within Groups	79.784	120	0.665	1.177	0.324	0.038
	Total	82.915	124	-			
Pedagogical Training Practices	Between Groups	0.685	4	0.171			
	Within Groups	80.382	120	0.670	0.256	0.906	0.008
	Total	81.067	124	-			
Supervision and Pedagogical Support	Between Groups	0.882	4	0.221			
	Within Groups	87.421	120	0.729	0.303	0.876	0.010
	Total	88.303	124	-			
Internship and CRMEF–Field Articulation	Between Groups	0.370	4	0.093			
	Within Groups	63.540	120	0.529	0.175	0.951	0.006
	Total	63.910	124	-			

developing and testing a multidimensional evaluation grid. The study was structured around four dimensions: training program organization, pedagogical training practices, supervision and pedagogical support, and internship–CRMEF field articulation. Importantly, the findings should be interpreted as reflecting teacher trainers' perceptions rather than as objective measures of training effectiveness or trainee teachers' competencies.

From a psychometric perspective, the exploratory analysis suggested a four-factor structure corresponding to the theoretical dimensions initially proposed during the development of the evaluation grid. After item purification, the final version included 26 items distributed across the four retained dimensions. The internal consistency coefficients were acceptable, indicating satisfactory homogeneity of the items within each dimension. These results support the use of the grid as an initial tool for examining teacher trainers' perceptions of PES teacher training, while further validation remains necessary. It is important to emphasize that the present findings provide only preliminary evidence regarding the psychometric properties of the evaluation grid. Although the exploratory factor analysis and internal consistency results are encouraging, they represent an initial stage in the validation process rather than definitive evidence of construct validity. Consequently, the instrument should currently be considered a promising exploratory measure of teacher trainers' perceptions rather than a fully validated assessment tool.

However, the psychometric results should be interpreted with caution. The present study relied on an exploratory approach and did not include confirmatory factor analysis, test–retest reliability, convergent validity, or discriminant validity. Therefore, the instrument cannot yet be considered fully validated. Rather, it should be viewed as an initial evaluation grid requiring further testing with larger and independent samples. Future studies should confirm the factorial structure through confirmatory factor analysis and examine whether the instrument produces stable and valid results across different populations, training contexts, and educational specializations. This cautious interpretation is consistent with methodological recommendations for scale development, which emphasize that exploratory factor analysis and internal consistency represent important but incomplete stages in the validation process (Fabrigar et al., 1999; Worthington & Whittaker, 2006; Boateng et al., 2018).

The descriptive findings showed that teacher trainers' perceptions of initial PES teacher training were generally moderate across the four dimensions. This suggests that teacher trainers generally hold moderately positive perceptions of the training system, while also identifying areas requiring improvement. The dimensions related to training program organization and supervision and pedagogical support obtained relatively higher scores. This may reflect the existence of formal institutional frameworks, centralized training programs, and common pedagogical guidelines within Moroccan CRMEFs. In this sense, the organization of the training program appears to be perceived as relatively structured by teacher trainers. However, this perception should not be confused with evidence of objective institutional performance. It reflects how trainers evaluate the organization and functioning of the training system based on their professional experience.

The relatively positive perception of supervision and pedagogical support may also be explained by the central role played by CRMEF trainers in accompanying trainee teachers during their professional preparation. Supervision, feedback, and pedagogical guidance are essential elements in teacher education because they contribute to the progressive construction of professional competencies. Previous research has emphasized that mentoring and pedagogical support are key mechanisms for helping trainee teachers connect theoretical knowledge with professional practice (Darling-Hammond, 2017; Baco et al., 2023). In PES teacher education, this support is particularly important because trainee teachers must learn to manage complex teaching situations involving motor learning, safety, equipment, space organization, and student heterogeneity.

In contrast, the lowest scores were observed in the dimension related to internship and CRMEF–field articulation. This result represents one of the most important findings of the study. It suggests that the main perceived weakness of initial PES teacher training lies not in the formal structure of the program, but in the connection between institutional training and real school-based practice. This weakness may be explained by several mechanisms. First, the alternation between CRMEF-based training and field-based internships may remain insufficiently integrated, causing theoretical courses, practical training activities, and internship experiences to operate as parallel rather than complementary components of professional preparation. Second, coordination among CRMEF trainers, mentor teachers, inspectors, and host schools may not always be sufficiently structured, which can lead to fragmented or inconsistent feedback for trainee teachers. Finally, the alignment between training content and the realities of school practice may be limited, reducing the perceived coherence of the professionalization process. Similar challenges have been reported in teacher education programs where institutional training and school-based experiences are not fully integrated.

Third, the specific nature of Physical Education may reinforce these difficulties. Unlike some classroom-based subjects, PES teaching requires immediate management of movement, space, safety, group dynamics, equipment, and differentiated motor abilities. Therefore, the transfer of theoretical knowledge into practice is particularly demanding. A trainee teacher may understand pedagogical principles at the CRMEF but still struggle to apply them in real teaching situations where time pressure, student behavior, and material constraints are present. This supports the idea that professionalization cannot be reduced to the acquisition of theoretical knowledge; it requires situated learning, guided practice, reflective feedback, and strong articulation between training institutions and school contexts (Korthagen & Kessels, 1999; Lave & Wenger, 1991).

These findings are consistent with previous studies highlighting the importance of practicum quality and institutional coordination in teacher education. Tamani et al. (2021), for example, identified several dysfunctions in qualifying teacher training within CRMEFs, including insufficient training time, weak communication between training actors, and limited pedagogical support during internship periods. Similarly, Greve et al. (2020) showed that field experience alone does not automatically improve

teaching performance in Physical Education; its impact depends on the quality of supervision, feedback, and reflective support provided during the practicum. Thus, the low scores observed in the internship–CRMEF field articulation dimension should not be interpreted simply as a logistical problem. They reveal a deeper issue related to the coherence of the professionalization process.

The inferential results showed no statistically significant differences between the five CRMEFs across the four dimensions of the evaluation grid. The effect sizes were very small, indicating that institutional affiliation explained only a limited proportion of the variance in teacher trainers' perceptions. These findings suggest a relative homogeneity of perceptions among teacher trainers across the participating CRMEFs. This may be related to the centralized nature of teacher education in Morocco, where CRMEFs operate under common national frameworks, similar institutional regulations, and standardized training orientations.

Nevertheless, this result must be interpreted carefully. The absence of statistically significant differences does not prove that training conditions are objectively equivalent across all CRMEFs. It only indicates that, within the present sample, teacher trainers reported relatively similar perceptions of the evaluated dimensions. Moreover, the small descriptive differences observed between centers may still reflect contextual specificities, such as differences in facilities, local partnerships with internship schools, trainers' professional experience, or practicum supervision procedures. These factors cannot be fully captured through quantitative scores alone and should be explored in future qualitative or mixed-method studies.

The present findings also highlight the need to distinguish clearly between three levels of analysis: institutional organization, perceived training quality, and professionalization outcomes. Institutional organization refers to the formal structure of the training system, including modules, planning, regulations, and training sequences. Perceived training quality refers to how teacher trainers evaluate the functioning of this system based on their experience. Professionalization outcomes refer to the actual competencies, practices, and professional development of trainee teachers. The present study mainly addresses the second level: teacher trainers' perceptions. It does not directly measure trainee teachers' classroom performance, professional competence development, or long-term teaching outcomes. This distinction is important to avoid overinterpreting the findings.

From a practical perspective, the results suggest several areas for improvement. First, the articulation between CRMEF training and field internship should be strengthened through clearer coordination mechanisms between CRMEF trainers, mentor teachers, inspectors, and host institutions. Second, internship supervision should be based on shared criteria, structured observation tools, and regular feedback sessions. Third, PES trainee teachers should be exposed to more authentic professional situations during training, including classroom management, safety management, lesson adaptation, and reflective analysis of teaching practice. Finally, the evaluation of initial teacher training should involve multiple stakeholders, including trainee teachers, mentor teachers, inspectors, and institutional leaders, in order to provide a more comprehensive understanding of the training process.

Despite its contribution, this study has several limitations. First, the sample was limited to 125 PES teacher trainers from five CRMEFs, which restricts the generalizability of the findings to all Moroccan CRMEFs. Second, the study relied exclusively on teacher trainers' perceptions. Although these actors have valuable professional experience, their perceptions do not provide a complete picture of the training process. Third, the study used a quantitative cross-sectional design, which does not allow causal interpretation or longitudinal analysis of professional development. Fourth, the validation process remains exploratory. Although the present study provides initial support for the factorial structure and internal consistency of the evaluation grid, the absence of confirmatory factor analysis (CFA), test–retest reliability, and assessments of convergent and discriminant validity limits the extent to which construct validity and stability can be established. Therefore, the psychometric properties of the instrument should be considered preliminary and require further validation in independent samples. Finally, the study focused only on the PES specialization, which limits comparison with other teacher education fields.

Future research should therefore adopt a more comprehensive approach by including trainee teachers, mentor teachers, inspectors, and institutional administrators. Mixed-method designs combining questionnaires, interviews, classroom observations, and document analysis would allow for a deeper understanding of the mechanisms underlying perceived strengths and weaknesses in initial teacher training. Longitudinal studies would also be useful to examine how perceived training quality relates to the development of professional competencies over time. Such research would help move beyond perceptions and provide stronger evidence regarding the relationship between institutional training, practicum experiences, and trainee teachers' professionalization.

Overall, the present study provides an initial contribution to the evaluation of PES teacher training within Moroccan CRMEFs. It proposes an exploratory evaluation grid and identifies perceived strengths and weaknesses in the training system. The findings suggest that program organization and pedagogical support are perceived relatively positively, whereas the articulation between CRMEF-based training and field internship remains a major area for improvement. Strengthening the connection between institutional training and real professional practice appears essential for improving the professional preparation of future PES teachers in Morocco.

Conclusion

This study examined teacher trainers' perceptions of initial Physical Education and Sport teacher training within five Moroccan CRMEFs and provided preliminary exploratory evidence for a multidimensional evaluation grid. The results suggest that the grid presents an acceptable exploratory factorial structure and satisfactory internal consistency. However, the validation process remains preliminary and should be strengthened in future studies through confirmatory factor analysis, test–retest reliability, and convergent and discriminant validity analyses. Accordingly, the proposed evaluation grid should not yet be regarded as a fully validated instrument. Rather, it constitutes a preliminary assessment framework that provides encouraging initial evidence and offers a foundation for

future psychometric refinement and validation across larger and more diverse samples of teacher education stakeholders.

From a substantive perspective, teacher trainers reported moderate perceptions of training quality, with relatively stronger evaluations of program organization and pedagogical support, and weaker evaluations of internship and CRMEF–field articulation. These findings suggest that the main challenge lies in connecting institutional training with situated professional practice. The absence of significant differences between CRMEFs indicates relatively homogeneous perceptions among trainers, but it should not be interpreted as evidence of equivalent training effectiveness across institutions.

Overall, the study contributes an initial evaluation framework that may support future research and institutional reflection on PES teacher education in Morocco. Nevertheless, further studies involving trainee teachers, mentor teachers, inspectors, and direct observation of professional practices are needed to better understand the relationship between perceived training quality, institutional organization, and professionalization outcomes.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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Ethics Approval

This study did not involve any experimental intervention on humans or animals. The research was based on voluntary questionnaire responses from adult teacher trainers. It was conducted in accordance with the principles of scientific integrity and applicable ethical standards. No sensitive personal data or confidential information were collected. Informed consent was obtained from all participants prior to data collection. Participation was entirely voluntary, and participants were clearly informed about the purpose of the study and their right to withdraw at any time without consequences. Given the non-interventional and anonymous nature of the study, formal ethical committee approval was not required.

Informed Consent

Informed consent was obtained from all participants prior to their inclusion in the study. Participation was voluntary, and participants were informed about the purpose of the research and their right to withdraw at any time without penalty.

Data Availability Statement

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

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Сприйняття викладачами початкової підготовки вчителів фізичної культури в марокканських Регіональних центрах професій освіти та підготовки: попереднє розроблення та експлораторна валідація оціночної шкали

Хамза Марзак[1ABDE], **Мухсін Ель Кр'єфі**[1CDE], **Ханан Ель Файлалі**[1CDE], **Юсеф Ель Мадхі**[1,2ABDE]

[1]Університет Ібн Тофайла
[2]Регіональний центр професій освіти та підготовки Рабат–Сале–Кенітра

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

Реферат. Стаття: 13 с., 9 табл., 43 джерел.

Мета. Метою цього дослідження було вивчити сприйняття викладачами професійної підготовки майбутніх учителів фізичної культури і спорту в Регіональних центрах професій освіти та підготовки Марокко, а також отримати попередні докази експлораторної валідності та внутрішньої узгодженості багатовимірної оціночної шкали.

Матеріали та методи. Було застосовано кількісний поперечний дизайн дослідження. До вибірки увійшли 125 викладачів, які здійснюють підготовку майбутніх учителів фізичної культури і спорту, із п'яти марокканських Регіональних центрів професій освіти та підготовки (CRMEF). Початковий варіант інструмента складався з 38 пунктів, розроблених на основі інституційних стандартів, очікуваного профілю випускника та наукової літератури з підготовки й професіоналізації вчителів. Після експертної оцінки інструмент було скорочено до 30 пунктів. Для експлораторного дослідження внутрішньої структури шкали застосовано аналіз головних компонент із Varimax-обертанням, а для оцінювання внутрішньої узгодженості розраховано коефіцієнт альфа Кронбаха.

Результати. Експлораторний аналіз засвідчив чотирифакторну структуру, що відповідала теоретичним складовим інструмента: організація освітньої програми, практики педагогічної підготовки, супервізія та педагогічний супровід, а також взаємозв'язок між педагогічною практикою та CRMEF. Після очищення інструмента його фінальна версія містила 26 пунктів. Внутрішня узгодженість була прийнятною для всіх чотирьох складових. Остаточна 26-пунктова версія продемонструвала прийнятні попередні психометричні показники, зокрема щодо експлораторної факторної структури та внутрішньої узгодженості. Описові результати показали помірний рівень оцінок за всіма складовими, при цьому відносно вищі значення спостерігалися для організації підготовки та педагогічного супроводу, а нижчі — для взаємозв'язку між педагогічною практикою та CRMEF. Результати дисперсійного аналізу (ANOVA) не виявили статистично значущих відмінностей між CRMEF, а величини ефекту були дуже малими.

Висновки. Отримані результати свідчать про відносно однорідне сприйняття системи підготовки викладачами в усіх досліджених CRMEF. Водночас дослідження не оцінює об'єктивну ефективність підготовки вчителів або їхні професійні результати. Натомість воно надає попередні експлораторні докази придатності запропонованої оціночної шкали та виявляє сприймані слабкі сторони взаємозв'язку між інституційною підготовкою та педагогічною практикою. Подальші дослідження із більшими вибірками, використанням конфірматорного факторного аналізу та залученням даних від різних груп учасників є необхідними.

Ключові слова: початкова підготовка, майбутні вчителі фізичної культури і спорту, конструктивна валідність, надійність, професійні практики.

Information about the Authors:

Marzak, Hamza: hamza.marzak@uit.ac.ma; https://orcid.org/0009-0002-4763-7837; Laboratory of Electronic Systems, Information Processing, Mechanics and Energetics, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco.

El Qryefy, Mouhcine: mouhcine.elqryefy@uit.ac.ma; https://orcid.org/0009-0008-3130-5866; Laboratory of Electronic Systems, Information Processing, Mechanics and Energetics, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco.

El Faylali, Hanan: hanan.elfaylali@uit.ac.ma; https://orcid.org/0000-0001-9750-9476; Laboratory of Electronic Systems, Information Processing, Mechanics and Energetics, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco.

El Madhi, Youssef: youssmad@yahoo.fr; https://orcid.org/0000-0002-2493-5121; Laboratory of Education, Environment & Health, CRMEF Rabat/Salé/Kenitra, Morocco; Laboratory of Biology and Health, Faculty of Sciences, University Ibn Tofail, Kenitra, Morocco.

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Game-Based Learning Effects on Holistic Outcomes in Pencak Silat Instruction

Nur Rohmah Muktiani[1ABCDE], Saryono[1ABCDE], Muhammad Sigit Antoni[1ABCDE], La Ode Adhi Virama[2ABCDE] and Dewangga Yudhistira[3ABCDE]

[1]Universitas Negeri Yogyakarta
[2]Institut Agama Islam Negeri Kendari
[3]Universitas Negeri Surabaya

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

Corresponding Author: Nur Rohmah Muktiani, e-mail: nur_rohmah@uny.ac.id
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Abstract

Background. Pencak Silat instruction in Indonesian secondary schools remains predominantly teacher-centered, limiting student engagement across cognitive, affective, and psychomotor domains.

Objectives. To examine the effects of an explicitly progressive Game-Based Learning (GBL) sequence based on modified Teaching Games for Understanding (TGfU) games on holistic learning outcomes in Pencak Silat instruction.

Materials and Methods. A quasi-experimental pre-test–post-test design was employed with 60 ninth-grade students assigned to an experimental group (n = 30; eight-week progressive GBL sequence) or a control group (n = 30; conventional instruction). Cognitive, affective, and psychomotor outcomes were assessed using instruments validated through expert content validity (Aiken's V), pilot testing of internal consistency, and dual-observer inter-rater reliability. Independent- and paired-samples t-tests and one-way MANOVA were conducted.

Results. The experimental group significantly outperformed the control group on cognitive (d = 0.579), affective (d = 4.580), and psychomotor (d = 4.294) post-test scores (all $p < .05$). MANOVA confirmed a significant simultaneous group effect across all three domains (Wilks' $\Lambda = 0.128$, $F = 131.68$, $p < .001$, $\eta^2 = .872$).

Conclusions. A progressively sequenced GBL intervention produced significantly superior holistic learning outcomes in Pencak Silat compared with conventional instruction. The exceptionally large affective and psychomotor effect sizes should be interpreted cautiously given the restricted-range rating instruments used and are best understood as indicating a clear directional advantage rather than a precise quantification of the true effect magnitude.

Keywords: game-based learning, pencak silat, physical education, cognitive outcomes, affective outcomes, psychomotor outcomes, teaching games for understanding.

Introduction

Physical education is widely recognized as a vital component of the school curriculum, charged with simultaneously fostering cognitive competence, affective development, and psychomotor mastery the three fundamental dimensions articulated in Bloom's Taxonomy (Bloom et al., 1956; Krathwohl, 2002). The integration of all three learning domains within a unified instructional framework is regarded as the hallmark of high-quality physical education, yet persistent challenges remain in designing instructional approaches capable of sustaining meaningful student engagement across all three dimensions concurrently (Bailey, 2006; Beni et al., 2019). In this regard, the quality of instructional approaches has been consistently identified as a critical determinant of student learning trajectories (Kirk & MacPhail, 2002; Rink, 2014).

Among contemporary instructional innovations, Game-Based Learning (GBL) broadly defined as an approach that integrates structured game elements such as rules, goals, feedback, and challenge into learning activities to promote active and purposeful participation (Plass et al., 2015; Van Eck, 2006) has attracted considerable scholarly attention. In physical education, GBL is operationalized through modified

games: systematic adaptations of sport and game structures that preserve motivational qualities while aligning with curricular objectives (Hastie & Curtner-Smith, 2006; Butler & McCahan, 2005). Empirical reviews consistently document that GBL interventions in physical education are associated with increased student engagement (Harvey & Jarrett, 2014; Yan et al., 2022), higher intrinsic motivation (Ntoumanis, 2001; Deci & Ryan, 2000), and improved learning outcomes compared with conventional direct instruction (Ezeddine et al., 2025; Ortiz et al., 2023).

In the Indonesian school curriculum, Pencak Silat a traditional martial art rooted in Nusantara cultural heritage occupies a mandatory position in physical education at primary and secondary levels (Ministry of Education and Culture of the Republic of Indonesia, 2016). As an activity integrating technical execution, tactical reasoning, and deeply embedded cultural values such as discipline, sportsmanship, and respect, Pencak Silat offers a uniquely rich pedagogical context in which cognitive, affective, and psychomotor domains converge (Maryono, 1998; Lubis & Wardoyo, 2016). Nevertheless, instruction in Pencak Silat in Indonesian secondary schools has been predominantly characterized by teacher-centered approaches emphasizing repetitive technique drills, with limited attention to pedagogical strategies capable of stimulating higher-order thinking, fostering affective internalization, or enhancing intrinsic motivation (Vertonghen & Theeboom, 2010; Vertonghen et al., 2014).

A critical gap exists in the GBL literature: research has largely focused on team and invasion sports such as football, basketball, and volleyball (Casey & MacPhail, 2018; Harvey & Jarrett, 2014), with very few studies examining GBL in martial arts or traditional sports contexts. More critically, existing GBL studies in physical education rarely adopt a multidomain learning outcomes framework that simultaneously investigates all three domains within a single experimental design (Camacho-Sánchez et al., 2023; Memmert et al., 2015), and fewer still specify the within-program progression by which a sequence of modified games is intended to scaffold increasingly complex cognitive, affective, and psychomotor demands. This represents a significant gap given that the three domains are inherently interdependent in culturally grounded activities such as Pencak Silat (Alafnan, 2025; Wilson, 2006).

This study is theoretically grounded in constructivist learning theory (Vygotsky, 1978) and the Teaching Games for Understanding (TGfU) model (Bunker & Thorpe, 1982). Within this framework, GBL through modified games positions students as active problem-solvers who simultaneously develop tactical understanding (cognitive), emotional engagement (affective), and technical execution (psychomotor) within authentic game contexts. Central to TGfU's instructional logic is the principle of progressive complexity: tasks are sequenced so that each game builds upon the technical and tactical foundation established by the preceding one, allowing the instructional demand on each domain to increase systematically across the program (Bunker & Thorpe, 1982; Kirk & MacPhail, 2002). This integrative, progression-based perspective aligns with recent developments in physical education pedagogy calling for instructional models capable of addressing the full spectrum of student learning outcomes through clearly specified instructional sequencing (Kirk, 2010; Light, 2012).

The present study therefore pursues two objectives: (1) to determine whether a progressively sequenced program of TGfU-based modified games produces significantly better cognitive, affective, and psychomotor learning outcomes in Pencak Silat instruction than conventional approaches; and (2) to provide an explicit, reproducible account of the instructional logic by which each modified game in the sequence was designed to target specific domain demands, thereby contributing experimental evidence and a transferable pedagogical model supporting the integration of TGfU-based GBL into Pencak Silat pedagogy in Indonesian secondary schools. Based on constructivist theory and the extant literature, it is hypothesized that the GBL group will demonstrate significantly superior post-test outcomes than the control group across all three learning domains, individually and simultaneously.

Materials and Methods

Research Design

A quasi-experimental non-equivalent control group pre-test–post-test design was employed (Thomas et al., 2022). Group assignment was based on intact class groupings, as is commonly applied in educational research in school settings where true randomization is logistically constrained (Creswell & Creswell, 2018). Both groups were assessed at identical time points before (pre-test) and after (post-test) the intervention. Baseline equivalence of groups was evaluated statistically prior to hypothesis testing. The study followed CONSORT guidelines for quasi-experimental designs insofar as applicable to non-randomized trials.

Participants

Participants were 60 Grade IX students from SMP Negeri 4 Sewon, Bantul Regency, Special Region of Yogyakarta, Indonesia. The control group (Class IX A, n = 30) received conventional instruction, and the experimental group (Class IX B, n = 30) received GBL. Participants were selected using purposive sampling based on the equivalence of baseline academic achievement and prior Pencak Silat learning experience between the two intact classes. A sample of 30 per group is considered adequate for two-group parametric comparisons with a medium effect size at $\alpha = .05$, power = .80 (Cohen, 1988). Participant characteristics are presented in Table 1.

Table 1. Participant Characteristics by Group

Characteristic	Control (n=30)	Experimental (n=30)
Class	IX A	IX B
Age M (SD), years	14.2 (0.7)	14.1 (0.8)
Boys, n (%)	16 (53.3)	17 (56.7)
Girls, n (%)	14 (46.7)	13 (43.3)
PE experience (years) M (SD)	3.1 (0.6)	3.0 (0.5)
Prior Pencak Silat exposure, n (%)	12 (40.0)	11 (36.7)

Note. PE = physical education.

Intervention: Progressive Sequence of Modified Games

In direct response to the requirement for a fully reproducible pedagogical model, the experimental group's

eight-week intervention was structured as an explicit progression of eight distinct modified games, each building cumulatively on the technical and tactical content of the preceding week. The progression followed TGfU's instructional logic of incremental complexity (Bunker & Thorpe, 1982; Kirk & MacPhail, 2002): Weeks 1–2 isolated single technical elements (stance, paired synchrony) under minimal cognitive load; Weeks 3–4 introduced spatial and tactical decision-making layered onto the established technical base; Weeks 5–6 integrated technical and tactical elements within small-sided cooperative game structures, introducing the affective dimension explicitly; and Weeks 7–8 required full integration of all three domains under authentic, scenario-based and student-directed conditions. This design ensures that observed cognitive, affective, and psychomotor gains can be traced to specific, identifiable instructional mechanisms at each stage of the program rather than to an undifferentiated eight-week exposure.

Table 2. Weekly Progression of TGfU-Based Modified Games: Rules, Domain Targets, and Instructional Mechanisms

Week	Modified Game	Rules & Progression Logic	Primary Domain Targeted	Instructional Mechanism
1.	"Stance Tag" (Kuda-Kuda Berkejar)	Students move using basic kuda-kuda (stance) transitions within a marked grid; 'it' must tag others while maintaining correct stance form. Low cognitive load: rules are simple, success criterion is purely technical (correct stance).	Psychomotor (stance accuracy)	Repetition under light game pressure; teacher calls out stance-check freezes
2.	"Mirror Stance" (Cermin Kuda-Kuda)	Paired students mirror each other's stance changes in real time; pairs alternate leader/follower roles. Introduces a second decision variable (timing synchrony) atop Week 1's technical base.	Psychomotor + early Affective (cooperation)	Peer-paced repetition; immediate visual feedback from partner
3.	"Evasion Circle" (Lingkaran Elak)	Students form a circle; one student in the center must evade two 'attackers' using only evasive footwork (elakan) without leaving the circle boundary. Adds spatial decision-making to the existing technical base.	Cognitive (spatial decision-making) + Psychomotor (footwork)	Constrained decision-making under time pressure; teacher prompts 'why did you move that way?'
4.	"Distance Keeper" (Penjaga Jarak)	Paired drill requiring students to maintain optimal striking distance (jarak pukul) while a partner varies approach speed unpredictably. Builds on Week 3's spatial awareness with an added tactical-timing layer.	Cognitive (tactical timing) + Psychomotor (distance control)	Trial-and-error with immediate consequence (contact = error signal); post-task group debrief
5.	"Controlled Strike-Counter" (Serang-Balas Terkendali)	Paired students alternate controlled, low-intensity strike and counter-strike sequences combining stance, evasion, and distance control learned in Weeks 1–4. Full technical integration begins here.	Psychomotor (integration) + Cognitive (sequencing)	Scaffolded complexity increase; teacher circulates with individualized prompts
6.	"Team Defense Line" (Garis Pertahanan Tim)	Small-sided team game (3v3) in which one team must collectively defend a line using stance, evasion, and distance principles against attacking partners. Introduces social/tactical cooperation under Week 5's technical base.	Affective (cooperation, respect for partner safety) + Cognitive (team tactics)	Cooperative small-sided game; teacher facilitates post-game group reflection on tactical choices
7.	"Scenario Sparring" (Sparring Skenario)	Controlled scenario-based paired sparring with assigned roles (e.g., 'defender must use only evasion for first 10 seconds'). Requires full integration of all previously learned tactical-technical elements under realistic time constraints.	All three domains integrated	Authentic game-like constraint application; teacher uses Socratic questioning post-bout
8.	"Values Showcase" (Unjuk Nilai)	Students design and perform a short paired routine integrating technical skill, tactical decision-making, and explicit demonstration of Pencak Silat values (respect, discipline, sportsmanship) for peer and teacher evaluation.	Affective (value internalization) + summative integration of all domains	Student-directed synthesis task with peer and teacher assessment using rubric criteria

Note. Game names presented in English with the original Bahasa Indonesia terminology in parentheses. Each week's game was designed to incorporate and extend the technical-tactical content of the preceding week(s), consistent with TGfU's principle of progressive complexity (Bunker & Thorpe, 1982).

Table 2 presents the complete weekly progression, including the rules, instructional logic, and primary domain target of each modified game.

Table 3 presents the standard five-phase structure applied within every session, into which the week-specific modified game (Table 2) was embedded as the core activity.

Table 3. Standard Session Structure and Instructional Purpose of Each Phase

Phase	Duration	Activity	Instructional Purpose
1	10 min	Warm-up game (low-intensity variant of week's modified game)	Activates relevant motor pattern; primes cognitive focus for the session theme
2	35 min	Core modified game task (see Table 2 for weekly content)	Primary vehicle for domain-targeted skill and tactical development
3	15 min	Tactical reflection discussion (teacher-facilitated, Socratic questioning)	Converts implicit game experience into explicit tactical/cognitive understanding
4	15 min	Technical practice (isolated repetition of session's key technique)	Consolidates motor pattern in a low-pressure, repetition-focused context
5	5 min	Cool-down and individual reflection log	Physiological recovery; reinforces self-monitoring habit

Note. The core modified game task (Phase 2) varied weekly according to the progression specified in Table 2; all other phases maintained a consistent structure across the eight-week program.

All sessions were delivered by the same licensed physical education teacher, who received four hours of standardized training in TGfU principles and the specific rules and progression logic of each modified game prior to the intervention, in order to control for teacher effects and to maximize fidelity of implementation. A second trained observer independently verified adherence to the planned game rules and session structure in 25% of randomly selected sessions (fidelity checklist agreement = 96%). The control group received conventional Pencak Silat instruction of equivalent total duration, comprising teacher demonstration, repetitive technique drilling, and structured practice under teacher direction, without modified games, tactical reflection discussion, or the progressive complexity structure described above.

Instrumentation, Validity, and Reliability

Three domain-specific instruments were administered at both pre-test and post-test. Table 4 summarizes the instrument type, item count, scoring range, and content coverage for each domain.

Content validity of all three instruments was established through review by three independent experts (two Pencak Silat coaching specialists and one physical education measurement specialist), who rated each item's relevance to its intended construct using Aiken's V coefficient (Aiken, 1985), with $V \geq .75$ considered acceptable for a three-rater panel. Three items in the initial affective rubric draft ($V < .75$) were revised based on expert feedback prior to piloting. All three instruments were subsequently piloted with a non-study class of comparable grade level and prior Pencak Silat exposure ($n = 28$) to assess internal consistency (Cronbach's alpha). Table 5 summarizes the content validity, internal consistency, and inter-rater reliability evidence for each instrument.

Because the affective and psychomotor domains depend on observer judgment, additional procedural safeguards were implemented to strengthen inter-rater reliability beyond the ICC values reported in Table 5. Table 6 details the observer qualification, training, scoring, and discrepancy-resolution procedures applied to both rubrics.

Table 4. Description of Cognitive, Affective, and Psychomotor Instruments

Domain	Instrument Type	Items & Scoring	Content Covered
Cognitive	Written test	30 items; scored 0–100	Technique names and sequences, tactical concepts, rules, philosophical values
Affective	Behavioural observation rubric	12 items; 4-point scale (1 = never, 4 = always); range 12–48	Discipline, cooperation, sportsmanship, self-confidence, responsibility
Psychomotor	Movement skill rubric	20 items; 4-point scale; range 20–80	Accuracy, coordination, and fluency of kuda-kuda (stances), punches, kicks, defensive movements

Note. All instruments were developed specifically for this study and administered identically at pre-test and post-test.

Table 5. Validity and Reliability Evidence by Domain

Domain	Content Validity (Aiken's V)	Internal Consistency (Pilot, n = 28)	Inter-Rater Reliability (ICC)
Cognitive	V = .79–.94 (3 expert raters)	Cronbach's α = .84	N/A (written test)
Affective	V = .76–.91 (3 items revised, initial V < .75)	Cronbach's α = .81	ICC = .88, 95% CI [.81, .93]
Psychomotor	V = .78–.93 (3 expert raters)	Cronbach's α = .86	ICC = .91, 95% CI [.85, .95]

Note. ICC = intraclass correlation coefficient (two-way random-effects, absolute agreement). Acceptable thresholds: Aiken's $V \geq .75$ (Aiken, 1985); Cronbach's $\alpha \geq .70$ (Streiner et al., 2015); $ICC \geq .75$ indicates excellent agreement (Landis & Koch, 1977). The cognitive instrument is a written test and therefore was not subject to inter-rater scoring.

Table 6. Observer Training and Scoring Procedure for Affective and Psychomotor Rubrics

Procedure Step	Description
Observer qualifications	Two independent observers, both certified Pencak Silat instructors with ≥ 5 years' coaching experience
Training	4-hour structured session using video-recorded reference performances and consensus-based criterion calibration, prior to data collection
Scoring protocol	Both observers rated all 60 participants independently at pre-test and post-test; blinded to each other's ratings and to group allocation
Discrepancy resolution	A third independent observer's rating was used as the final score when two raters differed by > 1 scale point; required for 4.2% of affective items and 3.1% of psychomotor items
Final score	Mean of the two primary observers' ratings (or third-observer score where the resolution procedure applied)

Note. Both observers were blinded to group allocation throughout the scoring process to minimize expectancy bias.

Statistical Analysis

All analyses were conducted using IBM SPSS Statistics Version 26 (α = .05). Descriptive statistics (mean, SD, minimum, maximum) were computed for all variables. Normality was assessed using the Shapiro–Wilk test (Field, 2024). Levene's test was used to assess homogeneity of variance; Welch's correction was applied where homogeneity was violated. For each domain, within-group improvement was examined using paired samples t-tests, and between-group post-test differences using independent samples t-tests. Effect sizes were calculated using Cohen's d (Cohen, 1988; Lakens, 2013): ≥ 0.20 small, ≥ 0.50 moderate, ≥ 0.80 large. The simultaneous effect of group across all three dependent variables was evaluated using one-way MANOVA (Wilks' Λ), with partial η^2 reported (≥ .01 small, ≥ .06 medium, ≥ .14 large). Given that the affective and psychomotor rubrics employed restricted four-point response scales, effect sizes for these two domains are interpreted with explicit caution in the Discussion, consistent with established guidance on effect size interpretation for restricted-range ordinal instruments (Lakens, 2013; Pallant, 2020).

Results

Descriptive Statistics

Table 7 presents pre-test, post-test, and gain scores for both groups across all three learning domains.

Both groups improved from pre-test to post-test across all three domains. The experimental group recorded higher post-test means than the control group in all three domains: cognitive (78.50 vs. 73.33), affective (47.53 vs. 42.17), and psychomotor (48.80 vs. 44.10).

Assumption Tests

Shapiro–Wilk normality test results are presented in Table 8.

Table 8. Shapiro–Wilk Normality Test Results by Variable, Group, and Stage

Variable	Group	Stage	W	p
Cognitive	Control	Pre-test	0.961	.152
	Control	Post-test	0.943	.066
	Experimental	Pre-test	0.966	.189
	Experimental	Post-test	0.944	.067
Affective	Control	Pre-test	0.808	< .001
	Control	Post-test	0.851	.008
	Experimental	Pre-test	0.839	.011
	Experimental	Post-test	0.720	< .001
Psychomotor	Control	Pre-test	0.702	< .001
	Control	Post-test	0.712	< .001
	Experimental	Pre-test	0.698	< .001
	Experimental	Post-test	0.688	< .001

Note. p > .05 indicates normality. Welch's t-test was applied for the affective domain where Levene's test indicated heterogeneous variance (p = .007); Levene's test indicated homogeneous variance for the cognitive (p = .083) and psychomotor (p = .637) domains.

Cognitive data were normally distributed in both groups at both time points (all p > .05). Affective and psychomotor data did not meet normality in most conditions (p < .05), attributable to low score variability reflecting convergence

Table 7. Descriptive Statistics by Group and Measurement Occasion

Variable	Group	n	Pre-test M (SD)	Post-test M (SD)	Gain M
Cognitive	Control	30	53.17 (8.04)	73.33 (6.74)	20.17
	Experimental	30	51.67 (14.16)	78.50 (10.68)	26.83
Affective	Control	30	19.67 (1.24)	42.17 (1.58)	22.50
	Experimental	30	24.33 (1.37)	47.53 (0.51)	23.20
Psychomotor	Control	30	24.17 (1.93)	44.10 (1.24)	19.93
	Experimental	30	29.10 (1.12)	48.80 (0.92)	19.70

Note. M = mean; SD = standard deviation. Affective and psychomotor scores reflect total rubric scores derived from the mean of two independent observer ratings.

toward upper response categories. Per the Central Limit Theorem, with n = 30 per group, sampling distributions of means approximate normality, justifying parametric inference (Field, 2024; Pallant, 2020). Levene's test confirmed homogeneous variance for cognitive (p = .083) and psychomotor (p = .637) data; Welch's correction was applied for the affective domain (Levene p = .007).

Hypothesis Testing

Table 9 presents paired and independent samples t-test results for all three domains.

Table 9. Paired and Independent Samples t-test Results by Domain

Test	t	df	p	Cohen's d
Cognitive: Paired – Control	-11.96	29	< .001	2.183
Cognitive: Paired – Experimental	-10.60	29	< .001	1.935
Cognitive: Independent (post-test)	2.241	58	.029	0.579
Affective: Paired – Control	-58.77	29	< .001	10.731
Affective: Paired – Experimental	-83.73	29	< .001	15.286
Affective: Independent (post-test)[a]	17.738	–	< .001	4.580
Psychomotor: Paired – Control	-69.36	29	< .001	12.662
Psychomotor: Paired – Experimental	-128.97	29	< .001	23.546
Psychomotor: Independent (post-test)	16.629	58	< .001	4.294

Note. [a]Welch's correction applied. Cohen's d classification: ≥ 0.20 small; ≥ 0.50 moderate; ≥ 0.80 large (Cohen, 1988).

Cognitive domain: paired t-tests confirmed significant within-group improvements in both groups (both p < .001). The independent samples t-test indicated a significantly higher post-test cognitive score in the experimental group than in the control group, t(58) = 2.241, p = .029, d = 0.579.

Affective domain: paired t-tests confirmed significant within-group improvements in both groups (both p < .001). The Welch-corrected independent samples comparison indicated a significantly higher post-test affective score in the experimental group than in the control group, t = 17.738, p < .001, d = 4.580.

Psychomotor domain: paired t-tests confirmed significant within-group improvements in both groups (both p < .001). The independent samples t-test indicated a significantly higher post-test psychomotor score in the experimental group than in the control group, t(58) = 16.629, p < .001, d = 4.294.

MANOVA: Table 10 presents the one-way MANOVA results testing the simultaneous group effect across all three domains.

MANOVA indicated a statistically significant simultaneous group effect across all three learning domains, Wilks' Λ = 0.128, F = 131.68, p < .001, η^2 = .872. Univariate follow-up tests indicated statistically significant group differences for each individual domain: cognitive (F = 5.02, p = .029, η^2 = .080), affective (F = 314.64, p < .001, η^2 = .844), and psychomotor (F = 276.52, p < .001, η^2 = .827).

Table 10. One-Way MANOVA Results for Simultaneous Group Effects

Effect	Wilks' Λ	F	p	η^2 (partial)
Group (GBL vs. Conventional)	0.128	131.68	< .001	.872
Cognitive (univariate)	–	5.02	.029	.080
Affective (univariate)	–	314.64	< .001	.844
Psychomotor (univariate)	–	276.52	< .001	.827

Note. η^2 classification: ≥ .01 small; ≥ .06 medium; ≥ .14 large (Cohen, 1988).

Discussion

This study examined whether a progressively sequenced program of TGfU-based modified games produces superior cognitive, affective, and psychomotor learning outcomes in Pencak Silat instruction relative to conventional instruction, and sought to provide a reproducible account of the pedagogical mechanisms underlying any observed effects. The confirmation of significant between-group differences across all three domains, together with a significant simultaneous MANOVA effect, supports the hypothesis that a well-specified instructional progression rather than mere exposure to game-based activity in general drives multidomain skill development.

The moderate cognitive effect (d = 0.579) is consistent with the constructivist learning framework (Vygotsky, 1978) and with TGfU's emphasis on tactical understanding as a foundation for technical mastery (Bunker & Thorpe, 1982; Kirk & MacPhail, 2002). The weekly progression documented in Table 2 offers a specific explanation for this effect: cognitive demand was deliberately layered across the program, beginning with technical-only tasks (Weeks 1–2) and progressively introducing spatial decision-making (Week 3), tactical timing (Week 4), and full scenario-based reasoning (Week 7). This staged increase in cognitive load is theoretically consistent with the "challenge point" framework (Guadagnoli & Lee, 2004), which holds that learning is optimized when task difficulty is incrementally matched to learners' developing competence rather than introduced all at once. The moderate (rather than large) cognitive effect size, relative to the very large affective and psychomotor effects, is itself informative: it suggests that higher-order tactical reasoning required more sustained, cumulative exposure to develop than the more direct behavioral and motor outcomes captured by the affective and psychomotor instruments, a pattern consistent with Mayer's (2019) observation that executive cognitive engagement in game-based learning develops more gradually than procedural or behavioral responses.

The affective and psychomotor effect sizes (d = 4.580 and d = 4.294, respectively) are exceptionally large by any conventional benchmark (Cohen, 1988; Lakens, 2013) and require explicit, critical interpretation rather than face-value acceptance. Three methodological features of the present design plausibly inflate these estimates beyond their true population magnitude. First, both the affective and psychomotor instruments employed restricted four-point rating scales; when post-test scores in the experimental group cluster near the scale ceiling (as observed, with 346 of 360 total experimental-group affective responses

falling in the 'Very Good' category), between-group variance is compressed and standardized effect size statistics such as Cohen's d become mathematically inflated independent of the true underlying difference between groups (Lakens, 2013; Pallant, 2020). Second, the same teacher-affiliated observers who delivered or were aware of group assignment scored the rubrics, introducing a plausible expectancy bias risk despite the blinded, dual-observer protocol implemented to mitigate it. Third, the quasi-experimental design without random allocation to condition may also have contributed to the larger observed standardized differences, as non-randomized designs are more susceptible than randomized designs to confounding by unmeasured pre-existing between-class differences that can inflate apparent treatment effects (Thomas et al., 2022). Taken together, these findings should be interpreted as providing strong evidence of a clear directional advantage favoring the experimental condition in the affective and psychomotor domains, rather than as precise, generalizable quantifications of true effect magnitude. Future replications using randomized allocation, rating instruments with wider response ranges (e.g., 7- or 10-point scales), or continuous performance-based measures are needed before the magnitude—rather than merely the direction—of these effects can be considered established.

With this caveat stated, the directional pattern of affective and psychomotor gains remains theoretically interpretable. The progression documented in Table 2 introduced the affective dimension explicitly only from Week 6 onward ("Team Defense Line"), through cooperative small-sided games requiring peer trust and shared tactical responsibility, and culminated in Week 8's "Values Showcase," which required explicit demonstration and peer evaluation of Pencak Silat values. This staged introduction of affective demand is consistent with Self-Determination Theory (Deci & Ryan, 2000, 2013): the modified games' game-embedded autonomy (tactical choice), competence (calibrated challenge), and relatedness (paired and small-group structures) jointly support intrinsic engagement, and the late-stage cooperative and values-based tasks plausibly account for the marked behavioral shift captured by the rubric. For the psychomotor domain, the variable, progressively complex demands of the modified games across Weeks 1-7 moving from isolated stance repetition to fully integrated scenario sparring are consistent with contextual interference and motor variability principles (Magill & Hall, 1990; Porter & Magill, 2010), which predict that variable practice conditions produce more robust and adaptable motor skill than blocked, repetitive drilling of the kind used in the control condition.

The MANOVA result ($\eta^2 = .872$) indicates that the three domains did not improve independently but covaried as a coherent outcome pattern under the GBL condition. Read alongside the weekly progression in Table 2, this multivariate result is consistent with the proposition that cognitive, affective, and psychomotor development are mutually reinforcing when instructional tasks are deliberately designed to integrate all three demands within a single, progressively sequenced activity (Alafnan, 2025; Wilson, 2006), rather than being independently caused by unrelated programme features. This extends the theoretical work of Light (2012) and Correia et al. (2019) on game-sense and nonlinear pedagogies by providing, for the first time, a fully specified and reproducible week-by-week progression demonstrating their multidomain effectiveness in a traditional martial arts context.

Compared with previous studies on game-based and TGfU-informed approaches, the present findings both corroborate and extend the existing evidence base. Harvey and Jarrett's (2014) review of game-centred approaches since 2006 reported consistent, though typically small-to-moderate, gains in tactical and technical performance across team and invasion sports; the present study's moderate cognitive effect ($d = 0.579$) falls within this established range, suggesting that GBL's cognitive benefits generalize from invasion-sport contexts to a culturally distinct, individual combat sport such as Pencak Silat. Casey and MacPhail (2018) similarly emphasized that models-based approaches to physical education tend to yield their most consistent advantages in engagement and participation-related (i.e., affective) outcomes rather than in technical performance alone; the markedly larger affective gains observed here are broadly consistent with this pattern, though as discussed above the magnitude reported in the present study substantially exceeds typical benchmarks and should be interpreted with the measurement caveats already noted. Ortiz et al.'s (2023) meta-analysis of TGfU randomized controlled trials reported pooled effects in the small-to-moderate range for game performance outcomes, a benchmark against which the present study's very large psychomotor effect again stands out as atypical, reinforcing the need for the cautious interpretation urged above rather than treating the present magnitude as representative of TGfU's typical effect. Finally, Ezeddine et al. (2025), in one of the most recent systematic treatments of game-based physical education, concluded that GBL's documented benefits for motivation and engagement are more consistently established in the literature than its benefits for measurable skill acquisition; the present study's pattern of comparatively modest cognitive gains alongside very large affective and psychomotor gains is therefore only partially aligned with this prior synthesis, and the divergence itself underscores why replication with more sensitive, less restricted measurement instruments is necessary before the present findings can be considered representative of GBL's effect on Pencak Silat skill acquisition specifically, as opposed to motivation and engagement more broadly.

Several limitations should be acknowledged, in addition to the measurement-related caveats discussed above. The quasi-experimental design with intact class assignment limits the strength of causal inference relative to full randomization, and the absence of random allocation may also have contributed to the magnitude of the standardized between-group differences observed, as quasi-experimental designs are known to be more susceptible to inflated effect size estimates than fully randomized designs (Thomas et al., 2022). The sample was drawn from a single school in one regency of Yogyakarta, which constrains generalizability to other regions, school types, and cultural contexts within Indonesia's diverse educational landscape. The eight-week intervention period does not permit conclusions about long-term skill retention or transfer. Future research should employ true randomization where ethically and logistically feasible, include retention tests at 6- and 12-week follow-up, use affective and psychomotor measurement instruments with wider response ranges or continuous scoring to address the ceiling-effect concern raised above, and extend

the sample to diverse school contexts across Indonesia and beyond.

Conclusions

This study provides preliminary evidence that a progressively sequenced program of TGfU-based modified games is associated with significantly greater improvements in cognitive, affective, and psychomotor learning outcomes in Pencak Silat instruction than conventional instruction, individually and in simultaneous combination. The cognitive effect (d = 0.579) can be interpreted with reasonable confidence as a moderate, genuine instructional advantage. The affective and psychomotor effects, while statistically significant and directionally consistent with the cognitive finding, were measured using restricted-range rating instruments within a non-randomized quasi-experimental design, both of which plausibly inflated their numerical magnitude; these results should therefore be read as suggestive evidence of a clear directional benefit rather than as precise, generalizable estimates of true effect size. The findings as a whole should be interpreted within the limitations of the quasi-experimental, single-school design described above, pending replication with randomized allocation and more sensitive instruments.

These findings carry practical implications specific to the scope of this study. Physical education teachers instructing Pencak Silat may consider adopting an explicitly progressive sequence of modified games—of the kind detailed in Table 2 as a candidate reproducible instructional model, rather than treating game-based activity as a generic supplementary technique. The detailed weekly progression provided here is intended to allow other practitioners and researchers to replicate, adapt, or critically test this specific instructional sequence in other settings. Given the single-school, eight-week, non-randomized scope of this study, broader claims regarding curriculum-wide or policy-level adoption are not warranted by the present data and would require replication across more diverse school contexts, randomized designs, longer intervention periods, and psychometrically refined affective and psychomotor instruments before such recommendations could be made with confidence.

Informed Consent

Written informed consent was obtained from the parents or guardians of all participants prior to study enrolment. Participants were informed that their involvement was voluntary and that they could withdraw at any time without academic consequence.

Data Availability Statement

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

Ai Transparency Statement

The authors used AI-assisted tools for language editing only and take full responsibility for the content of this manuscript.

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Conflict of Interest

The authors declare no conflicts of interest.

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Вплив навчання на основі ігрового підходу на цілісні результати навчання пенчак силату

Нур Рохмах Муктіані[1ABCDE], Сарьоно[1ABCDE], Мухаммад Сігіт Антоні[1ABCDE], Ла Оде Адхі Вірама[2ABCDE], Девангга Юдхістіра[3ABCDE]

[1]Державний університет Джок'якарти
[2]Державний ісламський інститут Кендарі
[3]Державний університет Сурабаї

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

Реферат. Стаття: 10 с., 10 табл., 45 джерел.

Передумови. Викладання пенчак силату в закладах середньої освіти Індонезії залишається переважно орієнтованим на вчителя, що обмежує залученість учнів у когнітивній, афективній та психомоторній сферах.

Мета. Дослідити вплив чітко структурованої прогресивної послідовності навчання на основі ігрового підходу (Game-Based Learning, GBL), побудованої на модифікованих іграх концепції Teaching Games for Understanding (TGfU), на цілісні результати навчання пенчак силату.

Матеріали і методи. Використано квазіекспериментальний дизайн із попереднім і підсумковим тестуванням. У дослідженні взяли участь 60 учнів дев'ятого класу, яких розподілили на експериментальну групу (n = 30; восьмитижнева прогресивна програма GBL) та контрольну групу (n = 30; традиційне навчання). Когнітивні, афективні та психомоторні результати оцінювали за допомогою інструментів, валідованих шляхом експертної оцінки змістової валідності (коефіцієнт V Айкена), пілотного тестування внутрішньої узгодженості та визначення міжекспертної надійності за участю двох спостерігачів. Для аналізу даних застосовано t-тести для незалежних і парних вибірок та одновимірний багатовимірний дисперсійний аналіз (MANOVA).

Результати. Експериментальна група продемонструвала статистично значуще кращі результати порівняно з контрольною за когнітивними (d = 0,579), афективними (d = 4,580) та психомоторними (d = 4,294) показниками підсумкового тестування (усі $p < 0,05$). Результати MANOVA підтвердили статистично значущий одночасний вплив групового чинника на всі три сфери (Wilks' $\Lambda = 0,128$, $F = 131,68$, $p < 0,001$, $\eta^2 = 0,872$).

Висновки. Прогресивно структуроване втручання на основі GBL забезпечило статистично значуще кращі цілісні результати навчання пенчак силату порівняно з традиційним навчанням. Водночас надзвичайно великі величини ефекту для афективної та психомоторної сфер слід інтерпретувати з обережністю з огляду на використання рейтингових інструментів з обмеженим діапазоном оцінювання; вони радше свідчать про чітку перевагу запропонованого підходу, ніж про точну кількісну оцінку істинної величини ефекту.

Ключові слова: навчання на основі ігрового підходу, пенчак силат, фізичне виховання, когнітивні результати, афективні результати, психомоторні результати, навчання через ігри для розуміння.

Information about the Authors:

Nur Rohmah Muktiani: nur_rohmah@uny.ac.id; https://orcid.org/0009-0005-6465-688X; Department of Sport Education, Faculty of Sport and Health Science, Universitas Negeri Yogyakarta, Jl. Colombo No. 1, Depok, Sleman, Yogyakarta 55281, Indonesia.

Saryono: saryono@uny.ac.id; https://orcid.org/0009-0006-9812-2349; Department of Sport Education, Faculty of Sport and Health Science, Universitas Negeri Yogyakarta, Jl. Colombo No. 1, Depok, Sleman, Yogyakarta 55281, Indonesia.

Antoni, Muhammad Sigit: sigitantoni@uny.ac.id; https://orcid.org/0000-0002-0944-6987; Department of Sport Education, Faculty of Sport and Health Science, Universitas Negeri Yogyakarta, Jl. Colombo No. 1, Depok, Sleman, Yogyakarta 55281, Indonesia.

Virama, La Ode Adhi: laodeadhivirama@iainkendari.ac.id; https://orcid.org/0000-0002-5081-1026; Faculty of Tarbiyah and Teacher Training, Institut Agama Islam Negeri Kendari, Jl. Sultan Qaimuddin No. 17, Kendari, Southeast Sulawesi 93116, Indonesia.

Yudhistira, Dewangga: dewanggayudhistira@unesa.ac.id; https://orcid.org/0000-0002-4194-1283; Department of Sport Coaching Education, Faculty of Sport and Health Science, Universitas Negeri Surabaya, Jl. Lidah Wetan, Surabaya, East Java 60213, Indonesia.

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Translation and Psychometric Validation of the Arabic Version of the Situational Motivation Scale (SIMS) in the Physical Education Context

Majdi Bouazizi[1,2ABCD], Mohamed Baaziz[2,3ABCD], Zainab Helmi Abumuaili[4ACD] and Foued Cheour[1AD]

[1]Virtual University of Tunis
[2]University of Gafsa
[3]University of Manouba
[4]University of Jordan

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

Corresponding Author: Majdi Bouazizi, e-mail: majdibouazizi4@gmail.com
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Abstract

Objectives. To translate and validate the Arabic version of the Situational Motivation Scale (SIMS) and evaluate its psychometric properties among Tunisian secondary school students in the physical education context.

Materials and Methods. A total of 580 secondary school students (mean age = 17.48 ± 1.46 years) from different regions of Tunisia participated in the study. The original SIMS comprises 16 items assessing intrinsic motivation, identified regulation, external regulation, and amotivation. Students completed the Arabic version of the scale during physical education classes. Exploratory factor analysis (EFA) was performed on a randomly selected subsample of 290 participants, whereas confirmatory factor analysis (CFA) was conducted on an independent subsample of 290 participants. Internal consistency, test–retest reliability, construct validity, convergent validity, and composite reliability were evaluated.

Results. One amotivation item demonstrated a factor loading below the 0.40 criterion and was removed, resulting in the SIMS-15. The revised scale demonstrated good internal consistency (Cronbach's $\alpha = 0.846$, McDonald's $\omega = 0.788$, Guttman's $\lambda^2 = 0.883$) and excellent temporal stability over a two-week interval (ICC = 0.950, 95% CI = 0.901–0.975; $r = 0.905$, 95% CI = 0.818–0.951, $p < 0.001$). CFA confirmed the four-factor structure of the SIMS-15 ($\chi^2/df = 1.542$, CFI = 0.99, GFI = 0.94, RMSEA = 0.04). Average variance extracted ranged from 0.708 to 0.864, whereas composite reliability ranged from 0.877 to 0.962, indicating satisfactory convergent validity and reliability.

Conclusions. The Arabic SIMS-15 demonstrated satisfactory reliability and validity and can be recommended as a psychometrically sound instrument for assessing situational motivation among secondary school students in physical education. The adapted scale preserves the original four-factor structure while providing evidence of its suitability for use in Arabic-speaking educational settings.

Keywords: psychometric properties, situational motivation, Arabic language, transcultural validation, physical education.

Introduction

Motivation is a central psychological construct that influences students' engagement, persistence, and learning outcomes, particularly in physical education and sports contexts (Curran & Standage, 2017; Zhou et al., 2025; Alixanov et al., 2026). It can be intrinsic, arising from inherent interest or personal value, or extrinsic, driven by external rewards or pressures. AM reflects a lack of intentionality or perceived competence (Deci & Ryan, 2000; Guay et al., 2000). Educators and coaches play a critical role in shaping motivational states by providing autonomy-supportive environments, constructive feedback, and fostering relatedness, which enhances engagement and IM.

PETM
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In contrast, controlling approaches may hinder motivation (Haerens et al., 2015; Taylor et al., 2008).

Self-determination theory offers a robust framework for understanding motivation, emphasizing the satisfaction of three basic psychological needs: autonomy, competence, and relatedness, which are essential for fostering IM and psychological well-being (Ryan & Deci, 2023; Vansteenkiste & Ryan, 2013). Self-determination theory conceptualizes motivation along a continuum from AM, through various forms of extrinsic motivation, to IM, with greater internalization marking more autonomous engagement (Vallerand, 1997; Ryan & Deci, 2000a; Rusmitaningsih et al., 2026). Within this framework, motivation operates at three levels: global, contextual, and situational, the latter referring to the "here and now" motivation experienced during a specific activity (Törmänen et al., 2025; Vallerand, 2001). Situational motivation is influenced by environmental factors such as pedagogical practices and social interactions, making it a dynamic determinant of students' behavioral, cognitive, and affective engagement (Ghazvini et al., 2025; Järvenoja et al., 2023).

Reliable measurement of situational motivation is essential for research and practice. The SIMS, developed by Guay et al. (2000), assesses IM, IR, ER, and AM. The SIMS has demonstrated strong reliability and validity across educational and sports contexts, linking motivational profiles to engagement, persistence, and physical activity participation (Hassani et al., 2024; Rodrigues et al., 2023; Grao-Crucesa et al., 2018). Despite its widespread use, no culturally adapted or psychometrically validated Arabic version exists, limiting the assessment of situational motivation in Arabic-speaking physical education contexts (Curran & Standage, 2017; Ryan & Deci, 2023).

This study aimed to address this gap by translating the SIMS into Arabic and evaluating its psychometric properties among secondary school students in physical education. Specifically, it seeks to confirm the factorial structure, assess reliability, and verify the suitability of the scale for future research and practical applications. Establishing a valid and reliable Arabic SIMS will enable educators and researchers to better understand the motivational processes and design interventions that foster autonomy, engagement, and sustained participation in physical activity.

Materials and Methods

Participants

A total of 580 students (296 men = 51.03%; 284 women = 48.97%; mean age = 17.48 ± 1.46 years; range 15-21 years) from secondary education classes participated voluntarily in this study. Regarding geographical distribution, participants were recruited from different regions of Tunisia: the north (199 = 34.31%), center (193 = 33.27%), and south (188 = 32.41%).

Two different populations were recruited for exploratory and confirmatory studies. The exploratory data were gathered from 290 students who were randomly chosen based on the data. The subjects were students of both sexes, with men (n = 147; 50.69%) and women (n = 143; 49.31%). Confirmatory data were collected from 290 students (149 men = 51.38%; 141 women = 48.62%). Parental consent was obtained for all participants aged < 18 years. In total, 600 questionnaires were distributed, and 580 valid responses were retained for analysis after excluding 20 due to missing data.

Measures

Situational motivation was assessed using the SIMS (Guay et al., 2000), which originally consists of 16 items measuring state motivation toward a specific activity. The SIMS has demonstrated internal consistency coefficients ranging from 0.77 to 0.95. Each item addresses the question, "Why did you engage in this activity?" and is organized into four subscales: IM (4 items; e.g., "Because I think that this activity is interesting"), IR (4 items; e.g., "Because I think that this activity is good for me"), ER (4 items; e.g., "Because I don't have any choice"), and AM (4 items; e.g., "There may be good reasons to do this activity, but personally I don't see any"). Responses were rated on a 7-point Likert scale ranging from 1 (does not correspond at all) to 7 (corresponds exactly), with 4 indicating moderate correspondence. In the original SIMS-16, subscale scores are obtained by summing the relevant items, yielding scores from 4 to 28 for each four-item dimension. In the retained Arabic SIMS-15, after the exclusion of item 4 from the AM subscale, the IM, IR, and ER subscales each retain four items and therefore range from 4 to 28, whereas the AM subscale includes three items and ranges from 3 to 21.

Procedure

The SIMS was translated into Arabic following a standardized back-translation procedure commonly applied in cross-cultural research (Núñez Alonso et al., 2005; Núñez et al., 2006; Vallerand et al., 1989). First, a bilingual expert translated the original English version into Arabic. A second independent bilingual translator, blinded to the original, back-translated the scale into English. This process was repeated twice to ensure accuracy and to minimize bias. A panel of four bilingual translators and two psychologists with expertise in motivation research then reviewed and refined the translated version, resulting in the final Arabic version of the SIMS.

Data were collected immediately after the physical education classes. Students were informed that their participation was voluntary and anonymous, and they were instructed to read each item carefully, respond honestly, and complete all the questions. No time limit was imposed, and students were permitted to ask clarification questions if necessary. Written parental consent was obtained for all underage participants, and the protocol was approved by the local ethics committee. All procedures were conducted in accordance with the ethical standards of the institutional and national research committees and the 1964 Helsinki Declaration and its later amendments.

Statistical Analysis

Data analyses were performed using JASP (version 0.19.3.0) and the Statistical Package for Social Sciences (SPSS and AMOS; version 28, IBM, Armonk, NY, USA). Descriptive statistics (means, standard deviations, skewness, and kurtosis) were computed to examine the distribution of the items. Data distribution was examined using kurtosis (Kr) and skewness (Sk). Kr values varied from -1.964 to 2.348, and Sk values ranged from -1.326 to 0.337 (Table 2).

Following established conventions, Sk and Kr values close to ±2 were interpreted as broadly compatible with approximately normal item distributions (López-Pina & Veas, 2024; Elliott & Woodward, 2007; Tabachnick et al., 2007).

The level of correlation between the students' answers was used to determine stability (Shrout & Fleiss, 1979). Test-retest reliability (bivariate correlations, intraclass correlation) was used to determine the SIMS-15's reliability. Cronbach's α, McDonald's ω, and Guttman's λ2 were used to assess the SIMS-15's internal reliability (Cronbach, 1951; McDonald, 1970; Raykov & Marcoulides, 2019). The level of inter-correlation between the scale items is indicated by internal consistency (Morrison et al., 2015). For these indices, a reliability criterion of 0.70 for acceptability and 0.80 for good reliability was recommended.

To ascertain the instrument's factor structure, an orthogonal Varimax-type EFA in accordance with the Varimax criterion of Kaiser (1958) with a principal component analysis was applied to the16 survey items of the scale (Everitt & Dunn, 2001). Items with a factor loading of 0.40 or less (Archer et al., 1997; Pett et al., 2003) were eliminated, and the Kaiser-Meyer-Olkin (KMO) statistic (Stafford & Bodson, 2006; Bartlett, 1950) was used to gauge the adequacy of the sample. The factor structure in the four SIMS dimensions was examined using a first-order CFA with maximum likelihood estimation. The following indices were highlighted to assess how well the models fit: the Not Normed Fit Index (NNFI) is based on the Tucker-Lewis Index, which was developed through factor analysis; an index value of 0.9 or above indicated a good or excellent fit for both indices (Bentler & Bonett, 1980). The Comparative Fit Index (CFI) is a normed fit index between 0 and 1, and the most widely accepted measure of good fit is a CFI ≥ 0.95 (Hu & Bentler, 1999). The Goodness of Fit Index (GFI) (Hooper et al., 2008) and Adjusted Goodness of Fit (AGFI) must be equal to or higher than 0.85 and 0.90, respectively (Schermelleh-Engel et al., 2003). According to Hu and Bentler (1998), a good fit for the Root Mean Square Error of Approximation (RMSEA) is defined as the Standardized Root Mean Square Residual (SRMR) being less than 0.08, the Parsimony Normed Fit Index (PNFI), and the Parsimony Comparative Fit Index (PCFI) greater than 0.5 (Hau, 2000). MacCallum et al. (1996) employed the frequently used χ 2 statistic (χ 2/df ratio of three or less) and chose 0.01, 0.05, and 0.08 to represent excellent, good, and mediocre fit, respectively. A non-significant value of χ 2 is required for the model fit of the retained data (Satorra & Bentler, 1994).

As a complementary validity check, the sensitivity analysis (ANOVA) was framed as an assessment of known-groups validity—that is, the ability of the SIMS-15 to detect theoretically expected score differences across contextually distinct subgroups (Terwee et al., 2007; Streiner et al., 2024). Geographic zone (northern, central, and southern Tunisia), gender, and their interaction were examined as grouping variables. Statistical significance was set at $p < 0.05$.

Results

Instrument Quality

The basic characteristics of the study sample are presented in Table 1.

Table 1. Basic characteristics of the sample population

Variable		Effective		Percentage (%)
Age	[15-17]	Total (N = 580)	299	51.55
		EFA (n = 290)	154	53.10
		CFA (n = 290)	145	50.00
		Test-retest (n = 35)	34	97.14
	[18-21]	Total (N = 580)	281	48.45
		EFA (n = 290)	136	46.90
		CFA (n = 290)	145	50.00
		Test-retest (n = 35)	1	2.86
Gender	Male	Total (N = 580)	296	51.03
		EFA (n = 290)	147	50.69
		CFA (n = 290)	149	51.38
		Test-retest (n = 35)	18	51.43
	Female	Total (N = 580)	284	48.97
		EFA (n = 290)	143	49.31
		CFA (n = 290)	141	48.62
		Test-retest (n = 35)	17	48.57
Region	North	Total (N = 580)	199	34.31
		EFA (n = 290)	101	34.83
		CFA (n = 290)	98	33.80
		Test-retest (n = 35)	13	37.14
	Center	Total (N = 580)	193	33.27
		EFA (n = 290)	94	32.41
		CFA (n = 290)	99	34.13
		Test-retest (n = 35)	11	31.43
	South	Total (N = 580)	188	32.41
		EFA (n = 290)	95	32.76
		CFA (n = 290)	93	32.07
		Test-retest (n = 35)	11	31.43

Note. EFA: exploratory factor analysis; CFA: confirmatory factor analysis.

The descriptive statistics (mean, standard deviation, skewness, and kurtosis) of the items included in this study are presented in Table 2. The data were normally distributed, based on the skewness and kurtosis values. The analysis of item 1 indicated a kurtosis value of 2.34, slightly exceeding the conventional normality threshold of ± 2. However, visual inspection of the corresponding Q-Q plot demonstrated adequate alignment with the expected normal distribution. Therefore, the assumption of normality for this item was acceptable for subsequent analyses.

For further analysis, Table 3 presents the means and standard deviations of the SIMS-15 subscales, categorized by geographical zone.

The SIMS was administered twice to the same sample, with a two-week interval, to evaluate its temporal stability through a test–retest reliability design. The sample was homogeneous in terms of gender and geographical region. A total of 35 students participated (mean age = 16.09 ± 0.78 years; 18 men, 51.43%; 17 women, 48.57%).

Table 2. Descriptive statistics and normality of the SIMS-15 (N = 290).

Item	M	SD	Sk	Kr (Zero Centered)
Item1	5.60	1.122	-1.326	2.348
Item5	5.58	1.135	-1.013	1.278
Item9	5.56	1.185	-0.776	0.449
Item13	5.51	1.352	-1.239	1.831
Item2	5.07	1.562	-0.833	-0.093
Item6	5.07	1.597	-0.848	0.032
Item10	5.03	1.684	-0.856	0.017
Item14	4.98	1.625	-0.752	-0.110
Item3	5.40	1.379	-0.994	0.553
Item7	5.52	1.308	-1.190	1.323
Item11	5.37	1.443	-1.090	0.791
Item15	5.52	1.334	-1.026	0.773
Item8	1.44	0.498	0.223	-1.964
Item12	1.80	0.732	0.337	-1.079
Item16	1.49	0.501	0.028	-2.013

Note. M: mean; SD: standard deviation; Sk: Skewness; Kr: Kurtosis.

Table 3. Distribution of SIMS-15 subscales across geographic zones.

Zone		IM	IR	ER	AM
Northern Tunisia	M	22.01	21.02	21.60	4.75
	SD	4.234	5.499	5.258	1.352
Central Tunisia	M	21.37	20.61	20.71	4.82
	SD	4.506	5.905	5.527	1.531
Southern Tunisia	M	23.38	18.80	23.12	4.63
	SD	3.594	6.555	3.992	1.422

Note. IM: intrinsic motivation; IR: identified regulation; ER: external regulation; AM: amotivation.

The results revealed a correlation coefficient of 0.905 ($p < 0.001$), indicating the satisfactory temporal stability of the SIMS. Because the bivariate correlation coefficient does not account for systematic differences, several authors have recommended using the intraclass correlation coefficient (ICC) as a more robust indicator of absolute agreement (Terwee et al., 2007). The sample size adequacy for the test-retest analysis was determined following the recommendations of Bujang and Baharum (2017); detecting an ICC of 0.50 at 80% power and an $\alpha = 0.05$ requires at least 22 participants. Considering an anticipated 20% attrition rate, the target sample was set at 27 participants, which was exceeded by our retest sample of 35 students.

Therefore, the inclusion of 35 participants in the retest phase was sufficient to confirm the instrument's temporal stability. The ICC obtained in this study was 0.950, which demonstrated excellent reliability. Table 4 presents the test–retest reliability results derived from the correlations between the two SIMS administrations.

Table 4. Test-retest reliability of the SIMS (n = 35).

Variable	Test-retest reliability	
	Bivariate correlations	Intra-class correlation
SIMS-15	0.905***	0.950
CI 95%	0.818-0.951	0.901-0.975

Note. CI: confidence interval; *** statistically significant at $p < 0.001$

An important overview of the internal structure of the SIMS, including its four hypothesized dimensions—IM (items 1, 5, 9, and 13), IR (items 2, 6, 10, and 14), ER (items 3, 7, 11, and 15), and AM (items 8, 12, and 16)—can be obtained by examining the inter-item correlation matrix presented in Table 5.

The analysis revealed a clear tendency toward strong positive correlations among items intended to measure the same underlying construct. Notably, the correlations between the IM items were high (e.g., r = 0.721 between items 1 and 9; r = 0.799 between items 5 and 9). Similarly, strong correlations, sometimes exceeding 0.850, were observed among the IR items (e.g., r = 0.870 between items 6 and 10; r = 0.894 between items 6 and 14). The ER dimension also showed substantial inter-item correlations (e.g., r = 0.828 between items 7 and 15; r = 0.774 between items 7 and 11), and comparable patterns emerged among the AM items (e.g., r = 0.824 between items 8 and 16).

Conversely, correlations between items belonging to different dimensions were markedly lower—for example, between IM and IR items (r = 0.129 between items 9 and 10; r = 0.142 between items 5 and 6), IM and AM items (r = 0.048 between items 5 and 8; r = −0.035 between items 13 and 12), and other cross-dimensional pairs.

In summary, the strong within-dimension correlations support the internal consistency of each subscale, indicating that the items measure the same underlying construct. Meanwhile, the weak correlations between dimensions provide evidence of discriminant validity, confirming that the SIMS-15 subscales—IM, IR, ER, and AM—represent distinct, yet theoretically related, motivational constructs. These findings suggest that the scale possesses a clear and stable four-factor structure (Field, 2024; Tavakol & Dennick, 2011), which is consistent with previous research (Elliott & Woodward, 2007; Tabachnick et al., 2007; Terwee et al., 2007).

Exploratory factor analysis

The internal reliability of the Arabic version of the SIMS-15 was assessed using McDonald's omega, Cronbach's alpha, and Guttman's λ^2. The scale demonstrated good internal consistency ($\omega = 0.788$, 95% CI = 0.753–0.824; $\alpha = 0.846$, 95% CI = 0.815–0.877; $\lambda^2 = 0.883$, 95% CI = 0.862–0.905). As indicated in Table 6, McDonald's omega is considered a superior indicator of reliability (Béland et al., 2017). Reliability coefficients above 0.60 are generally regarded as acceptable (Béland et al., 2017; Taber, 2018). Overall, the results confirm that the SIMS-15 exhibits high internal reliability and accurately reflects its theoretical construct.

Item 4 of the original SIMS-16, which belongs to the AM subscale ("There may be good reasons for doing this activity,

Table 5. Inter-item correlation matrix coefficients for the SIMS-15 Items (N = 290)

Item	Item1	Item5	Item9	Item13	Item2	Item6	Item10	Item14	Item3	Item7	Item11	Item15	Item8	Item12	Item16
Item1	1.000														
Item5	0.708	1.000													
Item9	0.721	0.799	1.000												
Item13	0.703	0.603	0.623	1.000											
Item2	0.100	0.159	0.167	0.184	1.000										
Item6	0.129	0.142	0.175	0.182	0.816	1.000									
Item10	0.148	0.103	0.129	0.240	0.754	0.870	1.000								
Item14	0.167	0.159	0.199	0.217	0.816	0.894	0.845	1.000							
item3	0.410	0.346	0.325	0.441	0.179	0.154	0.156	0.137	1.000						
Item7	0.371	0.317	0.305	0.399	0.164	0.120	0.124	0.118	0.863	1.000					
Item11	0.367	0.280	0.274	0.361	0.080	0.055	0.056	0.071	0.766	0.774	1.000				
Item15	0.426	0.308	0.319	0.397	0.090	0.076	0.083	0.076	0.859	0.828	0.765	1.000			
Item8	0.059	0.048	0.052	0.032	0.039	0.044	0.048	0.069	0.032	0.004	-0.027	0.020	1.000		
Item12	-0.074	-0.090	-0.092	-0.035	-0.081	-0.089	-0.039	-0.079	-0.046	-0.037	-0.040	-0.072	0.439	1.000	
Item16	0.051	0.047	0.018	0.041	0.056	0.053	0.066	0.083	-0.011	-0.039	-0.047	-0.033	0.824	0.388	1.000

Table 6. Internal consistency of the Arabic version of the SIMS-15 (N = 290)

Scale	McDonald's omega	Cronbach alpha	Guttman's lambda-2
SIMS-15	0.788	0.846	0.883
CI 95%	0.753-0.824	0.815-0.877	0.862-0.905

Note. CI: confidence interval

but personally, I don't see any"), was excluded because its factor loading was below the 0.40 retention threshold (Archer et al., 1997). In cross-cultural psychometric adaptation, removing items with low discriminatory capacity is an accepted procedure when it improves factorial clarity and preserves the coherence of the construct (Beaton et al., 2000). The resulting 15-item scale (SIMS-15) retains three AM items (items 8, 12, and 16), which is sufficient for structural identification in confirmatory models (Kline, 2023). This three-item AM structure also showed strong convergent validity, with AVE (0.708) and CR (0.877) values above recommended thresholds (Fornell & Larcker, 1981), supporting a coherent latent construct.

The analysis identified four distinct factors, each with eigenvalues surpassing the thresholds recommended by Cattell (1966) and Kaiser (1960). Sampling adequacy was confirmed using the KMO statistic (KMO = 0.838) and Bartlett's test of sphericity ($p < 0.001$). Together, these factors explained 81.32% of total variance. The factor loadings for the four-factor model ranged from 0.679 to 0.954, as detailed in Table 7.

Confirmatory factor analysis

The CFA indicated a good model fit, as suggested by Wheaton et al. (1977), Hermann (1980), and Tabachnick et al. (2007). In addition to the chi-square (χ^2) and normalized chi-square (χ^2/df), several fit indices were evaluated, including AGFI, GFI, CFI, TLI (NNFI), NFI, PNFI, PCFI, RMSEA, and SRMR. The critical cutoff values for AGFI, GFI, NFI, CFI, and TLI are recommended to exceed 0.95 (Tabachnick et al., 2007; Fan et al., 1999)2007; Fan et al., 1999, whereas RMSEA and SRMR values should be below 0.05 and 0.08, respectively, for an acceptable fit (MacCallum et al., 1996; Jöreskog & Sörbom, 1996; Byrne, 2013).

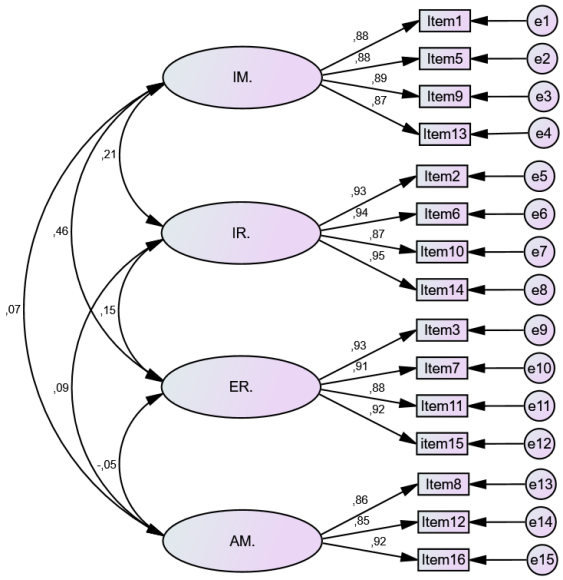

Fig 1. Standardized results of the confirmatory factor analysis for the Arabic version of the SIMS-15 (N = 290). Note. IM: Intrinsic Motivation; IR: Identified Regulation; ER: External Regulation; AM: Amotivation

The CFA results for the four-factor SIMS-15 model were as follows: χ^2/df = 1.542, df = 84, $p < 0.001$; NFI = 0.97; TLI = 0.98; IFI = CFI = 0.99; PNFI = 0.77; PCFI = 0.80; GFI = 0.94; AGFI = 0.92; SRMR = 0.02; RMSEA = 0.04 (90%

Table 7. Standardized factor loadings for the SIMS-15

	SIMS items	Components			
	1	2	3	4	
Item1	لأنني أعتقد أن هذا النشاط مثير للاهتمام. Because I think that this activity is interesting.			0.855	
Item5	لأنني أعتقد أن هذا النشاط ممتع. Because I think that this activity is pleasant.			0.884	
Item9	لأن هذا النشاط ممتع. Because this activity is fun.			0.893	
Item13	لأنني أشعر بالرضا عندما أقوم بهذا النشاط. Because I feel good when doing this activity.			0.761	
Item2	لأنني أقوم بذلك لصالحي الشخصي. Because I am doing it for my own good.	0.898			
Item6	لأنني أعتقد أن هذا النشاط مفيد لي. Because I think that this activity is good for me.	0.954			
Item10	بقرار شخصي. By personal decision.	0.923			
Item14	لأنني أؤمن بأن هذا النشاط مهم بالنسبة لي. Because I believe that this activity is important for me.	0.943			
Item3	لأن من المفترض أن أقوم بذلك. Because I am supposed to do it.		0.911		
Item7	لأن هي شيء يجب عليّ القيام به. Because it is something that I have to do.		0.914		
Item11	لأنني لا أملك أي خيار. Because I don't have any choice.		0.875		
Item15	لأنني أشعر أن من يجب عليّ القيام به. Because I feel that I have to do it.		0.907		
Item8	أقوم بهذا النشاط ولكنني لست متأكد إذا ما كان يستحق ذلك. do this activity but I am not sure if it is worth it.				0.921
Item12	لا أعرف، لا أرى ما يجلبه هذا النشاط لي. I don't know; I don't see what this activity brings me.				0.679
Item16	أقوم بهذا النشاط، ولكنني لست متأكد من أن هي شيء جيد أن أستمر فيه. I do this activity, but I am not sure it is a good thing to pursue it.				0.902

Table 8. Summary of fit indices for the SIMS-15 confirmatory factor analysis models (N = 290)

Model	χ^2/df	AGFI	GFI	NFI	TLI	IFI = CFI	PNFI	PCFI	RMSEA (CI 95%)	SRMR
SIMS-15	1.542	0.92	0.94	0.97	0.98	0.99	0.77	0.80	0.04 (0.02-0.05)	0.02

Note. χ^2/df: relative chi-square; AGFI: Adjusted Goodness of Fit Index; GFI: Goodness of Fit Index; NFI: Normed Fit Index; IFI: Incremental Fit Index; TLI: Tucker-Lewis Index; CFI: Comparative Fit Index; PNFI: Parsimony Normed Fit Index; PCFI: Parsimony Comparative Fit Index; SRMR: Standardized Root Mean Square Residual; RMSEA: Root Mean Square Error of Approximation; CI: Confidence Interval.

CI = 0.02–0.05). The AGFI and GFI exceeded 0.92, while the CFI, NFI, and TLI were above 0.98, indicating an overall satisfactory fit. The PCFI and PNFI values were higher than 0.77. Both the SRMR and RMSEA indicated an excellent fit, remaining below 0.02 and 0.04, respectively.

These results demonstrate that the Arabic version of the SIMS-15 four-factor model exhibited excellent fit indices, confirming the scale's construct validity (Table 8).

The four-factor structure of the SIMS-15 was confirmed for a sample of Tunisian secondary school students, demonstrating an excellent fit to the proposed theoretical model across all examined indices (Figure 1).

Average variance extracted (AVE) and composite reliability (CR) coefficients

To assess convergent validity, factor loadings for each item, along with the corresponding AVE and CR values, were calculated (Hair et al., 2013). The AVE provides a summary measure of convergence among items that represent a latent construct (Fornell & Larcker, 1981). Both the AVE and CR ranged between 0 and 1, with higher values indicating greater reliability. AVE is mathematically expressed as the sum of squared factor loadings divided by the number of items: $AVE = \Sigma\lambda^2/n$.

CR quantifies the internal consistency among scale items (Netemeyer et al., 2003) and represents the shared variance between the observed indicators of a latent construct (Fornell & Larcker, 1981). It is computed as:

$CR = \Sigma \lambda^2 / [(\Sigma\lambda^2 + \Sigma(1-\lambda^2)]$

CR values between 0.6 and 0.7 are generally acceptable, whereas values above 0.7 are preferred in advanced research settings. According to Fornell and Larcker (1981), convergent validity remains acceptable if the AVE falls below 0.5 and the CR exceeds 0.6. A measurement model is considered reliable when the CR exceeds 0.7 (Hair et al., 2019).

In the present study, the AVE values were 0.722 for IM, 0.864 for IR, 0.813 for ER, and 0.708 for AM (Table 9). These values exceeded the recommended thresholds, indicating that the majority of the variance in the items was attributable to the underlying constructs rather than measurement error.

Table 9. The average variance extracted and composite reliability for each subscale of the SIMS-15

Dimension	AVE	CR
Intrinsic motivation	0.722	0.912
Identified regulation	0.864	0.962
External regulation	0.813	0.945
Amotivation	0.708	0.877

Note. AVE: Average Variance Extracted; CR: Composite Reliability.

Sensitivity analysis

The sensitivity analysis assessed the ability of the SIMS-15 to discriminate between theoretically distinct subgroups, thereby providing evidence of known-groups validity within the broader construct-validation framework (Terwee et al., 2007). The MANOVA showed a significant multivariate effect of region on the SIMS dimensions, Pillai's Trace = 0.098, $F_{(8, 564)} = 3.620$, $p < 0.001$. In contrast, neither gender, Pillai's Trace = 0.004, $F_{(4, 281)} = 0.295$, $p = 0.881$, nor the Region × Gender interaction, Pillai's Trace = 0.001, $F_{(8, 564)} = 0.051$, $p = 1.000$, reached statistical significance.

Follow-up univariate analyses indicated significant regional effects for IM, $F_{(2, 284)} = 5.821$, $p = 0.003$, $\eta p^2 = 0.039$, 95% CI [0.005, 0.088]; IR, $F_{(2, 284)} = 3.698$, $p = 0.026$, $\eta p^2 = 0.025$, 95% CI [0.000, 0.067]; and ER, $F_{(2, 284)} = 5.613$, $p = 0.004$, $\eta p^2 = 0.038$, 95% CI [0.004, 0.086]. No significant regional effect was observed for AM, $F_{(2, 284)} = 0.405$, $p = 0.667$, $\eta p^2 = 0.003$, 95% CI [0.000, 0.021] (Table 10).

Descriptively, students from Southern Tunisia reported the highest scores for IM (M = 23.38) and ER (M = 23.12), whereas students from Northern Tunisia showed the highest mean score for IR (M = 21.02). AM scores were low and relatively similar across the three regions (Table 3). Overall, regional differences were statistically significant for IM, IR, and ER, but the effect sizes were small, indicating that region explained only a modest proportion of variance in these motivational dimensions. No meaningful effect of gender or Region × Gender interaction was found across the four SIMS subscales.

Discussion

The purpose of motivational pedagogy is to enhance students' IM to learn by employing effective instructional strategies and supportive practices. This pedagogical approach is grounded in the belief that motivation constitutes a central component of learning and that teachers can substantially influence students' engagement and academic success by creating a classroom environment that nurtures motivation (Ryan & Deci, 2000b; Stipek, 2002). Accordingly, the present study aimed to translate the SIMS into Arabic and validate its psychometric properties by examining its internal consistency and factorial structure. The findings revealed that the Arabic version of the SIMS-15 demonstrated strong psychometric soundness and is suitable for use in physical education contexts. These outcomes are consistent with those of prior validation studies in both the academic and physical activity domains (Guay et al., 2000; Hassani et al., 2024; Gamboa et al., 2017; Martin-Albo et al., 2009; Wasicek & McHugh, 2024; Muniandy et al., 2023; Standage et al., 2003).

Both exploratory and confirmatory analyses provided strong evidence supporting the factorial validity of SIMS-15. The CFA confirmed the four-factor structure—IM, IR, ER, and AM—in line with the self-determination theory (Deci & Ryan, 1985). This structure replicates the findings of prior validation studies across educational and physical activity settings (Guay et al., 2000; Hassani et al., 2024; Martin-Albo et al., 2009; Østerlie et al., 2019). The sample's adequacy for factor analysis was verified using a robust KMO value of

Table 10. Effects of region, gender, and their interaction on the SIMS-15 dimensions.

Effect	IM	IR	ER	AM
Region	$F(2, 284) = 5.821^{**}$ $\eta p^2 = 0.039$ 95% CI [0.005, 0.088]	$F(2, 284) = 3.698^{*}$ $\eta p^2 = 0.025$ 95% CI [0.000, 0.067]	$F(2, 284) = 5.613^{**}$ $\eta p^2 = 0.038$ 95% CI [0.004, 0.086]	$F(2, 284) = 0.405$ $\eta p^2 = 0.003$ 95% CI [0.000, 0.021]
Gender	$F(1, 284) = 0.466$ $\eta p^2 = 0.002$ 95% CI [0.000, 0.024]	$F(1, 284) = 0.038$ $\eta p^2 < 0.001$ 95% CI [0.000, 0.013]	$F(1, 284) = 0.280$ $\eta p^2 = 0.001$ 95% CI [0.000, 0.021]	$F(1, 284) = 0.641$ $\eta p^2 = 0.002$ 95% CI [0.000, 0.026]
Region × Gender	$F(2, 284) = 0.046$ $\eta p^2 < 0.001$ 95% CI [0.000, 0.004]	$F(2, 284) = 0.002$ $\eta p^2 < 0.001$ 95% CI [0.000, 0.000]	$F(2, 284) = 0.079$ $\eta p^2 = 0.001$ 95% CI [0.000, 0.008]	$F(2, 284) = 0.057$ $\eta p^2 < 0.001$ 95% CI [0.000, 0.006]

Note. IM: intrinsic motivation; IR: identified regulation; ER: external regulation; AM: amotivation. ηp^2: partial eta squared. **: $p < 0.01$; *: $p < 0.05$. The 95% confidence intervals for ηp^2 were estimated from the F statistics using the noncentral F-distribution approach (Lakens, 2013).

0.838 and a highly significant Bartlett's test of sphericity ($p < 0.001$). The factor loadings ranged from 0.679 to 0.954, indicating clear item–factor relationships (Tabachnick et al., 2007; Hayton et al., 2004). The CFA yielded excellent model-fit indices ($\chi^2/df = 1.542$, CFI = 0.99, TLI = 0.98, SRMR = 0.02, RMSEA = 0.04), satisfying the stringent criteria for a well-fitting model (Hu & Bentler, 1999; Schermelleh-Engel et al., 2003). The SIMS-15 demonstrated excellent convergent validity. Within each subscale, inter-item correlations were strong, while correlations across subscales were notably weaker, indicating that the four dimensions assess distinct yet conceptually related constructs (Floyd & Widaman, 1995; Tabachnick & Fidell, 2013). AVE values ranged from 0.708 to 0.864, well above the recommended threshold of 0.50, and the CR values ranged from 0.877 to 0.962, exceeding the 0.70 benchmark (Fornell & Larcker, 1981; Hair et al., 2019).

The transition from the original 16-item scale to the Arabic SIMS-15 preserves conceptual equivalence and remains aligned with self-determination theory (Deci & Ryan, 2000). Item 4 captures a meta-cognitive facet of AM, in which students acknowledge that reasons for engagement may exist while personally failing to see their relevance. This formulation likely created psycholinguistic and cultural interpretation difficulties among Tunisian students (Beaton et al., 2000). Thus, the weak loading appears to reflect cultural specificity rather than a weakness in the AM construct itself, a pattern also reported in non-Western adaptations of self-determination theory instruments (Hassani et al., 2024). Importantly, the three retained AM items (8, 12, and 16) still capture the definitional core of AM, including lack of intentionality and low perceived outcome contingency. With three indicators, the AM factor remains structurally identifiable and psychometrically stable (Kline, 2023). Consequently, the four-factor motivational continuum of the original SIMS (Guay et al., 2000) is retained while the Arabic version shows clearer factorial performance in this educational context.

The Arabic version of the SIMS-15 exhibited high internal consistency and temporal stability. Reliability indices were robust, with Cronbach's alpha (0.846), McDonald's omega (0.788), and Guttman's λ^2 (0.883) all exceeding recommended thresholds (Cronbach, 1951; Tavakol & Dennick, 2011). Test–retest reliability over a two-week interval among 35 participants yielded a Pearson correlation of 0.905 and an ICC of 0.950, confirming strong stability over time (Shrout & Fleiss, 1979; Bujang & Baharum, 2017). These findings indicate that the SIMS-15 provides consistent measurements suitable for both longitudinal and cross-sectional applications. From a psychometric standpoint, the sensitivity analysis provides evidence of known-groups validity: significant zone effects on IM, IR, and ER show that the SIMS-15 is sensitive to contextual variation in motivational profiles. The absence of significant gender-related effects offers preliminary evidence of cross-group consistency, although formal invariance testing is still required, as noted in the Limitations section. The absence of a zone effect for AM probably reflects floor-level scores in this sample, which limited between-group variability (Terwee et al., 2007).

The replication of the SIMS four-factor structure in an Arabic-speaking North African context provides cross-cultural support for the self-determination theory motivational continuum (Ryan & Deci, 2023; Chirkov et al., 2003). Several cultural features of the Tunisian educational context may help explain the factor solution. The strong coherence of the IR and ER subscales (AVE = 0.864 and 0.813, respectively) may reflect the salience of both internalized value and social obligation as distinct motivational forces in a broadly collectivist setting. This interpretation is consistent with cross-cultural self-determination theory research showing that autonomous and controlled motivations remain structurally distinguishable in collectivist societies (Chirkov et al., 2003; Vansteenkiste et al., 2006). In addition, the uniformly low AM scores may partly reflect social desirability tendencies in a compulsory school activity, as students may be less inclined to endorse a complete absence of motivation (Markus & Kitayama, 1991). Finally, the psycholinguistic distance between Modern Standard Arabic and the Tunisian vernacular (Darija) may have contributed to differential item comprehension, particularly for item 4. Future adaptations should therefore consider register-sensitive formulations for Maghrebi Arabic populations.

Limitations

This study had several limitations that warrant consideration. First, the sample consisted solely of secondary education students; thus, future research should include participants from different educational levels and institutions. Second, the sample was limited to Tunisian students, which restricts the generalizability of the findings to broader Arabic-speaking populations. Third, the SIMS does not include all types of motivational regulation described in self-determination theory; specifically, integrated and introjected regulations are absent. Future studies should examine whether including these dimensions enhances the understanding of situational motivation. Fourth, although the exclusion of item 4 from the AM subscale was psychometrically justified and preserved the theoretical continuum, the resulting three-item subscale provides slightly narrower coverage of the AM facet originally conceptualized by Guay et al. (2000). Future research should develop and validate a culturally and linguistically appropriate replacement item to capture this specific meta-cognitive dimension of AM in Arabic-speaking educational contexts. Fifth, the present study did not conduct formal measurement invariance testing across gender and age groups. Without establishing at least configural and metric invariance through multi-group CFA (Vandenberg & Lance, 2000; Putnick & Bornstein, 2016), ANOVA-based group comparisons should be interpreted cautiously, because observed score differences may partly reflect measurement non-equivalence rather than true latent mean differences. Future studies should systematically test the measurement equivalence of the Arabic SIMS-15 across gender, age, and regional subgroups. Finally, future investigations should also consider additional cognitive and affective correlates of motivation, as well as contextual antecedents such as perceived competence and motivational climate.

Conclusion

This study assessed the psychometric properties of the Arabic version of the SIMS-15 among secondary school

students in physical education. Results indicated strong construct validity, excellent internal consistency, and temporal stability. After the removal of one item, the 15-item model demonstrated superior fit and reliability. Hence, the Arabic SIMS-15 can be considered a reliable and valid tool for assessing situational motivation among Arabic-speaking students. Its brevity, clarity, and practicality make it particularly suitable for educational settings. Future work should explore how this instrument can support the design of motivational learning environments that foster students' self-determination and engagement in physical education.

Ethical Approval

This study was approved by the local ethics committee (approval obtained prior to data collection) and conducted in full accordance with the 1964 Declaration of Helsinki and its later amendments. Informed consent was obtained from all participants or their legal guardians.

Data Availability Statement

The data that supports the findings of this study 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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Conflicts of Interest

The authors declare no conflicts of interest.

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Переклад та психометрична валідизація арабської версії Шкали ситуативної мотивації в контексті фізичного виховання

Маджді Буазізі[1,2ABCD], Мохамед Баазіз[2,3ABCD], Зейнаб Хельмі Абумуаїлі[4ACD], Фуед Шеур[1AD]

[1]Віртуальний університет Тунісу
[2]Університет Гафси
[3] Університет Мануби
[4]Йорданський університет

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

Реферат. Стаття: 13 с., 10 табл., 1 рис., 82 джерела.

Мета. Перекласти та валідизувати арабську версію Шкали ситуативної мотивації (Situational Motivation Scale, SIMS), а також оцінити її психометричні властивості серед учнів закладів загальної середньої освіти Тунісу в контексті фізичного виховання.

Матеріали та методи. У дослідженні взяли участь 580 учнів закладів загальної середньої освіти (середній вік = 17,48 ± 1,46 року) з різних регіонів Тунісу. Оригінальна версія SIMS містить 16 пунктів, що оцінюють внутрішню мотивацію, ідентифіковану регуляцію, зовнішню регуляцію та амотивацію. Під час уроків фізичного виховання учні заповнювали арабську версію шкали. Пошуковий факторний аналіз (EFA) було проведено на випадково відібраній підвибірці з 290 учасників, тоді як підтверджувальний факторний аналіз (CFA) виконано на незалежній підвибірці з 290 учасників. Оцінювали внутрішню узгодженість, тест-ретестову надійність, конструктивну валідність, конвергентну валідність і композитну надійність.

Результати. Один пункт субшкали амотивації продемонстрував факторне навантаження нижче критеріального значення 0,40 і був вилучений, унаслідок чого сформовано версію SIMS-15. Переглянута шкала продемонструвала добру внутрішню узгодженість (α Кронбаха = 0,846; ω Макдональда = 0,788; λ2 Гуттмана = 0,883) та відмінну часову стабільність упродовж двотижневого інтервалу (ICC = 0,950; 95% ДІ = 0,901–0,975; r = 0,905; 95% ДІ = 0,818–0,951; p < 0,001). Підтверджувальний факторний аналіз засвідчив чотирифакторну структуру SIMS-15 (χ^2/df = 1,542; CFI = 0,99; GFI = 0,94; RMSEA = 0,04). Середня вилучена дисперсія (AVE) становила від 0,708 до 0,864, тоді як композитна надійність (CR) — від 0,877 до 0,962, що свідчить про задовільну конвергентну валідність і надійність.

Висновки. Арабська версія SIMS-15 продемонструвала задовільні показники надійності та валідності й може бути рекомендована як психометрично обґрунтований інструмент для оцінювання ситуативної мотивації учнів закладів загальної середньої освіти на уроках фізичного виховання. Адаптована шкала зберігає оригінальну чотирифакторну структуру та підтверджує свою придатність для використання в арабомовному освітньому середовищі.

Ключові слова: психометричні властивості, ситуативна мотивація, арабська мова, транскультурна валідизація, фізичне виховання.

Information about the Authors:

Bouazizi, Majdi: majdibouazizi4@gmail.com; https://orcid.org/0000-0002-2117-8997; High Institute of Education and Continuing Training of Tunis, Virtual University of Tunis, Tunis, Tunisia; High Institute of Sport and Physical Education of Gafsa, University of Gafsa, Gafsa, Tunisia.

Mohamed, Baaziz: baazizmohamed420@gmail.com; https://orcid.org/0000-0001-7822-2015; High Institute of Sport and Physical Education of Gafsa, University of Gafsa, Gafsa, Tunisia; Higher Institute of Sport and physical education of Ksar Said, University of Manouba, Tunis, Tunisia.

Helmi Abumuaili, Zainab: Zainab.helmy2010@gmail.com; https://orcid.org/0000-0002-4765-842X; School of Sport Sciences, University of Jordan, Amman, Jordan.

Cheour, Foued: fouedcheour@yahoo.fr; https://orcid.org/0000-0002-1763-5016; High Institute of Education and Continuing Training of Tunis, Virtual University of Tunis,Tunis, Tunisia.

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An Investigation into the Biomechanical Role of Peak Pelvic Rotation in Golf Swing

Minh Hieu Vo[1ACD], Thi Tham Nguyen[2AD] and Ngoc Tuyet Minh Cao[1BCD]

[1]Ton Duc Thang University
[2]Ho Chi Minh City University of Physical Education and Sport

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Corresponding Author: Minh Hieu Vo, e-mail: vominhhieu@tdtu.edu.vn
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Abstract

Background. Clubhead speed (CHS) is a key determinant of golf performance and is influenced by the efficient transfer of energy throughout the kinematic sequence. Peak pelvic rotation angle (PPRA) at the top of the backswing has been proposed as an important biomechanical factor contributing to swing performance; however, previous studies have reported conflicting findings regarding whether greater pelvic rotation is associated with superior outcomes. Consequently, the biomechanical role of PPRA in golf performance remains unclear.

Objectives. This study aimed to (1) determine the association between PPRA and CHS, (2) compare PPRA characteristics between golfers with different performance levels, and (3) clarify the biomechanical role of PPRA in golf swing performance.

Materials and Methods. Eighteen male amateur golfers performed 30 valid swings using a 7-iron under standardized conditions, resulting in 540 analyzed swings. PPRA was measured using an inertial measurement unit (IMU)-based motion capture system, while CHS was assessed using Golfzon Vision. A Linear Mixed Model (LMM) was applied to examine the association between PPRA and CHS, and independent-samples t-tests were used to compare PPRA between the high-CHS and low-CHS groups.

Results. PPRA was significantly associated with CHS ($\beta = 0.164$, $p < 0.001$), indicating that greater pelvic rotation contributed to increased clubhead speed. However, golfers in the high-CHS group demonstrated significantly smaller PPRA values than those in the low-CHS group (18.49 ± 1.86° vs. 22.45 ± 4.38°; $p = 0.019$, Cohen's $d = 1.085$). Additionally, the high-CHS group exhibited lower variability in PPRA, suggesting greater movement consistency.

Conclusions. PPRA contributes to CHS generation; however, superior performance appears to depend more on the optimization and consistency of pelvic rotation than on greater rotational magnitude. These findings suggest that PPRA should be interpreted as a movement coordination characteristic within the kinematic sequence rather than as a performance variable that should simply be maximized.

Keywords: IMU-based, golf biomechanics, peak pelvic rotation angle, clubhead speed.

Introduction

Clubhead speed (CHS) is widely recognized as one of the primary determinants of golf performance because it directly influences ball velocity, shot distance, and competitive success. The generation of CHS depends on the efficient transfer of mechanical energy throughout the body during the golf swing, which is considered a highly coordinated multi-segment movement. Previous biomechanical investigations have established that the golf swing follows a proximal-to-distal kinematic sequence, whereby movement is initiated by the pelvis, followed sequentially by the thorax, lead arm, and finally the club. During the transition from backswing to downswing, each segment changes direction in a coordinated manner, allowing energy to be transferred efficiently through the kinetic chain and ultimately contributing to clubhead acceleration at impact. Consequently, understanding the biomechanical factors that influence this kinematic sequence is essential for improving golf performance and optimizing training strategies (Ball & Best, 2007; Roberts et al., 2024).

Within this kinematic sequence, pelvic motion has been identified as a critical contributor to power generation. As

PETM
LLC OVS

the most proximal rotational segment, the pelvis initiates the transfer of energy from the lower extremities to the upper body and club. Previous studies have shown that skilled golfers generally demonstrate superior pelvic rotational characteristics compared with less-skilled golfers, suggesting an important role of pelvic function in swing performance (Callaway et al., 2012; Cheetham et al., 2008). Furthermore, biomechanical research has consistently reported significant relationships between pelvic kinematics and performance-related outcomes, including CHS, ball speed, driving distance, and impact quality (Myers et al., 2008; Meister et al., 2011; Sim et al., 2017). In addition to pelvic rotation angle, variables such as X-factor, pelvic rotational velocity, pelvis-thorax coordination, and pelvic obliquities have been identified as important contributors to golf swing effectiveness (Meister et al., 2011; Steele et al., 2018).

Among these variables, peak pelvic rotation angle (PPRA) at the top of backswing may represent a particularly important biomechanical factor because it reflects the rotational loading achieved before downswing initiation. From a biomechanical perspective, greater rotational loading may enhance the storage of elastic energy and facilitate its subsequent transfer through the kinetic chain, thereby contributing to higher clubhead speed. Supporting this concept, Myers et al. (2008) demonstrated that trunk and pelvic rotational characteristics are associated with driving performance, whereas Hume et al. (2005) reported that the ability to maximize rotational separation between the shoulders and pelvis is strongly related to driving distance in skilled golfers. These findings suggest that PPRA may play an important preparatory role in generating the rotational energy required for effective downswing acceleration.

Despite the recognized importance of pelvic motion, the specific biomechanical role of PPRA remains unclear. Existing evidence presents conflicting findings regarding whether greater pelvic rotation is beneficial for golf performance. On one hand, several studies suggest that rotational variables contribute positively to CHS and overall swing effectiveness (Myers et al., 2008; Meister et al., 2011). On the other hand, evidence indicates that maximizing pelvic rotation may not necessarily result in superior performance. Myers et al. (2008) reported that golfers seeking to increase clubhead speed often achieve greater upper trunk rotation while simultaneously limiting excessive pelvic rotation at the top of backswing. Similarly, Lynn et al. (2013) found no significant differences in peak pelvic angular velocity between elite and recreational golfers, challenging the assumption that greater pelvic motion automatically leads to better performance.

These contradictory findings may be interpreted through the perspective of motor control theory. According to Bernstein's theory of motor redundancy, the human movement system possesses multiple coordination solutions for achieving the same performance outcome, meaning that skilled performers are not constrained to a single optimal movement pattern (Bernstein, 1967). Similarly, Schmidt and Lee (2019) proposed the concept of motor equivalence, whereby different movement strategies can produce equivalent task outcomes. Applied to golf, these theories suggest that golfers may achieve similar or even superior CHS through different pelvic rotation strategies, provided that energy transfer within the kinematic sequence remains efficient. Therefore, superior performance may depend less on maximizing pelvic rotation magnitude and more on optimizing the coordination and timing of segmental motion throughout the swing. This perspective provides a theoretical explanation for the inconsistent findings reported in previous biomechanical studies and highlights the need to clarify the specific role of PPRA in golf performance.

Consequently, a significant knowledge gap remains regarding whether PPRA should be interpreted as a biomechanical factor that directly enhances performance or as a movement characteristic reflecting individual coordination strategies within the golf swing. Although previous studies have investigated pelvic biomechanics using laboratory-based motion capture systems, relatively little evidence is available concerning the use of wearable technologies to examine the relationship between PPRA and performance outcomes in amateur golfers. Recent advancements in inertial measurement unit (IMU) technology have enabled practical and field-based biomechanical assessment. IMUs have demonstrated acceptable validity for measuring golf swing rotational biomechanics and offer several advantages over traditional motion capture systems, including portability, lower cost, and real-time feedback capabilities (Lee & Lee, 2022; Kim et al., 2023). As a result, IMU-based systems provide a promising opportunity to investigate the biomechanical significance of PPRA in ecologically valid training and performance environments.

Therefore, the present study aimed to investigate the biomechanical role of peak pelvic rotation angle in golf swing performance using an IMU-based motion capture system. Specifically, the purposes of this study were to: (1) determine the association between PPRA and clubhead speed, (2) compare PPRA characteristics between golfers with different performance levels, and (3) clarify the biomechanical role of PPRA in golf swing performance. By integrating biomechanical theory, motor control principles, and wearable sensor technology, this study seeks to contribute to a more comprehensive understanding of how pelvic rotation influences golf swing mechanics and performance.

Material and Methods

Study Design

This study employed a cross-sectional repeated-measures biomechanical design to investigate the role of PPRA in golf swing performance. The design was developed based on the theoretical framework of the proximal-to-distal kinematic sequence, which proposes that rotational energy is transferred sequentially from the pelvis to the thorax, upper extremities, and ultimately the club during the golf swing (Roberts et al., 2024). Within this framework, PPRA at the top of backswing was considered a key biomechanical variable reflecting rotational loading prior to downswing initiation. To address the study objectives, two complementary analytical approaches were adopted. First, a Linear Mixed Model (LMM) was used to examine the association between PPRA and clubhead speed (CHS) while accounting for repeated observations within participants. Second, golfers were classified into high-performance and low-performance groups according to CHS to compare PPRA characteristics between performance levels. This

approach was selected to evaluate whether PPRA functions primarily as a performance-related biomechanical factor or as an individual movement strategy within the golf swing.

Participants

A total of 18 male undergraduate students majoring in Golf at Ton Duc Thang University, Vietnam voluntarily participated in this study. All participants met the following inclusion criteria: (1) completion of the course: Golf Swing Technique with Mid-Irons (6, 7, 8) with at least 60 hours of practice, (2) a minimum of 1.5 years of golf experience, (3) right-handed dominance, and (4) no musculoskeletal injuries within the previous six months. Participants had not yet obtained an official handicap (System 36), representing an amateur skill level. The age, height, and body mass of the participants (Mean± SD) were 20.3 ± 1.1 years, 174.72 ± 5.26 cm, and 66.72 ± 9.75 kg, respectively. All participants were informed about the study procedures and provided voluntary consent prior to participation. The study was conducted in accordance with ethical standards for human research.

Procedure and Instruments

In order to ensure consistency across sessions, data gathering was carried out in a controlled 3D golf simulation environment. To reduce variation in equipment settings, participants had a standardised warm-up and familiarity session with a 7-iron club and standardised golf balls before to testing. Pelvic kinematics were recorded using an IMU-based system (Noraxon Ultium Portable Lab), which has been widely used for wearable motion analysis in sports biomechanics. The IMU sensor was securely attached to the sacral region (between the posterior superior iliac spines at the L5-S1 level) following established protocols to capture pelvic rotation during the golf swing (Wolski et al., 2024). The system was calibrated using the MyoMOTION

Fig. 1. Experimental setup including Noraxon Ultium Portable Lab , IMU sensor placement, Golfzon Vision system, 7-Iron Club, NiNox 120fps Camera

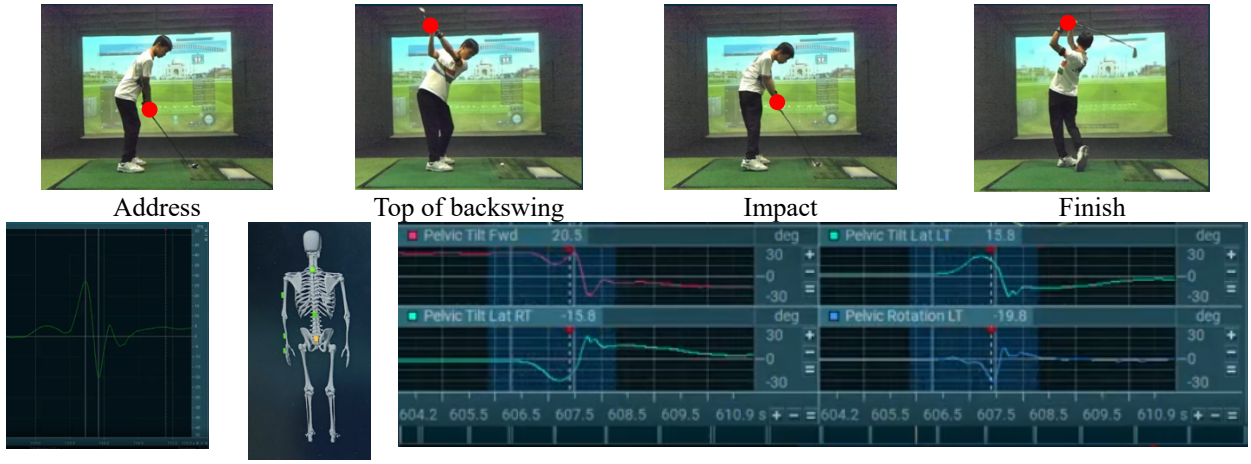

Fig. 2. PPRA measured by IMU across key phases of the golf swing (Address, Top of Backswing, Impact, and Finish)

calibration procedure prior to data collection to ensure measurement accuracy. NiNOX 120 fps camera was used to visually verify swing phases and synchronize kinematic data. CHS was measured using the Golfzon Vision system, which utilizes high-speed optical tracking technology to provide reliable ball and club metrics.

Each participant performed 30 valid golf swings using a 7-iron, resulting in a total of 540 swings included in the analysis. This repeated-measures design was adopted to capture within-subject variability and improve the robustness of the dataset (Tirrell et al., 2018).

Data Collection and Statistical Analysis

Raw data were exported and organized using Microsoft Excel prior to statistical analysis. Descriptive statistics (Mean ± SD) were calculated to summarize participant characteristics and key variables, including PPRA and CHS. Given the repeated-measures structure of the data (multiple swings per participant), a Linear Mixed Model (LMM) was employed to examine the relationship between PPRA and CHS while accounting for inter-individual variability. This approach is appropriate for hierarchical biomechanical data and allows for more accurate estimation of fixed an d random effects (Tirrell et al., 2018).

To further explore performance differences, participants were divided into two groups (high CHS and low CHS) based on the overall mean CHS value. The normality of the data was assessed using the Shapiro-Wilk test. Independent samples t-tests were then conducted to compare peak pelvic rotation angle between groups. Effect sizes were calculated using Cohen's d and interpreted as small (0.2), medium (0.5), and large (≥ 0.8) (Cohen, 1988). The level of statistical significance was set at $\rho < 0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0

Results

Characteristics of Peak Pelvic Rotation and Clubhead Speed

Descriptive statistics of the main variables are presented in Table 1. The mean CHS of the participants was 34.35 ± 2.59 m/s, representing an intermediate amateur performance level. The mean peak pelvic rotation angle was 20.91 ± 4.06°, with a relatively wide range (13.85° - 27.43°), indicating notable inter-individual variability in pelvic kinematics during the backswing phase. The relatively large standard deviation suggests inconsistent motor control among amateur golfers, particularly in the coordination of pelvic rotation within the kinematic sequence.

Table 1. Descriptive statistics of PPRA and CHS

Variable	N	Min	Max	Mean SD
PPRA(°)	18	13.85	27.43	20.91±4.06
CHS(m/s)	18	31.13	39.40	34.35±2.59

Association between PPRA and CHS

The LMM analysis revealed a statistically significant positive association between PPRA and CHS (Table 2). Specifically, pelvic rotation significantly predicted CHS (β = 0.164, SE = 0.016, t = 9.966, $\rho < 0.001$), indicating that a 1° increase in pelvic rotation was associated with an average increase of 0.164 m/s in CHS, after accounting for inter-individual variability. The 95% confidence interval (0.132 - 0.196) did not include zero, confirming the robustness of this relationship. Variance component analysis indicated substantial between-subject variability (Variance = 3.208) and within-subject residual variance (2.189), resulting in an intraclass correlation coefficient (ICC) of approximately 0.594. This suggests that 59.4% of the variance in CHS can be attributed to differences between individuals.

Table 2. LMM examining for the association between PPRA and CHS

Parameters	Estimate (β)	Std. Error	t	Sig	95% CI
Intercept	30.770	0.751	40.921	0.000	29.229-32.311
PPRA (°)	0.164	0.016	9.966	0.000	0.132-0.196

PPRA Characteristics across performacne levels: High-CHS and Low-CHS Groups

To address the second and third objectives, participants were categorized into high-CHS and low-CHS groups according to the overall mean CHS. Independent-samples t-tests demonstrated significant differences in PPRA between groups (t = -2.643, $\rho = 0.019$). Interestingly, golfers in the high-CHS group exhibited significantly smaller PPRA values (18.49 ± 1.86°) than golfers in the low-CHS group (22.45 ± 4.38°). Furthermore, the standard deviation of PPRA was substantially lower in the high-performance group, indicating greater movement consistency. The effect size was large (Cohen's d = 1.085), suggesting a meaningful practical difference between groups.

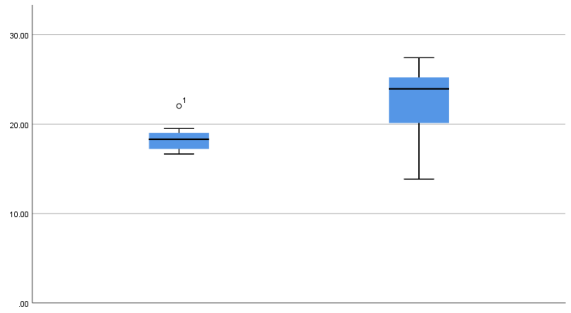

Fig. 3. Distribution of PPRA by High CHS and Low CHS performance group

Summary of findings related to the Biomechanical role of PPRA

The combined findings from the LMM and group comparison analyses indicate that PPRA is associated with CHS but does not appear to function as a performance variable that should be maximized. Although greater PPRA was positively associated with CHS across repeated swings, golfers who achieved higher-CHS demonstrated smaller

Table 3. Comparison of PPRA between high and low CHS groups

Variable	High CHS Group (N = 7), Mean ± SD	Low CHS Group (N=11), Mean ± SD	t(df)	p-value	Cohen's d
PPRA (o)	18.49 ± 1.86	22.45 ± 4.38	-2.643(14.526)	0.019	1.085

Note: *Statistical significance at < 0.05

and more consistent PPRA values than lower-CHS golfers. These findings suggest that the biomechanical role of PPRA may be better understood as a movement coordination characteristic within the kinematic sequence rather than a variable whose magnitude alone determines performance.

Discussion

The purpose of this study was to investigate the biomechanical role of peak pelvic rotation angle (PPRA) in golf swing performance using an IMU-based motion capture system. Three principal findings emerged from the study. First, PPRA demonstrated a significant positive association with clubhead speed (CHS). Second, golfers with higher-CHS exhibited significantly smaller and more consistent PPRA values than lower-CHS golfers. Third, the combined findings suggest that PPRA should not be interpreted solely as a performance-enhancing variable but rather as a movement coordination characteristic that contributes to the optimization of the kinematic sequence.

The positive association observed between PPRA and CHS supports the first study objective and is consistent with previous biomechanical research emphasizing the importance of pelvic motion in golf swing performance. The pelvis serves as the initial segment within the proximal-to-distal kinematic sequence and plays a fundamental role in transferring rotational energy from the lower body to the thorax, upper extremities, and ultimately the club (Neal et al., 2007; Roberts et al., 2024). From a biomechanical perspective, greater pelvic rotation at the top of backswing may increase rotational loading and contribute to the storage of elastic energy that can subsequently be released during the downswing. Previous studies have reported significant relationships between trunk-pelvis rotational characteristics and clubhead speed, suggesting that rotational preparation during the backswing is an important determinant of swing power generation (Hume et al., 2005; Myers et al., 2008; Meister et al., 2011). Therefore, the present findings provide further evidence that PPRA contributes to the generation of CHS by supporting the effective transfer of energy throughout the kinetic chain.

However, the second finding revealed an apparently contrasting pattern. Although PPRA was positively associated with CHS across repeated swings, golfers in the high-CHS group demonstrated significantly smaller PPRA values than those in the low-CHS group. Moreover, PPRA variability was substantially lower among higher-performing golfers. This finding suggests that superior performance is not necessarily achieved through maximizing pelvic rotation magnitude. Instead, it appears that skilled performers may operate within a more optimal range of pelvic rotation while maintaining greater movement consistency. Similar observations have been reported in previous golf biomechanics research, where elite golfers did not always exhibit larger rotational amplitudes than less-skilled golfers despite achieving superior performance outcomes (Lynn et al., 2013). Myers et al. (2008) likewise suggested that increasing upper trunk rotation while limiting excessive pelvic rotation may contribute to higher clubhead speeds, indicating that effective performance may depend on how rotational movements are coordinated rather than on the magnitude of a single kinematic variable.

The apparent discrepancy between the LMM results and the group comparison findings can be interpreted through motor control theory. Bernstein's theory of motor redundancy proposes that the human movement system possesses multiple coordination solutions capable of producing the same performance outcome (Bernstein, 1967). Similarly, Schmidt and Lee (2019) described the concept of motor equivalence, whereby different movement patterns may generate equivalent task results. Applied to golf, these theories suggest that golfers can achieve high clubhead speeds through different movement strategies, provided that the overall kinematic sequence remains efficient. Consequently, larger PPRA values may contribute to CHS generation within an individual golfer, but superior performers may not require greater pelvic rotation if they possess more efficient coordination between the pelvis, thorax, arms, and club. This interpretation provides a theoretical explanation for the contradictory findings reported in previous golf biomechanics studies and supports the notion that movement efficiency is more important than movement magnitude alone.

From a biomechanical standpoint, the present findings suggest that PPRA functions as a component of movement optimization rather than a variable that should be maximized. Previous research has demonstrated that successful golf swings depend on the timing and sequencing of body segments rather than on the isolated magnitude of individual movements (Cheetham et al., 2008; Neal et al., 2007). Excessive pelvic rotation may disrupt the temporal organization of the kinematic sequence, potentially reducing the efficiency of energy transfer from the pelvis to the thorax and club. Conversely, an optimal level of pelvic rotation may facilitate effective rotational loading while preserving segmental coordination. Therefore, the biomechanical role of PPRA appears to involve supporting the organization of the kinematic sequence rather than directly determining performance through larger rotational amplitudes.

An important practical implication of these findings is that golf coaching should not focus exclusively on increasing pelvic rotation range. Traditional coaching approaches often encourage golfers to maximize backswing rotation in an effort to increase power output. However, the present results indicate that higher performance may be characterized by more controlled and consistent pelvic motion rather than greater rotational magnitude. Coaches should therefore prioritize movement quality, timing, and coordination

within the kinematic sequence. The use of wearable IMU technology may facilitate this process by providing objective feedback regarding pelvic motion characteristics during training and competition settings. Such information may help coaches identify individualized movement strategies that optimize performance while avoiding excessive or inefficient movement patterns.

Taken together, the findings of the present study suggest that PPRA occupies a dual biomechanical role within the golf swing. On one hand, PPRA contributes to clubhead speed generation through its involvement in rotational loading and energy transfer. On the other hand, superior performance appears to be associated with the optimization and consistency of pelvic rotation rather than its absolute magnitude. Therefore, PPRA should be viewed not simply as a performance variable to be maximized but as a movement coordination characteristic that reflects the efficiency of the golfer's kinematic sequence.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, the sample consisted of a relatively small group of amateur male golfers, which may limit the generalizability of the results to other populations. Second, the study focused exclusively on PPRA and CHS, without considering other biomechanical variables such as X-factor, trunk rotation, ground reaction forces, or muscle activation patterns that may influence golf performance. Third, although IMU technology provides a practical method for field-based biomechanical assessment, measurement errors associated with sensor placement and soft tissue movement cannot be completely excluded. Future research should investigate PPRA within a multi-sensor framework incorporating motion capture, force plate, and EMG measurements to better understand the mechanisms underlying energy transfer during the golf swing. Additionally, studies involving elite golfers, female golfers, and longitudinal intervention designs are needed to determine whether optimizing PPRA and movement consistency can enhance golf performance.

Conclusion

This study demonstrated a significant positive association between Peak Pelvic Rotation Angle (PPRA) and Clubhead Speed (CHS), indicating that pelvic rotational loading contributes to golf swing performance. However, golfers with higher CHS exhibited smaller and more consistent PPRA values than lower-CHS golfers, suggesting that superior performance is not achieved through maximizing pelvic rotation magnitude. Collectively, these findings indicate that the biomechanical role of PPRA extends beyond power generation and is more closely related to the optimization of movement coordination within the kinematic sequence. Therefore, PPRA should be considered a movement-control characteristic that supports efficient energy transfer rather than a performance variable that should simply be increased.

Data Availability Statement

The datasets generated and analyzed during the current study, including IMU-based measurements of peak pelvic rotation angle (PPRA) and clubhead speed (CHS), are available from the corresponding author upon reasonable request.

AI Transparency Statement

During the preparation of this work the authors used ChatGPT 5.1 (OpenAI) in order to support the refinement of English academic writing, including language polishing, structural editing, and alignment with international journal stylistic conventions. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Дослідження біомеханічної ролі максимального кута повороту таза під час свінгу в гольфі

Мінь Хієу Во[1ACD], Тхі Тхам Нгуєн[2AD], Нгок Туеть Мінь Као[1BCD]

[1]Університет Тон Дик Тханг
[2]Університет фізичного виховання і спорту міста Хошимін

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

Реферат. Стаття: 8 с., 3 табл., 3 рис., 18 джерел.

Передумова. Швидкість головки ключки (CHS) є одним із ключових чинників результативності в гольфі та залежить від ефективної передачі енергії вздовж кінематичного ланцюга. Максимальний кут повороту таза (PPRA) у верхній точці замаху (backswing) розглядається як важливий біомеханічний фактор, що впливає на ефективність свінгу; однак попередні дослідження повідомляють суперечливі результати щодо того, чи пов›язаний більший поворот таза з вищими показниками результативності. У зв›язку з цим біомеханічна роль PPRA у результативності гри в гольф залишається недостатньо з›ясованою.

Мета дослідження. Метою цього дослідження було: (1) визначити зв›язок між PPRA та CHS; (2) порівняти характеристики PPRA у гольфістів різного рівня результативності; (3) уточнити біомеханічну роль PPRA у забезпеченні ефективності свінгу в гольфі.

Матеріали та методи. У дослідженні взяли участь 18 чоловіків-аматорів, які виконали по 30 валідних свінгів ключкою 7-iron за стандартизованих умов, у результаті чого було проаналізовано 540 свінгів. PPRA визначали за допомогою системи захоплення рухів на основі інерціального вимірювального модуля (IMU), тоді як CHS оцінювали за допомогою системи Golfzon Vision. Для аналізу зв›язку між PPRA та CHS застосовували лінійну змішану модель (Linear Mixed Model, LMM), а для порівняння PPRA між групами з високою та низькою CHS використовували t-тест для незалежних вибірок.

Результати. Встановлено статистично значущий зв›язок між PPRA та CHS ($\beta = 0.164$, $p < 0.001$), що свідчить про те, що більший поворот таза сприяв збільшенню швидкості головки ключки. Водночас гольфісти з високою CHS продемонстрували статистично значуще менші значення PPRA порівняно з гольфістами з низькою CHS (18.49 ± 1.86° проти 22.45 ± 4.38°; $p = 0.019$; d Коена = 1.085). Крім того, група з високою CHS характеризувалася меншою варіабельністю PPRA, що свідчить про вищу узгодженість рухів.

Висновки. PPRA сприяє формуванню CHS, однак вищий рівень результативності, імовірно, більшою мірою залежить від оптимізації та стабільності повороту таза, ніж від максимальної амплітуди його обертання. Отримані результати свідчать про те, що PPRA слід розглядати як характеристику координації рухів у межах кінематичного ланцюга, а не як показник результативності, який необхідно просто максимізувати.

Ключові слова: інерціальний вимірювальний модуль (IMU), біомеханіка гольфу, максимальний кут повороту таза, швидкість головки ключки.

Information about the Authors:

Vo, Minh Hieu: vominhhieu@tdtu.edu.vn; https://orcid.org/0009-0001-8322-0724; Faculty of Sport Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam.

Nguyen, Thi Tham: thamtn@upes.edu.vn; https://orcid.org/0000-0003-2305-1663; Ho Chi Minh City University of Physical Education and Sport, Ho Chi Minh City, Vietnam.

Cao, Ngoc Tuyet Minh: cntmjinh@gmail.com; https://orcid.org/0000-0003-0064-1257; Faculty of Sport Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam.

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Post-Exercise Physiological Recovery and Academic Achievement in Adolescents: The Role of Autonomic Regulation

Emma Saraiello[1ABD], Francesca Latino[2ABCD], Giulia Amato [1BCD] and Maria Giovanna Tafuri[3ABC]

[1]University of Naples "Parthenope"
[2]University of Salento
[3]Pegaso University

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

Corresponding Author: Francesca Latino, e-mail: francesca.latino@unisalento.it
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Abstract

Background. Physical education represents a regular physiological stimulus within the school day, yet little is known about autonomic recovery following curricular lessons and its relationship with academic achievement.

Objectives. To compare post-exercise autonomic recovery following a regular physical education lesson with a time-matched control condition and to determine whether autonomic recovery is associated with academic achievement in adolescents.

Materials and Methods. Ninety-two adolescents completed both a physical education condition and a time-matched control condition using a within-participant repeated-measures design. Heart rate variability was recorded before and after each condition, and the root mean square of successive differences was analyzed after natural logarithmic transformation (lnRMSSD). Academic achievement was assessed using the official grade point average.

Results. A significant Condition × Time interaction was observed for lnRMSSD ($F(1,91)=4.06$, $p=0.047$, partial $\eta^2=0.043$). Post hoc analyses demonstrated a significant increase in lnRMSSD following physical education ($p=0.003$), whereas no significant change occurred during the control condition ($p=0.292$). Autonomic recovery following physical education was positively associated with academic achievement ($r=0.52$, $p<0.001$). Linear regression analysis showed that autonomic recovery explained 27.5% of the variance in academic achievement ($R^2=0.275$, $p<0.001$).

Conclusions. A regular physical education lesson elicited significantly different autonomic responses compared with a time-matched control condition. Adolescents exhibiting greater post-exercise parasympathetic recovery achieved higher academic performance. These findings indicate that autonomic recovery following physical education may represent a meaningful physiological correlate of scholastic achievement and support further longitudinal and intervention-based research examining the role of autonomic regulation in educational outcomes.

Keywords: heart rate variability, cardiac vagal modulation, school performance, parasympathetic reactivation, exercise physiology, secondary school students.

Introduction

Academic achievement represents a central indicator of educational success and a major determinant of subsequent opportunities across the course of life (Steinmayr et al., 2014). Although academic outcomes are commonly expressed through grades, examination scores, or standardized assessments, scholastic performance emerges from the interaction of cognitive, behavioral, social, and physiological processes (Osman et al., 2021). Attention, working memory, executive control, emotional regulation, motivation, and the capacity to adapt to environmental demands all contribute to students' ability to engage effectively with learning tasks. Consequently, increasing attention has been directed toward factors that extend beyond conventional instructional practices and may support the conditions under which learning occurs (Alfonsi et al., 2020). Within this perspective, physical activity and school based physical education have gained considerable relevance because of their potential contribution not only to physical health

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and motor development, but also to cognitive functioning, psychological well-being, and educational outcomes.

The relationship between physical activity and academic achievement has been examined extensively in children and adolescents. A substantial body of evidence suggests that regular participation in physical activity is positively associated with cognitive performance and may support selected dimensions of academic attainment. Several mechanisms have been proposed to explain these relationships (Latino et al., 2025a,b). From a neurobiological perspective, physical exercise may influence cerebral blood flow, neurotrophic signaling, synaptic plasticity, and the functional efficiency of neural networks involved in executive control and memory. At the behavioral level, physically active students may benefit from improved emotional regulation, reduced psychological distress, enhanced classroom engagement, and more effective management of academic demands. However, the magnitude and consistency of the observed associations vary across studies, suggesting that the relationship between movement behaviors and scholastic outcomes cannot be explained exclusively by the amount of physical activity performed. The physiological responses elicited by exercise and the capacity to recover after physical exertion may provide an additional perspective through which this relationship can be investigated (James et al., 2023).

Physical education occupies a distinctive position within this field. Unlike extracurricular sport or voluntary physical activity, physical education is embedded within the educational curriculum and reaches students with heterogeneous levels of fitness, motor competence, and previous sport experience (Canli et al., 2024). Its educational purpose extends beyond the promotion of physical fitness and includes the development of motor competence, self-regulation, cooperation, decision making, and positive attitudes toward active lifestyles. In adolescence, diversified physical activity programs have also been associated with favorable changes in body related perceptions, supporting the broader developmental relevance of structured motor experiences during this stage of life (Latino et al., 2025). At the same time, each physical education lesson constitutes an acute physiological stimulus that temporarily alters cardiovascular and autonomic function. The transition from exercise to subsequent recovery therefore represents a potentially informative phase, particularly within the school setting, where students are generally expected to return to cognitively demanding academic activities shortly after the conclusion of the lesson (Martín-Rodríguez et al., 2024).

The acute physiological consequences of exercise are not limited to changes in heart rate and energy expenditure. Physical exertion produces a dynamic reorganization of autonomic regulation characterized by parasympathetic withdrawal and increased sympathetic influence during exercise, followed by progressive vagal reactivation during recovery (Marschin, & Herbert, 2026). The speed and magnitude of this post exercise autonomic restoration reflect the capacity of the organism to transition from physiological activation toward a more regulated state. This process is particularly relevant during adolescence, a developmental period characterized by substantial changes in cardiovascular regulation, emotional reactivity, executive functioning, and sensitivity to social and academic stressors. Individual differences in autonomic regulation may therefore contribute to variations in how students respond to and recover from the demands of both physical and educational environments (López-Bueno et al., 2025).

Heart rate variability, HRV, provides a non-invasive method for examining cardiac autonomic modulation through the analysis of beat-to-beat variations in heart rate. Among the available HRV indices, the root mean square of successive differences, RMSSD, is widely used in exercise and psychophysiological research because it predominantly reflects parasympathetic modulation and can be obtained through relatively short recordings under standardized conditions (Soares-Miranda et al., 2014). Higher vagally mediated HRV at rest has frequently been interpreted as an indicator of greater autonomic flexibility and adaptive capacity, although HRV should always be considered within the specific physiological and contextual conditions in which it is measured. In young populations, HRV has been investigated in relation to physical fitness, psychological stress, emotional regulation, and cognitive functioning. Nevertheless, its potential relevance to academic achievement remains comparatively underexplored, particularly when HRV is examined dynamically rather than exclusively through a single resting measurement (El-Malahi et al., 2024).

This distinction is important because resting HRV and post exercise autonomic recovery provide related but conceptually different information. A resting measurement describes cardiac autonomic modulation under relatively stable conditions, whereas recovery assessment captures the organism's response following a defined physiological challenge. From this perspective, autonomic recovery may represent a functional characteristic of regulatory capacity rather than merely a static physiological state. Two students with comparable resting values may exhibit different recovery trajectories after the same educationally embedded physical activity. Such differences may reflect variation in physical conditioning, stress responsiveness, autonomic flexibility, or the efficiency with which physiological systems return toward baseline conditions. Examining this recovery process may therefore provide information that cannot be obtained from resting HRV alone (Dong, 2016).

The possible connection between autonomic regulation and academic achievement is supported by broader psychophysiological models linking vagal function with cognitive and emotional self-regulation. Successful participation in school requires students to sustain attention, inhibit irrelevant responses, adapt behavior to changing demands, manage frustration, and maintain goal directed engagement (Yoo et al., 2021). These processes depend on coordinated regulatory mechanisms involving interactions between central and peripheral systems. Cardiac autonomic regulation has been associated with executive functioning, attentional control, and the capacity to respond adaptively to environmental challenges. Accordingly, students who demonstrate more efficient autonomic recovery following physical exertion may also possess physiological regulatory characteristics that support adaptation to academic demands. This proposition does not imply that autonomic recovery directly determines academic achievement. Rather, it suggests that physiological flexibility may constitute one component within the broader network of individual characteristics associated with successful functioning in educational contexts (Mendoza-Castejón, & Clemente-Suárez, 2020).

Despite increasing interest in the cognitive and academic implications of physical activity, research conducted in schools has predominantly focused on chronic interventions, fitness levels, habitual activity, or comparisons between physically active and inactive students (Trudeau, & Shephard, 2008). These approaches have provided valuable evidence but have often treated physiological adaptation as an inferred mechanism rather than a directly measured process. Furthermore, studies examining acute exercise have generally concentrated on immediate cognitive outcomes, including attention, inhibition, and working memory, while comparatively less consideration has been given to autonomic recovery following ordinary physical education lessons (Yan et al., 2025). This represents a relevant gap because school-based physical education differs from laboratory exercise protocols. Lessons occur within authentic educational schedules, involve naturally heterogeneous groups of students, and are followed by a return to classroom activities. Understanding physiological recovery in this ecological context may therefore contribute to a more integrated interpretation of the relationship between physical education and educational functioning.

Another methodological consideration concerns the interpretation of autonomic changes across the school day. HRV is sensitive to multiple influences, including time of day, posture, recent physical activity, respiration, psychological stress, and environmental conditions. A decrease or increase observed after physical education cannot be interpreted adequately without considering the changes that might occur during a comparable period without exercise (Tornberg et al., 2019). For this reason, the inclusion of a minimally intrusive control condition, in which the same students are assessed at corresponding time points during a school day without physical education, may strengthen the interpretation of post lesson autonomic responses. A within participant approach also reduces the influence of stable interindividual characteristics and is particularly suitable for school-based research, where the creation of separate experimental groups may be impractical or educationally inappropriate.

The investigation of academic achievement alongside autonomic recovery may also help bridge a persistent conceptual separation between exercise physiology and educational research. Physical education is frequently evaluated through motor, fitness, or behavioral outcomes, whereas academic research often examines scholastic performance without direct consideration of physiological regulation. Integrating these domains does not require complex experimental protocols or extensive batteries of psychological assessments (Frank et al., 2020). A focused examination of autonomic recovery and academic achievement may provide an initial empirical basis for understanding whether physiological responsiveness to a routine physical education lesson is related to broader educational outcomes. Such an approach is particularly relevant in adolescence, when increasing academic demands coexist with changes in physical activity patterns, physiological maturation, and heightened exposure to school related stress (Wang et al., 2025).

Accordingly, the present study aimed to examine autonomic recovery following a regular physical education lesson and its association with academic achievement in adolescents. Using a within participant design, HRV responses were assessed across a physical education condition and a time matched control condition without structured physical activity. Academic achievement was evaluated through students' scholastic performance. It was hypothesized that the physical education condition would produce a distinct pattern of autonomic change compared with the control condition, reflecting the physiological activation and subsequent recovery associated with the lesson. It was further hypothesized that more favorable post exercise autonomic recovery would be positively associated with higher academic achievement. By examining a naturally occurring component of the school curriculum through a psychophysiological perspective, the study seeks to clarify whether individual differences in autonomic recovery are meaningfully related to educational performance during adolescence.

Materials and Methods

Study Design

This study adopted a within participant repeated measures design to examine cardiac autonomic responses following a regular physical education lesson and their association with academic achievement in adolescents. Each participant was assessed under two conditions, a physical education condition and a time matched control condition, thereby allowing each student to serve as his or her own control. The two assessment sessions were conducted on separate school days within the same week and at comparable times of day to minimize the potential influence of circadian variation on heart rate variability, HRV. During the physical education condition, HRV was recorded before the beginning of the lesson and during a standardized recovery period following its completion. During the control condition, HRV was recorded at corresponding time points, while students followed their usual academic schedule without engaging in structured physical activity between measurements.

The study was conducted in accordance with the principles of the Declaration of Helsinki and received approval from the competent institutional ethics committee. Before data collection, written informed consent was obtained from the parents or legal guardians of all participants, while students provided their assent to participate. Participation was voluntary, and students were informed that withdrawal from the study was possible at any time without consequences for their school activities or academic evaluation. The study was conducted between September 2025 and January 2026.

Participants

Participants were recruited from a secondary school and included male and female students. Recruitment was conducted through school-based information sessions in which students and their families received a detailed explanation of the study aims and assessment procedures. The study was designed to include adolescents attending regular curricular physical education lessons, independently of their participation in extracurricular sport, in order to preserve the ecological characteristics of the school population.

The inclusion criteria were enrollment in the participating secondary school, age between 14 and 18 years, regular attendance at curricular physical education lessons,

eligibility to participate in school based physical activity according to school regulations, and provision of written parental or guardian consent and student assent. Students were required to complete both experimental conditions and to have valid HRV recordings at all assessment time points.

Exclusion criteria included medical conditions contraindicating participation in regular physical education, acute illness or injury at the time of assessment, use of medications known to substantially influence cardiac autonomic regulation, inability to complete the physical education lesson, and HRV recordings of insufficient quality for analysis. Students were also excluded from the final analysis if they were absent from either assessment session or failed to comply with the standardized pre assessment instructions.

An a priori sample size calculation was conducted using G*Power software. The calculation was based on the primary correlational hypothesis concerning the association between autonomic recovery and academic achievement. Assuming a moderate expected correlation of $r = 0.30$, a two tailed significance level of $\alpha = 0.05$, and statistical power of 0.80, the minimum required sample size was 84 participants. To account for potential absences, incomplete assessments, and HRV recordings unsuitable for analysis, 92 students were targeted for initial recruitment. Therefore, the final sample consisted of 92 adolescents, with a mean age of 16.01 ± 1.02 years. The sample included 49 females, 53.3%, and 43 males, 46.7%. The mean academic achievement score, expressed as grade point average, was 7.39 ± 0.71.

Procedures

Data collection was carried out during the regular school timetable and within the students' usual educational environment. To reduce variability related to circadian influences, all HRV assessments were scheduled within the same morning time window. The two assessment conditions were completed within the same week whenever possible, with sufficient separation between sessions to avoid any immediate carryover effect.

Before the first assessment session, students received standardized instructions regarding behaviors that could acutely affect autonomic regulation. They were asked to avoid vigorous physical activity for 24 hours before testing and to refrain from consuming caffeinated beverages or other stimulants on the morning of assessment. Students were also instructed to maintain their usual sleep and eating habits and to report any acute illness or unusual condition that could interfere with participation.

In the physical education condition, participants completed an initial five-minute seated stabilization period in a quiet environment, followed by a five-minute HRV recording. Students then participated in their regularly scheduled physical education lessons. Immediately after the lesson, participants returned to the assessment area and assumed the same seated position used during the baseline recording. Following a standardized five-minute transition period, a second five-minute HRV recording was obtained to characterize early post exercise autonomic recovery.

The control condition followed the same temporal structure. Participants underwent the initial stabilization and HRV recording procedures at a time corresponding to the pre lesson assessment of the physical education condition. They then continued their regular classroom activities without structured physical exercise. After a time, interval corresponding to the duration of the physical education lesson, the second HRV recording was conducted using the same stabilization period, body position, equipment, and environmental procedures applied in the physical education condition.

Whenever organizationally feasible, the order of the two conditions was counterbalanced across participants to reduce potential order effects. All measurements were conducted by trained researchers using standardized verbal instructions and identical recording procedures.

Physical Education Condition

The physical education condition consisted of a regular curricular lesson conducted by the school physical education teacher according to the planned educational program. The lesson lasted approximately 60 minutes and reflected the typical structure of secondary school physical education. It included an initial warm up phase, a central phase involving motor and sport-based activities, and a final phase characterized by progressively reduced exercise intensity.

The lesson was not designed as a laboratory-based exercise protocol or as a specific training intervention. Rather, it was intentionally embedded within ordinary school practice to examine autonomic recovery under ecologically valid educational conditions. The central phase included continuous and intermittent physical activities, coordination tasks, and participation in individual or group motor and sport activities. The same lesson structure and organizational procedures were maintained for all participating students within each class.

The control condition consisted of the students' normal classroom schedule and did not include structured physical activity during the period corresponding to the physical education lesson. Students remained engaged in their usual academic activities and were instructed not to participate in vigorous movement or organized exercise before the second HRV assessment. The control condition was designed to provide a minimally intrusive time matched comparison and to account for autonomic changes potentially associated with the passage of time and the ordinary school environment.

Measures

Heart Rate Variability

Cardiac autonomic modulation was assessed through short term HRV recordings (Brage et al., 2007). Heart rate data were collected using a Polar H10 (Polar Electro Oy, Kempele, Finland) heart rate sensor, which records R to R intervals and has been widely used in field based physiological research. Recordings were performed for five minutes with participants in a seated position, with their feet placed on the floor and hands resting comfortably on their thighs. Students were instructed to remain still, avoid speaking, and breathe spontaneously throughout the recording period.

The root mean square of successive differences between normal heartbeats, RMSSD, was selected as the primary HRV outcome because of its established sensitivity to vagally

mediated cardiac autonomic modulation and its suitability for short term recordings. The same recording duration, posture, equipment, and environmental conditions were maintained across all assessment sessions.

Autonomic change during early recovery was operationalized as the difference in RMSSD between the pre lesson recording and the standardized post lesson recovery recording, calculated as post minus pre. The corresponding change observed during the control condition was calculated using the same procedure. This index was used to characterize the direction and magnitude of autonomic change during the defined early recovery window rather than the complete temporal kinetics of post exercise autonomic recovery.

All R-to-R interval recordings were visually inspected for artifacts and ectopic beats before analysis. Recordings that did not meet predetermined quality criteria were excluded from the final analysis. Where required by the distribution of the data, RMSSD values were natural logarithm transformed before inferential statistical analyses.

Academic Achievement

Academic achievement was assessed using students' official school grades obtained from school records. Academic achievement was expressed as the grade point average calculated from the official grades obtained across all curricular subjects during the first semester of the academic year. The use of official grades was selected to provide an ecologically valid indicator of students' educational performance and to avoid the potential biases associated with self-reported academic achievement.

Academic data were collected only after the necessary institutional and parental permissions had been obtained. Individual records were anonymized before statistical analysis, and academic information was matched with physiological data through coded identifiers.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics, version 30.0. Before inferential analyses, data were screened for completeness, potential outliers, and distributional assumptions. Continuous variables were summarized using means and standard deviations, while categorical variables were reported as frequencies and percentages. The normality of continuous variables was assessed using the Shapiro Wilk test and visual inspection of histograms and Q Q plots. HRV data were inspected for distributional characteristics, and RMSSD values were natural logarithm transformed, lnRMSSD, before inferential analyses to reduce distributional skewness and improve conformity with parametric assumptions.

Changes in cardiac autonomic modulation were examined using a 2 × 2 repeated measures analysis of variance, ANOVA. The model included Condition, physical education and control, and Time, pre and post, as within participant factors. The Condition × Time interaction was considered the primary effect of interest, as it indicated whether the temporal change in lnRMSSD differed between the physical education and control conditions. Main effects of Condition and Time were also examined. Because within participant factors included only two levels, the assumption of sphericity was inherently satisfied. Effect sizes for ANOVA results were expressed as partial eta squared, ηp^2. Baseline lnRMSSD values between the physical education and control conditions were compared using a paired samples to test to identify potential precondition differences.

When a significant Condition × Time interaction was identified, paired samples t tests were conducted as post hoc comparisons to examine pre to post changes separately within the physical education and control conditions. Cohen's dz was calculated to quantify the magnitude of within participant differences. All post hoc comparisons were interpreted in relation to the interaction effect and were not considered independent primary hypothesis tests.

Autonomic change during early recovery following physical education was operationalized as the difference in lnRMSSD between the pre lesson assessment and the standardized post lesson recovery assessment, calculated as post minus pre. The association between PE Δ lnRMSSD and academic achievement was examined using Pearson's product moment correlation coefficient. The correlation coefficient was reported together with its 95% confidence interval. The direction and magnitude of the association were interpreted according to the absolute value of the correlation coefficient.

A simple linear regression analysis was subsequently conducted to examine the association between autonomic recovery following physical education and academic achievement. Academic achievement was entered as the dependent variable, while PE Δ lnRMSSD was entered as the independent variable. The regression model was evaluated using the F statistic, coefficient of determination, R^2, adjusted R^2, unstandardized regression coefficient, B, standard error, standardized regression coefficient, β, and corresponding t and p values. The assumptions of linearity, normality of residuals, homoscedasticity, and the absence of excessively influential observations were assessed before interpretation of the model. All statistical tests were two tailed, and statistical significance was set at $p < 0.05$.

Results

Participant Characteristics and Descriptive Statistics

Descriptive statistics for HRV across the physical education and control conditions are presented in Table 1. In the physical education condition, mean lnRMSSD increased from 3.60 ± 0.43 before the lesson to 3.67 ± 0.52 during the post lesson recovery assessment. In the control condition, lnRMSSD showed only a limited variation, from 3.48 ± 0.42 at the first assessment to 3.50 ± 0.44 at the corresponding second assessment. The mean change in lnRMSSD was 0.07 ± 0.23 for the physical education condition and 0.02 ± 0.17 for the control condition.

Autonomic Responses Across Physical Education and Control Conditions

A 2 × 2 repeated measures analysis of variance was conducted to examine changes in cardiac autonomic modulation across conditions. The analysis included Condition, physical education and control, and Time, pre and post, as within participant factors.

Table 1. Descriptive statistics for the main study variables

Variable	Mean	SD
Age, years	16.01	1.02
Academic achievement, GPA	7.39	0.71
PE pre lnRMSSD	3.60	0.43
PE post recovery lnRMSSD	3.67	0.52
PE Δ lnRMSSD	0.07	0.23
Control pre lnRMSSD	3.48	0.42
Control post lnRMSSD	3.50	0.44
Control Δ lnRMSSD	0.02	0.17

The analysis revealed a significant main effect of Time, $F_{(1, 91)} = 8.47$, $p = 0.005$, partial $\eta^2 = 0.085$, indicating that lnRMSSD values changed across the two assessment time points when both conditions were considered. A significant main effect of Condition was also observed, $F_{(1, 91)} = 5.62$, $p = 0.020$, partial $\eta^2 = 0.058$, reflecting differences in mean lnRMSSD values between the physical education and control conditions.

More importantly, the Condition × Time interaction was statistically significant, $F_{(1, 91)} = 4.06$, $p = 0.047$, partial $\eta^2 = 0.043$. This interaction indicated that the pattern of change in lnRMSSD across time differed between physical education and control conditions.

Post hoc comparisons were subsequently conducted to examine significant interaction. In the physical education condition, lnRMSSD increased significantly from the pre lesson assessment, 3.60 ± 0.43, to the post lesson recovery assessment, 3.67 ± 0.52, $t_{(91)} = 3.06$, $p = 0.003$, Cohen's dz = 0.32. Conversely, the control condition showed no statistically significant change between the first assessment, 3.48 ± 0.42, and the second assessment, 3.50 ± 0.44, $t_{(91)} = 1.06$, $p = 0.292$, Cohen's dz = 0.11.

The significant interaction, together with the post hoc comparisons, indicates that autonomic modulation followed a different temporal pattern after the physical education lesson compared with the corresponding period of a regular school day without structured physical activity. Specifically, the physical education condition was characterized by a significant increase in vagally mediated HRV during the standardized post lesson recovery assessment, whereas no comparable change was observed in the control condition.

Table 2. Repeated measures ANOVA for lnRMSSD

Effect	F	df	p value	Partial η^2
Condition	5.62	1, 91	0.020	0.058
Time	8.47	1, 91	0.005	0.085
Condition × Time	4.06	1, 91	0.047	0.043

Association Between Autonomic Recovery and Academic Achievement

Pearson's product moment correlation coefficient was calculated to examine the association between autonomic recovery following physical education and academic achievement. Autonomic recovery was operationalized as the change in lnRMSSD between the pre lesson assessment and the post lesson recovery assessment in the physical education condition.

The analysis revealed a statistically significant positive correlation between PE Δ lnRMSSD and academic achievement, $r = 0.52$, $p < 0.001$. Students who displayed greater increases in lnRMSSD during the recovery period following physical education tended to have higher grade point averages. The magnitude of the correlation indicated a moderate positive association between autonomic recovery and scholastic performance.

The squared correlation coefficient was approximately 0.27, indicating that the two variables shared approximately 27% of their variance. Although this relationship does not imply a causal connection between autonomic recovery and academic performance, it suggests that individual differences in post exercise autonomic regulation are meaningfully associated with educational achievement.

Table 4. Pearson correlation between autonomic recovery and academic achievement

Variables	r	p value	95% CI
PE Δ lnRMSSD and academic achievement	0.52	<0.001	0.35 to 0.66

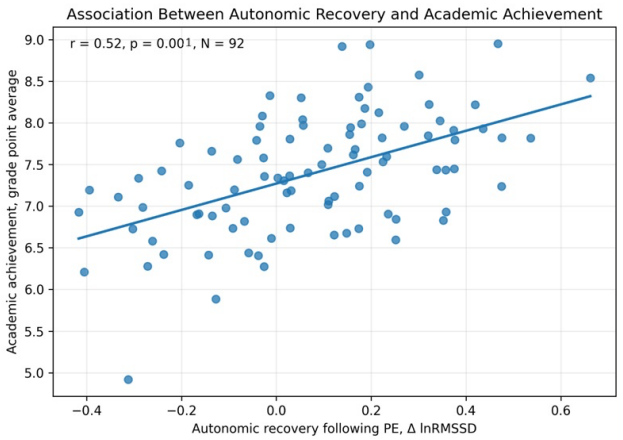

Fig. 1. Association between autonomic recovery following physical education and academic achievement in adolescents. Note: The scatterplot illustrates the positive relationship between the change in lnRMSSD from pre lesson assessment to post lesson recovery, PE Δ lnRMSSD, and academic achievement expressed as grade point average, GPA. The solid line represents the linear regression fit, $r = 0.52$, $p < 0.001$.

Linear Regression Analysis

A simple linear regression analysis was conducted to further examine the association between autonomic recovery

Table 3. Post hoc comparisons of lnRMSSD changes within conditions

Condition	Pre, Mean ± SD	Post, Mean ± SD	Mean change	t	p value	Cohen's dz
Physical education	3.60 ± 0.43	3.67 ± 0.52	0.07	3.06	0.003	0.32
Control	3.48 ± 0.42	3.50 ± 0.44	0.02	1.06	0.292	0.11

following physical education and academic achievement. Academic achievement was entered as the dependent variable, while PE Δ lnRMSSD was entered as the predictor.

The regression model was statistically significant, $F_{(1, 90)} = 34.18$, $p < 0.001$, and accounted for 27.5% of the variance in academic achievement, $R^2 = 0.275$, adjusted $R^2 = 0.267$. Autonomic recovery following physical education was significantly and positively associated with academic achievement, B = 1.58, SE = 0.27, β = 0.52, t = 5.85, $p < 0.001$.

The positive regression coefficient indicates that greater increases in lnRMSSD during the post physical education recovery period were associated with higher academic achievement scores. According to the estimated model, a one unit increase in PE Δ lnRMSSD corresponded to an expected increase of 1.58 units in grade point average. Given the observed range of lnRMSSD change scores, the coefficient should be interpreted in relation to the scale and variability of the physiological measure rather than as evidence of a causal effect.

Visual inspection of residual plots and examination of standardized residuals did not indicate substantial violations of linearity, normality, or homoscedasticity assumptions. No observations exerted excessive influence on the regression estimates.

Table 5. Simple linear regression analysis for academic achievement

Predictor	B	SE	β	t	p value
Constant	7.27	0.03		242.33	<0.001
PE Δ lnRMSSD	1.58	0.27	0.52	5.85	<0.001

Model statistics: $R^2 = 0.275$, adjusted $R^2 = 0.267$, $F(1, 90) = 34.18$, $p < 0.001$.

Discussion

The present study examined autonomic recovery following a regular physical education lesson and its association with academic achievement in adolescents. By comparing HRV responses across a physical education condition and a time-contained control condition, the study sought to determine whether autonomic modulation followed a distinct temporal pattern after curricular physical activity and whether individual differences in this response were associated with scholastic performance. The findings showed a significant Condition × Time interaction for lnRMSSD, characterized by an increase during the post lesson recovery assessment in the physical education condition and no significant change across the corresponding time interval in the control condition. In addition, greater PE related changes in lnRMSSD were positively associated with academic achievement, and the regression analysis confirmed a significant relationship between autonomic recovery and grade point average.

The first relevant finding was the different temporal pattern of lnRMSSD observed across the two conditions. The significant Condition × Time interaction indicates that the autonomic change occurring after the physical education lesson differed from the variation observed during a comparable period without structured physical activity. More specifically, lnRMSSD increased significantly from the pre lesson assessment to the standardized recovery measurement following physical education, whereas no significant variation emerged in the control condition. This pattern suggests that the post lesson assessment captured a condition specific change in vagally mediated cardiac modulation rather than a fluctuation attributable solely to the passage of time during the school morning (May et al., 2017). The small magnitude of the interaction effect, however, indicates that this difference should be interpreted as a modest physiological response rather than a pronounced autonomic alteration.

This finding is consistent with the physiological framework of post exercise autonomic regulation. Physical exercise induces a marked reorganization of cardiac autonomic control, while the period following exercise cessation is characterized by progressive parasympathetic reactivation (Yue et al., 2025). RMSSD is commonly used to describe vagally mediated HRV, and its behavior during recovery provides information concerning the restoration of parasympathetic influence after physical exertion. Previous investigations of post exercise autonomic recovery have shown that parasympathetic reactivation contributes substantially to cardiovascular adjustment following exercise cessation, although its time course varies according to exercise characteristics and individual factors. Research specifically examining young populations has also identified age related characteristics in post exercise parasympathetic reactivation, supporting the relevance of studying recovery responses within developmentally defined groups rather than extrapolating directly from adult samples (Medeiros et al., 2021).

The present findings also extend previous evidence concerning exercise and autonomic modulation in children and adolescents. Existing research has primarily examined the effects of repeated exercise exposure or structured training programs on HRV. Systematic evidence suggests that exercise interventions can improve indices of autonomic modulation in young populations, although considerable heterogeneity exists in exercise modalities, intervention duration, and HRV assessment procedures. The current study addresses a different aspect of this relationship by examining autonomic change following a routine curricular physical education lesson rather than adaptation to a prolonged exercise intervention. This distinction is relevant because the observed response occurred within the ordinary organization of the school day and was compared with a time matched condition involving the same participants (Speer et al., 2022).

The absence of a significant change in lnRMSSD during the control condition provides an important context for interpreting the physical education response. HRV is sensitive to measurement conditions, including posture, time of assessment, recent activity, and contextual influences (Makivić et al., 2013). Consequently, interpreting changes recorded at different points of a school day without a corresponding comparison condition could lead to uncertainty regarding whether the observed variation is related to physical activity or to temporal variability. In the present study, the stability of lnRMSSD across the control period, together with the significant interaction effect, supports the interpretation that the pattern observed

after physical education was distinguishable from ordinary variation across the corresponding time interval. This methodological consideration is particularly relevant in educational research, where HRV assessment is increasingly used but substantial variability remains in recording and analytical procedures. A recent systematic review of HRV applications in educational research emphasized the importance of standardized measurement conditions and careful interpretation of physiological data within the specific context in which recordings are obtained (May et al., 2017).

The second principal finding was the positive association between autonomic recovery following physical education and academic achievement. Students who exhibited greater increases in lnRMSSD from the pre lesson assessment to the post lesson recovery period tended to have higher grade point averages. The correlation was moderate in magnitude, indicating a meaningful association while also demonstrating that the two constructs remain clearly distinct. This result should therefore be interpreted as evidence of covariation between the physiological response observed after physical education and scholastic performance, rather than as evidence that either variable determines the other (Buchheit et al., 2007).

One possible interpretation, restricted to the variables assessed in the present study, is that academic achievement differs systematically in relation to individual variability in autonomic recovery following physical exertion. The result indicates that students were not homogeneous in their post lesson HRV responses and that part of this interindividual variation was associated with differences in grade point average. Importantly, the present data do not identify the processes underlying this association. The study did not assess cognitive performance, psychological stress, classroom behavior, or other potential explanatory variables, and these mechanisms therefore cannot be inferred from the observed relationship. The finding instead establishes a direct empirical association between a physiological recovery index and an educational outcome, providing a focused basis for subsequent investigation (Chen et al., 2022).

The relationship observed in the present study can be situated within the emerging use of HRV in educational research (Kim et al., 2024). The literature in this area remains comparatively limited and has focused predominantly on physiological responses to stress and on university populations, while studies involving school aged participants and educational outcomes are less represented. The growing interest in HRV within educational contexts reflects the possibility of integrating objective physiological measures with conventional indicators of educational functioning. At the same time, current methodological reviews emphasize that the validity of HRV interpretation depends on the research question, recording context, and analytical approach. The present findings contribute to this developing field by showing that a dynamically derived HRV measure, obtained in relation to a naturally occurring physical education lesson, was associated with official academic performance in adolescents (Silva et al., 2022).

The positive correlation between PE Δ lnRMSSD and academic achievement was further supported by the regression analysis. Autonomic recovery was significantly associated with grade point average, with the model accounting for approximately 27.5% of the variance in academic achievement. This proportion indicates that the association was statistically meaningful within the present sample, while leaving most of the variability in academic performance unexplained. Such a pattern is consistent with the multifactorial nature of scholastic achievement and reinforces the need for a circumscribed interpretation of the regression model. The regression analysis confirmed the statistical association between autonomic change during early recovery and academic achievement. However, given the concurrent nature of this association, the model should not be interpreted as evidence of prospective prediction or causality (Ketelhut et al., 2024).

Taken together, the findings provide two complementary observations. First, autonomic modulation differed across the physical education and control conditions, with a modest but statistically significant condition dependent on temporal response. Second, individual differences in the HRV change observed following physical education were positively associated with academic achievement. These results connect an acute physiological response to a routine component of the school curriculum with an objective indicator of scholastic performance, while preserving a clear distinction between association and causation. The findings are particularly relevant because physical education was examined within its ordinary curricular context rather than through an externally imposed laboratory exercise protocol.

Several strengths of the study should be acknowledged. The within participant design allowed each student to serve as his or her own control, thereby reducing the influence of stable interindividual differences when comparing the physical education and control conditions. The inclusion of a time matched control condition strengthened the interpretation of temporal changes in HRV and reduced the possibility of attributing ordinary within day variation to the physical education lesson. The use of standardized recording procedures, a single prespecified HRV index, and official school grades limited measurement complexity and ensured direct alignment between the study aims, physiological assessment, and educational outcome. Furthermore, conducting the study during regular school activities increased ecological validity and allowed autonomic responses to be examined within the context in which physical education ordinarily occurs.

The study also presents limitations. First, although the repeated measures design supports comparison between conditions, the association between autonomic recovery and academic achievement remains observational and does not permit causal inference. Second, autonomic recovery was assessed through a single standardized post lesson HRV recording. Consequently, the study captured autonomic status during a defined recovery window rather than the complete temporal trajectory of parasympathetic restoration. Future research could incorporate repeated post exercise measurements to characterize the recovery curve more comprehensively. Third, the study relied on grade point average as the sole indicator of academic achievement. Although official grades provide an ecologically meaningful measure of school performance, the findings cannot be generalized to other educational outcomes that were not assessed. Fourth, the study was conducted within a specific school context, which may limit the generalizability of the

findings to educational systems with different curricular structures or physical education practices. Finally, the regression model included autonomic recovery as a single predictor and was intentionally designed to examine a focused bivariate relationship. The proportion of unexplained variance confirms that the model should not be interpreted as a comprehensive account of academic achievement, but as an examination of the specific association between post physical education autonomic recovery and scholastic performance.

Conclusions

The present study showed that cardiac autonomic modulation followed a different temporal pattern after a regular physical education lesson compared with a time matched control condition. The increase in lnRMSSD observed during the post lesson recovery period, together with the significant Condition × Time interaction, indicates that curricular physical education was followed by a distinct autonomic response within the school day. Furthermore, greater autonomic recovery following physical education was positively associated with academic achievement, and this relationship was supported by both correlation and regression analyses. These findings provide evidence of a meaningful association between post exercise autonomic regulation and scholastic performance in adolescents, while the observational nature of the relationship precludes causal interpretation. Assessing HRV responses to physical education within authentic school settings may offer a useful physiological perspective for research examining the relationship between curricular physical activity and educational outcomes. Future studies should investigate autonomic recovery across multiple post exercise time points and in larger and more diverse school populations to determine the consistency and temporal characteristics of the observed association.

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Institutional Review Board Statement

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).

Informed Consent Statement

Informed consent was obtained from all participants prior to participatioin the study. For participants under 18 years of age, written informed consent was n additionally obtained from 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 (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. All study design, data collection, data analysis, interpretation of findings, and final scientific content were developed, verified, and approved by the authors. The authors accept full responsibility for the accuracy, integrity, and originality of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Післянавантажувальне фізіологічне відновлення та академічна успішність підлітків: роль автономної регуляції

Емма Сарайелло[1ABD], Франческа Латіно[2ABCD], Джулія Амато[1BCD], Марія Джованна Тафурі[3ABC]

[1]Університет Неаполя «Партенопе»
[2]Університет Саленто
[3]Університет «Пегасо»

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

Реферат. Стаття: 11 с., 5 табл., 1 рис., 32 джерела.

Передумови. Фізичне виховання є регулярним фізіологічним стимулом упродовж навчального дня, проте автономне відновлення після уроків фізичної культури та його зв'язок з академічною успішністю залишаються недостатньо вивченими.

Мета. Порівняти автономне відновлення після звичайного уроку фізичної культури з відповідною за тривалістю контрольною умовою та визначити, чи пов'язане автономне відновлення з академічною успішністю підлітків.

Матеріали та методи. Дев'яносто два підлітки взяли участь у дослідженні з повторними вимірюваннями, у якому виконували програму в умовах уроку фізичної культури та в контрольній умові аналогічної тривалості. Варіабельність серцевого ритму реєстрували до та після кожної умови, а квадратний корінь із середнього квадрата різниць між послідовними інтервалами аналізували після натурального логарифмічного перетворення (lnRMSSD). Академічну успішність оцінювали за офіційним середнім балом успішності.

Результати. Виявлено статистично значущу взаємодію «Умова × Час» для показника lnRMSSD, $F_{(1, 91)} = 4{,}06$, $p = 0{,}047$, часткова $\eta^2 = 0{,}043$. Апостеріорний аналіз показав статистично значуще підвищення lnRMSSD після уроку фізичної культури ($p = 0{,}003$), тоді як у контрольній умові статистично значущих змін не виявлено ($p = 0{,}292$). Автономне відновлення після уроку фізичної культури позитивно корелювало з академічною успішністю ($r = 0{,}52$, $p < 0{,}001$). Регресійна модель була статистично значущою та пояснювала 27,5 % варіації академічної успішності ($R^2 = 0{,}275$, $p < 0{,}001$).

Висновки. Автономна модуляція після уроку фізичної культури відрізнялася від такої після контрольної умови аналогічної тривалості, а більш виражене автономне відновлення після уроку було пов'язане з вищою академічною успішністю. Отримані результати свідчать, що автономне відновлення після уроку фізичної культури може бути важливим фізіологічним корелятом академічної успішності підлітків та підтверджують доцільність подальших лонгітюдних і інтервенційних досліджень ролі автономної регуляції в освітніх результатах.

Ключові слова: варіабельність серцевого ритму, кардіальна вагусна модуляція, академічна успішність, парасимпатична реактивація, фізіологія фізичних вправ, учні закладів загальної середньої освіти.

Information about the Authors:

Saraiello Emma: esaraiello@gmail.com; https://orcid.org/0000-0002-8783-6112; Department of Medical, Human Movement and Well-Being Sciences, University of Naples "Parthenope", 80100 Naples, Italy.

Latino Francesca: francesca.latino@unisalento.it; https://orcid.org/0000-0003-0302-6145; Department of Biological and Environmental Sciences and Technologies, University of Salento, 73100 Lecce, Italy.

Amato Giulia: giulia.amato@uniparthenope.it; https://orcid.org/0009-0004-4383-175X; Department of Medical, Human Movement and Well-Being Sciences, University of Naples "Parthenope", 80100 Naples, Italy.

Tafuri Maria Giovanna: mariagiovanna.tafuri@unipegaso.it; https://orcid.org/0009-0008-5835-1846; Department of Literary, Linguistic and Philosophical Studies, Pegaso University, 80143 Naples, Italy.

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Original Scientific Articles. Training Effects and Experimental Design

Effect of Training Load and Recovery Time on Neuromuscular Performance in Elite Youth Soccer Players

Walid Bouzid[1ABCDE], Carla Lourenço[3,4,5ABCDE], Khalaf Waleed Khalaf Diabat[6ABCDE], Omar Ben Rakaa[2ABCDE], Aziz Chokri[1ABCDE], Aziz Eloirdi[1ABCDE] and Mohamed Barkaoui[1ABCDE]

[1]Hassan 1st University
[2]Hassan II University of Casablanca
[3]Polytechnic Institute of Viseu
[4]University of Beira Interior
[5]Centre for Studies in Education and Innovation
[6]Al al-Bayt University

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

Corresponding Author: Walid Bouzid, e-mail: walidbouzidphd@gmail.com
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Abstract

Background. Managing training load and recovery in developing elite footballers is a major challenge for optimizing performance while limiting the risk of neuromuscular fatigue. Vertical jump with countermovement (VJM) remains a preferred indicator of neuromuscular status, but recovery kinetics after microcycles of contrasting intensity remain insufficiently documented in young athletes.

Objectives. To examine the impact of training load and recovery time on neuromuscular performance by analyzing the modulating effects of microcycle type, age category, and acute-to-chronic workload ratio (ACWR).

Materials and Methods. Seventy-five elite male footballers (U16-U18) participated in a six-month longitudinal protocol including CMJ assessments before and 24 h and 48 h after moderate- and high-intensity microcycles. Linear mixed models were used to analyze main effects and interactions.

Results. Significant effects were observed for microcycle type ($F = 69.93$, $p < 0.001$), measurement time ($F = 374.48$, $p < 0.001$), and ACWR ($F = 7.41$, $p = 0.007$). High-intensity microcycles induced greater decreases in CMJ performance at 24 h ($\beta = -1.072$, $p < 0.001$), followed by partial recovery at 48 h. ACWR was strongly correlated with CMJ changes at 24 h ($r = -0.766$, $p < 0.001$).

Conclusion. A critical window of neuromuscular fatigue exists 24 h after a microcycle, modulated by training intensity and workload context, supporting the value of systematic neuromuscular monitoring following high-intensity microcycles.

Keywords: neuromuscular fatigue, countermovement jump, training load, acute-to-chronic workload ratio, young footballers, recovery.

Introduction

Training load management is a major challenge in modern soccer, where congested competition schedules force elite players to compete in more than 60 matches per season with limited recovery windows. Consequently, finding the optimal balance between applying sufficient training stimuli to induce physiological adaptations and preventing excessive fatigue accumulation is a central concern for coaching staff (West et al., 2021). This issue is particularly critical for reducing the risk of non-contact injuries, which are often associated with acute peaks in training load or chronic inadequate preparation (Malone et al., 2017a). Therefore, longitudinal monitoring of neuromuscular responses to training loads allows for the early identification of fatigue states and the adjustment of training programs accordingly (Evans et al., 2022). However, the temporal kinetics of recovery and its modulation by training load intensity

remain insufficiently documented, especially in developing populations. Moreover, developing elite footballers (U16-U18) exhibit specific physiological characteristics that make training load management a complex task.

This period coincides with major biological transformations linked to pubertal maturation, including changes in body composition, force production capacity, and the mechanical properties of the musculo-tendinous system (García-Santamaría et al., 2024; Wenger & Csapo, 2025). Although biological maturation status is a key determinant of load tolerance, the present study relies on chronological age as a developmental indicator. This methodological choice is based on the logistical feasibility of longitudinal follow-up in an applied context and the systematic availability of this variable in soccer academies, while recognizing that this approach does not fully capture inter-individual maturational heterogeneity. Nevertheless, considerable variability in maturation status at identical chronological ages generates substantial heterogeneity in injury susceptibility, with biologically less mature players demonstrating increased vulnerability when exposed to loads comparable to those of their more developmentally advanced peers (Gundersen et al., 2022). Elite soccer academies impose dense competition and training schedules during this critical phase, making it imperative to implement robust, individualized monitoring strategies to optimize the load-adaptation-recovery continuum (Hannon et al., 2021).

The countermovement jump (CMJ) test has established itself as a reference tool for quantifying neuromuscular performance and detecting residual fatigue in team sports (R. Gathercole et al., 2015). Indeed, its non-invasiveness, logistical feasibility, short administration time, and proven sensitivity to training- and competition-induced alterations in neuromuscular function make it particularly suitable for the longitudinal monitoring of young athletes (Silva et al., 2021). The CMJ evaluates the capacity of the stretch-shortening cycle (SSC), a fundamental mechanism underlying explosive soccer actions such as sprints, changes of direction, and jumps (Falces-Prieto et al., 2022). Variations in jump height reflect the functional state of peripheral (muscle contractility, tendon elastic properties) and central (corticospinal excitability, recruitment strategies) components of the neuromuscular system, enabling an integrative assessment of fatigue (Muñoz-Gracia et al., 2025). Small to moderate reductions in CMJ performance (ES = -0.38 to -0.42) have been documented within 12 to 24 hours after matches in footballers, with a trend toward partial recovery at 48 hours, confirming its validity as a marker of recovery (Akyildiz et al., 2022).

However, the majority of previous studies have adopted cross-sectional designs or focused on adult populations, limiting the generalizability of their findings to young elite players. The temporal dynamics of neuromuscular recovery are a crucial parameter for rational training planning, particularly in microcycles in which several high-intensity sessions must be scheduled (Clemente et al., 2025). The 24- and 48-hour post-exercise windows represent critical decision points: at 24 hours, neuromuscular fatigue generally reaches its peak, whereas at 48 hours, partial recovery is expected, although its magnitude remains influenced by the initial training load (Evans et al., 2022). Understanding precisely how microcycle intensity (moderate versus high) modulates these recovery kinetics would make it possible to optimize session spacing and individualize the required recovery periods. High-load microcycles, characterized by greater training volumes and intensities, induce more pronounced and prolonged neuromuscular disturbances than moderate microcycles, but precise quantitative data for elite young footballers remain scarce (Martin-Garetxana et al., 2024). The potential interaction between microcycle type, recovery time, and age category has not been systematically explored using appropriate analytical models that account for the hierarchical structure of longitudinal data.

Integrated quantification of training load via complementary internal and external methods is a recommended practice in contemporary soccer (West et al., 2021). Subjective effort perception (session-RPE) offers a global estimate of internal load, while global positioning systems (GPS) and accelerometry provide objective data on external mechanical load (Benson et al., 2020). The Acute:Chronic Workload Ratio (ACWR) has emerged as a contextualized indicator for relating recent training load to chronic exposure (Malone et al., 2017a). However, the use of ACWR is the subject of substantial methodological debate because of several fundamental limitations. First, the inherent mathematical coupling between the numerator and denominator (the acute workload being included in the calculation of the chronic workload) introduces an artificial statistical dependence that can confound associations with outcome variables.

Secondly, the debate over the use of ratios versus differences has highlighted that ACWR does not adequately normalize the acute workload relative to the chronic workload, making its interpretation ambiguous. Thirdly, the optimal time windows for calculating acute (7 days) and chronic (21–28 days) workloads, as well as the calculation methods (moving averages versus exponentially weighted moving averages), remain controversial. Several authors have recently questioned the causal validity of ACWR for predicting injury risk, arguing that the observed associations may reflect methodological artifacts rather than true prognostic relationships. Despite these critical considerations, ACWR remains a potentially relevant heuristic tool when integrated into a multimodal monitoring approach, particularly when examined in conjunction with direct measures of neuromuscular performance such as the CMJ (Bowen et al., 2017). Despite the accumulation of knowledge, several substantial gaps remain. First, the majority of studies have adopted cross-sectional designs, limiting the understanding of individual longitudinal recovery trajectories (Wiewelhove et al., 2024).

No investigation has simultaneously examined the influence of microcycle type (moderate versus high), recovery time (baseline, 24 h, 48 h), and chronological age category (U16, U17, U18) on neuromuscular performance using appropriate statistical models that account for repeated measures. This specific combination of factors in a controlled longitudinal design represents a novel contribution beyond the work of Martin-Garetxana et al. (2024), which did not simultaneously integrate these three temporal and developmental dimensions. Thirdly, the application of linear mixed models, which account for the dependence of intra-individual observations and explicitly model fixed and random effects, remains underutilized in this field of

research (Connolly et al., 2024). Fourthly, the time-specific predictive ability of ACWR for 24- and 48-hour changes in CMJ performance, as well as the magnitude of these associations, has not been systematically quantified in elite youth footballers despite the methodological controversies surrounding this indicator.

Finally, the practical implications for individualized training planning according to developmental status require empirical documentation. To address these gaps, this study aims to examine the impact of training load and recovery time on neuromuscular performance, as assessed by the CMJ, in developing elite footballers. A longitudinal design was adopted and analyzed using linear mixed models, allowing the hierarchical and repeated structure of the data to be taken into account. Specifically, the study aims to analyze the temporal evolution of CMJ performance at baseline and 24 and 48 hours after moderate- and high-load microcycles; to compare the kinetics of neuromuscular recovery among the U16, U17, and U18 chronological age categories; to examine the association between ACWR and changes in CMJ performance at different measurement time points; and to identify predictive factors (ACWR, total load, RPE, age, category, and microcycle type) associated with changes in neuromuscular performance at 24 and 48 hours after the microcycle.

Materials and Methods

This study adopted a within-subjects, repeated-measures design. Specifically, Each player was assessed at three time points (baseline, 24 h and 48 h post-microcycle) in two conditions corresponding to a moderate-load microcycle (MOD) and a high-load microcycle (HIGH), generating six measures of neuromuscular performance (CMJ) per participant (2 microcycles × 3 time points). The two microcycles were conducted during the competitive season and separated by a minimum interval of three weeks. Furthermore, the order of exposure to MOD and HIGH conditions was counterbalanced between participants. Although The microcycles had a comparable structure (4-5 sessions over 7 days) but differed intentionally in terms of internal and external load.

In this context, HIGH microcycles corresponded to weeks characterized by high acute load (ACWR ≥ 1.3), associated with higher volumes of total distance and accelerations, while MOD microcycles corresponded to acute loads between 0.8 and 1.3 of the individual chronic load. Importantly, The classification of microcycles was based on the weekly planning of the technical staff and was validated a posteriori by analysis of the recorded loads. All evaluations were carried out in a standardized training environment. Players followed a common weekly program within their age category.

Study Participants

Seventy-five (n = 75) elite male footballers in the training phase were included in this study and divided into three chronological age categories: U16 (n = 25; age: 15.4 ± 0.5 years; body mass: 63.2 ± 7.8 kg; height: 172.5 ± 6.3 cm), U17 (n = 24; age: 16.5 ± 0.4 years; body mass: 67.1 ± 8.2 kg; height: 176.2 ± 5.9 cm) and U18 (n = 26; age: 17.6 ± 0.5 years; body mass: 71.3 ± 7.5 kg; height: 178.9 ± 6.1 cm). All participants played for a professional soccer club at national level and had a minimum of five years' structured playing experience, including organized club training. To characterize developmental status, the players' biological maturation was estimated retrospectively using the maturity offset (years from peak statural growth velocity, PHV), calculated according to the regression equation proposed by (Monasterio et al., 2024) integrating chronological age and body size. This indirect approach, widely used in applied contexts where direct assessment of maturation is not feasible, provides a continuous estimate of individual maturational status. Descriptive analyses revealed a progressive increase in offset maturity with chronological age, with mean values of 1.40 ± 0.37 years in U16s, 2.02 ± 0.42 years in U17s and 2.79 ± 0.43 years in U18s, indicating that the majority of players were in the post-PHV phase. These results confirm the existence of differences in biological maturation between age categories, while also highlighting inter-individual variability within each group (Table 1).

Biological Maturation Characteristics

Descriptive analysis of biological maturation revealed a progressive increase in maturity offset across age categories. Mean maturity offset values were 1.40 ± 0.37 years in U16 players, 2.02 ± 0.42 years in U17 players, and 2.79 ± 0.43 years in U18 players, indicating that the majority of players were post–peak height velocity. These results confirm substantial inter-category differences in biological maturation status within the sample.

Inclusion and Exclusion Criteria

Inclusion criteria included: (1) regular participation in training and competitions during the study period, (2) absence of musculoskeletal injury limiting full-intensity practice during the three months prior to inclusion, and (3) absence of medical contraindication to intensive sports practice. Exclusion criteria included less than

Table 1. Biological maturation characteristics by age category (maturity offset, years from PHV)

Variable	U16 (n = 25)	U17 (n = 24)	U18 (n = 26)
Maturity offset (years from PHV), mean ± SD	1.40 ± 0.37	2.02 ± 0.42	2.79 ± 0.43
Median [IQR]	1.39 [1.16–1.63]	1.92 [1.72–2.31]	2.91 [2.61–3.14]
Min–Max	0.69–2.11	1.44–3.19	1.91–3.35

Note. Maturity offset (years from peak height velocity, PHV) was retrospectively estimated from chronological age and standing height using a regression-based prediction model. Positive values indicate post-PHV maturation status. Descriptive statistics are reported per player (baseline values only).

90% participation in scheduled training sessions, or the occurrence of an injury resulting in prolonged unavailability incompatible with longitudinal follow-up.

This 90% threshold was chosen to guarantee sufficient and homogeneous exposure to the micro-training cycles analyzed, a necessary condition for valid interpretation of neuromuscular responses to imposed loads. Over the entire investigation period, the average rate of participation in the training sessions was 93.4 ± 4.1%, with no difference between age categories. During follow-up, no participant was excluded from the final analysis due to major injury. Players with transient discomfort or short-term unavailability (≤ 7 days) returned to full training after recovery, and their data were retained in the analyses. No partial data censoring was applied, and all 75 participants initially recruited were included in the final analyses.

The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and received approval from the local institutional ethics committee. Written informed consent was obtained from all participants, and from their legal representatives in the case of minors. A prior information meeting was organized with the players and their parents to present the objectives, procedures, expected benefits and potential risks associated with participation. Participants were informed of their right to withdraw from the study at any time, without justification or consequence. A two-week familiarization period preceded data collection in order to limit learning effects, particularly for neuromuscular performance assessments and the use of the perception of effort scale.

Measuring Instrument

Assessment of Neuromuscular Performance

Countermovement jump (CMJ): Neuromuscular performance was assessed using the countermovement vertical jump (CMJ) test, widely recognized as a valid and sensitive indicator of neuromuscular status and training-induced fatigue in team sports athletes (R. Gathercole et al., 2015). Jumps were performed using a Chronojump Boscosystem contact platform (version 1.6.2, Barcelona, Spain). The validity of this tool was demonstrated by near-perfect correlation with reference force platforms ($r \approx 0.99$), as well as excellent intra-device reliability (coefficient of variation < 5%) for jump height measurement (Pueo et al., 2020). Participants performed the test with feet shoulder-width apart, hands on hips to eliminate upper limb contribution. After a standardized 10-minute warm-up, three maximal trials were performed, separated by 60 seconds of passive recovery. The best performance (jump height in cm) among the three trials was retained for analysis, in line with methodological recommendations (R. Gathercole et al., 2015) in accordance with standard protocols. Testing occurred consistently between 09:00–11:00 to minimize circadian effects.

Quantifying Drive Load

Internal training load was quantified with the session-rating of perceived exertion (sRPE) method, using Foster's modified CR-10 scale (Foster et al., 2001). Approximately 20 minutes after each session, players individually answered the question: "How would you rate the overall difficulty of this session?", on a scale ranging from 0 (rest) to 10 (maximum effort). The internal load for each session was calculated by multiplying the RPE score by the session duration (sRPE = RPE × duration, in arbitrary units). This method is widely validated in footballers, with strong correlations with physiological markers and heart rate-based methods (Impellizzeri et al., 2020).

External training load was measured using Catapult Sports® global positioning systems (GPS), model OptimEye S5 (Catapult Sports, Melbourne, Australia), sampling at 10 Hz, with integrated triaxial accelerometers at 100 Hz. The validity and reliability of this device for analyzing locomotor demands in soccer have been widely documented (Akyildiz et al., 2024; Kielė & Solianik, 2023). Each player wore the same GPS unit throughout the study to limit inter-unit variability. Variables analyzed included total distance covered (m), number of accelerations > 2 $m \cdot s^{-2}$ and number of high-intensity accelerations > 3 $m \cdot s^{-2}$. Data were processed with proprietary OpenField™ software (Catapult Sports), using the manufacturer's standard filtering algorithms, in accordance with the methodological recommendations for the analysis of GPS data in soccer.

Acute-to-chronic Workload Ratio (ACWR)

The acute-to-chronic workload ratio (ACWR) was calculated to contextualize each player's recent workload versus chronic exposure. Acute workload was defined as the current week's total training load (sRPE) (7 days), while chronic workload was defined as the moving average of the previous four weeks (28 days). ACWR was calculated according to the following formula: ACWR = acute load / chronic load, using a coupled rolling average, a method commonly employed in the soccer literature (Pinelli et al., 2025a). ACWR values were interpreted according to the classically proposed thresholds: < 0.8 (underexposure), 0.8-1.3 (optimal zone), 1.3-2.0 (preparation zone) and > 2.0 (increased risk zone) (Qin et al., 2025a).

Although maturity offset (years from peak growth velocity, PHV) was estimated for descriptive purposes to characterize the developmental profile of the sample, it was not incorporated into the main inferential models for two reasons. Firstly, the study was designed and scaled around the grouping strategy applied in elite soccer academies (U16-U18 categories), making chronological age category the most ecologically valid decision variable for practitioners. Secondly, as maturity offset is mathematically derived from age and body size, it exhibits substantial overlap with chronological age and/or age category in predominantly post-PHV samples, which may introduce redundancy and collinearity in multivariate models. Consequently, offset maturity was reported to describe the sample and inform interpretation of the results, while chronological age category was retained as the main developmental factor in inferential analyses.

Ethical Considerations

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki for research involving human participants. All procedures were designed to ensure the safety, well-being, and rights of the participants throughout the study. Prior to inclusion, all players and their

legal guardians (for minors) received detailed information regarding the study objectives, procedures, expected benefits, and potential risks. Written informed consent was obtained from all participants and their legal guardians before data collection.

Participation in the study was entirely voluntary, and participants were informed of their right to withdraw at any time without any consequences. The collected data were anonymized and handled confidentially in accordance with applicable data protection regulations.

The procedures implemented (countermovement jump testing and training load monitoring) are non-invasive and commonly used in sports science, thus presenting minimal risk to participants.

Statistical Analysis

All statistical analyses were performed with significance set at $p < 0.05$ using SPSS software, version 27.0.1.0. Descriptive statistics are presented as means ± standard deviation and 95% confidence intervals. The effect of microcycle type (moderate vs. high), recovery time (baseline, 24 h, 48 h), age category (U16, U17, U18) and acute-to-chronic workload ratio (ACWR) on neuromuscular performance (CMJ) was examined using a linear mixed model, including a random intercept per participant to account for intra-individual repeated measures. Degrees of freedom were estimated using the Satterthwaite method. In the presence of significant effects, post-hoc comparisons were made using estimated marginal means (EMM), with Bonferroni adjustment for multiple comparisons. Separate multiple linear regressions were used to identify predictors of variations in CMJ performance at 24 h and 48 h post-microcycle. Models included ACWR, total training load, mean RPE, age category and microcycle type. Regression coefficients, fit indices (R^2, adjusted R^2) and root mean square error (RMSE) were reported. Pearson correlations were calculated to examine associations between load indicators and CMJ performance variations. Sensitivity analyses related to collinearity between ACWR and total load are presented in supplementary material.

Results

The results are organized to describe the evolution of neuromuscular performance according to microcycle type, recovery time, and age category. The effect of moderate and high-load microcycles is examined based on variations in CMJ height measured at rest, then 24 and 48 hours after training, taking into account the load context represented by the ACWR. Comparisons between conditions allow us to characterize the kinetics of fatigue and recovery, as well as the differences observed between the U16, U17, and U18 categories. Finally, the association between training load indicators and CMJ variations is explored in order to identify the factors most closely related to short- and medium-term alterations in neuromuscular performance.

Effects of Training Load and Recovery Time on CMJ Performance

Descriptive statistics for countermovement jump (CMJ) height across experimental conditions are summarized in Table 2. The analysis included 450 total observations with no missing values. When examining main effects, CMJ height increased with age category, with U18 players demonstrating the highest mean performance (38.82 ± 3.29 cm), followed by U17 (36.27 ± 3.33 cm) and U16 players (33.30 ± 3.53 cm). Regarding recovery kinetics, CMJ performance was highest at baseline (38.21 ± 3.02 cm), decreased substantially at 24 h post-training (34.30 ± 4.41 cm), and showed partial recovery at 48h (35.99 ± 3.70 cm). High-load microcycles resulted in significantly lower CMJ values (34.20 ± 4.03 cm) compared to moderate-load microcycles (38.13 ± 3.04 cm), reflecting the differential neuromuscular impact of training intensity.

Table 2. Descriptive statistics for Countermovement Jump (CMJ) height across experimental factors

Factor	Level	n	Mean ± SD (cm)	95% CI
Category	U16	150	33.30 ± 3.53	[32.73, 33.87]
	U17	144	36.27 ± 3.33	[35.72, 36.82]
	U18	156	38.82 ± 3.29	[38.30, 39.34]
Timepoint	Baseline	150	38.21 ± 3.02	[37.72, 38.70]
	24h Post	150	34.30 ± 4.41	[33.59, 35.01]
	48h Post	150	35.99 ± 3.70	[35.39, 36.58]
Microcycle Type	High	225	34.20 ± 4.03	[33.67, 34.73]
	Moderate	225	38.13 ± 3.04	[37.73, 38.53]
Overall	Total	450	36.16 ± 4.07	[35.78, 36.54]

Note. SD = Standard Deviation; CI = Confidence Interval; n = number of observations. Data represent raw CMJ height measurements before statistical modeling. The sample size per cell in the complete factorial design (3 Categories × 2 Microcycle Types × 3 Timepoints) is 25 observations.

To further investigate these preliminary observations, linear mixed models were employed to account for repeated measures and examine the independent and interactive effects of microcycle type, recovery timepoint, age category, and ACWR on CMJ performance. This approach allows us to move beyond descriptive statistics and assess the statistical significance of observed differences while controlling for inter-individual variability.

The results of the linear mixed model analysis are presented in Table 3 and Table 4. A significant main effect was found for ACWR, Microcycle Type, Timepoint, and Category (all $p < .001$). Crucially, a significant two-way interaction was observed between Microcycle Type and Timepoint ($F_{(2, 214.53)} = 138.45$, $p < .001$). No other interactions (Microcycle Type × Category, Timepoint × Category, or the three-way interaction) were statistically significant (all $p > .34$).

Post-hoc examination of the significant interaction (Table 3) revealed that the negative effect of a high-load microcycle on CMJ height was most pronounced at the 24-hour post-training timepoint (interaction term: $\beta = -1.07$, $t_{(214.53)} = -13.88$, $p < .001$), indicating a more severe and prolonged neuromuscular fatigue compared to a moderate-load microcycle. By 48 hours, the difference in CMJ performance between microcycle types was no longer significant (interaction term: $\beta = -0.08$, $p = .315$). Furthermore, a higher ACWR was independently associated with lower CMJ performance ($\beta = -1.77$, $p = .007$). The model

included a random intercept for each participant ('ID') to account for baseline inter-individual variability. Random slopes for the Microcycle Type Timepoint interaction could not be reliably estimated due to constraints in the data structure and were therefore omitted from the final model to ensure convergence and stability of the estimates.

Table 3. Analysis of fixed effects from the linear mixed model on Countermovement Jump (CMJ) height

Effect	df_num	df_den	F	p
ACWR	1	198.66	7.412	.007
Microcycle Type	1	191.47	69.930	< .001
Timepoint	2	77.29	374.481	< .001
Category	2	71.90	65.698	< .001
Microcycle Type × Timepoint	2	214.53	138.445	< .001
Microcycle Type × Category	2	124.19	0.856	.427
Timepoint × Category	4	77.29	1.044	.390

Note. df_num = numerator degrees of freedom; df_den = denominator degrees of freedom (Satterthwaite method). Significant effects ($p < .05$) are highlighted in bold. The model included ACWR as a continuous covariate, Microcycle Type (Moderate, High), Timepoint (Baseline, 24h, 48h), and Category (U16, U17, U18) as fixed factors, and a random intercept for participant ID.

Building on the results of the mixed model analysis, estimated marginal means were calculated to visualize the temporal evolution of CMJ performance across microcycle types and age categories. These estimates provide a clearer understanding of the magnitude and direction of neuromuscular fatigue and recovery, and facilitate interpretation of practical differences between conditions.

Temporal Evolution of Neuromuscular Performance as a Function of Age, Training Load, and Microcycle Type

Estimated marginal means demonstrated a progressive increase in CMJ performance across age categories, with U16 players exhibiting the lowest values and U18 players the highest across all conditions. Within each age category, moderate-load microcycles consistently yielded higher estimated marginal mean values compared to high-load microcycles at all measurement timepoints. At 24 hours post-training, the difference between moderate- and high-load conditions was most pronounced across all age groups (U16: $\Delta = 5.15$ cm; U17: $\Delta = 5.14$ cm; U18: $\Delta = 5.15$ cm). For high-load microcycles, the lowest CMJ values were observed at 24 hours post-training (U16: 28.72 ± 0.42 cm; U17: 31.84 ± 0.43 cm; U18: 34.50 ± 0.42 cm), followed by partial recovery at 48 hours and near-complete recovery at baseline. Standard errors remained consistent across conditions (SE ≈ 0.42), indicating stable precision of the estimated values throughout the model. The significant main effect of age category observed in the model should be interpreted with caution, as the classification was based on chronological age and may, at least in part, reflect underlying inter-individual differences in biological maturation status rather than the effect of chronological age per se.

Building on the patterns observed in the estimated marginal means, multiple linear regression models were developed to predict CMJ changes at 24 and 48 hours post-microcycle. This approach allows us to quantify the relative contributions of ACWR, training load, perceived exertion, age category, and microcycle type to neuromuscular performance recovery, moving beyond descriptive observations to predictive analysis.

Prediction of CMJ Recovery at 24 and 48 h Following Training Microcycles

The multiple linear regression model predicting CMJ changes at 24 hours post-microcycle (M_1) explained 65.6% of the variance ($R^2 = 0.656$, adjusted $R^2 = 0.651$), with a root mean square error of 1.659 cm. The model demonstrated strong predictive capacity ($R = 0.81$), indicating that the combination of ACWR, training load, RPE, age, category, and microcycle type accounted for a substantial proportion of neuromuscular performance changes at this timepoint. For CMJ changes at 48 hours post-microcycle, the null

Table 4. Parameter estimates for key fixed effects from the linear mixed model

Parameter	Estimate(β)	SE	df	t	p
Intercept	38.372	0.847	214.95	45.316	< .001
ACWR	-1.771	0.651	198.66	-2.722	.007
Microcycle Type (High vs. Ref.)	-1.504	0.180	191.47	-8.362	< .001
Timepoint (24h vs. Baseline)	-1.870	0.092	72.96	-20.393	< .001
Timepoint (48h vs. Baseline)	-0.180	0.091	77.91	-1.985	.051
Category (U16 vs. Ref.)	-2.826	0.281	71.89	-10.057	< .001
Category (U17 vs. Ref.)	0.131	0.284	71.91	0.460	.647
Microcycle Type (High) × Timepoint (24 h)	-1.072	0.077	214.53	-13.881	< .001
Microcycle Type (High) × Timepoint (48 h)	-0.078	0.077	214.53	-1.006	.315

Legend. SE = Standard Error; df = denominator degrees of freedom. Factors were sum-coded. The Intercept represents the estimated grand mean of CMJ height (cm). The reference levels (Ref.) for the contrasts are the overall means across factor levels. For clarity, only parameters for significant main effects and the significant interaction are shown; non-significant higher-order interaction terms (involving Category) are omitted. The estimates for Microcycle Type and Timepoint represent the deviation of the «High» level and the post-training timepoints from the grand mean, respectively. The negative estimate for the interaction term (Microcycle Type (High) × Timepoint (24 h)) indicates a greater decrease in CMJ performance 24 hours after a high-load microcycle.

Table 5. Estimated marginal means of countermovement jump height according to age category, microcycle type, and recovery timepoint

Category	Microcycle	Timepoint	EMM (cm)	SE	95% CI Lower	95% CI Upper
U16	HIGH	24 h	28.72	0.422	27.89	29.55
	MOD	24 h	33.87	0.422	33.04	34.70
	HIGH	48 h	31.55	0.422	30.73	32.38
	MOD	48 h	34.72	0.422	33.89	35.55
	HIGH	Baseline	35.12	0.422	34.29	35.95
	MOD	Baseline	35.84	0.422	35.01	36.67
U17	HIGH	24 h	31.84	0.427	31.00	32.67
	MOD	24 h	36.98	0.431	36.14	37.83
	HIGH	48 h	34.39	0.427	33.55	35.23
	MOD	48 h	37.56	0.431	36.71	38.40
	HIGH	Baseline	38.04	0.427	37.20	38.88
	MOD	Baseline	38.76	0.431	37.92	39.60
U18	HIGH	24 h	34.50	0.417	33.69	35.32
	MOD	24 h	39.65	0.414	38.84	40.46
	HIGH	48 h	37.16	0.417	36.34	37.98
	MOD	48 h	40.32	0.414	39.51	41.14
	HIGH	Baseline	40.30	0.417	39.48	41.12
	MOD	Baseline	41.02	0.414	40.21	41.83

Legend. EMM = estimated marginal means; SE = standard error; CI = confidence interval; MOD = moderate-load microcycle; HIGH = high-load microcycle. Estimated marginal means were adjusted for acute:chronic workload ratio as covariate. U16, U17, and U18 represent age categories of elite youth soccer players. All values are expressed in centimeters.

model (M_0) explained no variance, whereas the full model (M_1) accounted for 36.7% of the variance (R^2 = 0.367, adjusted R^2 = 0.357, RMSE = 1.672 cm). The moderate predictive capacity observed at 48 hours (R = 0.61) suggests greater inter-individual variability in recovery patterns compared with the 24-hour timepoint, with predictor variables explaining a smaller proportion of differences in neuromuscular performance restoration. Due to the conceptual collinearity between chronological age and age category, the results of the regression models are presented based on the model including age category as the primary developmental indicator.

Table 6. Model fit indices for multiple linear regression models predicting countermovement jump changes at 24h and 48h post-microcycle

Outcome	Model	R	R^2	Adjusted R^2	RMSE
ΔCMJ_24 h	M_1	0.810	0.656	0.651	1.659
ΔCMJ_48 h	M_0	0.000	0.000	0.000	2.086
ΔCMJ_48 h	M_1	0.606	0.367	0.357	1.672

Legend. ΔCMJ_24h = change in countermovement jump height from baseline to 24 hours post-microcycle; ΔCMJ_48h = change in countermovement jump height from baseline to 48 hours post-microcycle; M_0 = null model (intercept only); M_1 = full model including acute:chronic workload ratio, training load (arbitrary units), mean rating of perceived exertion, chronological age, age category, and microcycle type as predictors; R = multiple correlation coefficient; R^2 = coefficient of determination; Adjusted R^2 = adjusted coefficient of determination; RMSE = root mean square error (expressed in centimeters).

To further ensure the robustness of these predictive findings, a sensitivity analysis was conducted by including chronological age as a proxy covariate for biological maturation. This step verifies whether the main effects identified in the regression models remain consistent when accounting for inter-individual differences in developmental status.

Sensitivity Analysis: Inclusion of Age as a Proxy Covariate for Biological Maturation

To address concerns regarding the integration of biological maturation in our models, a sensitivity analysis was performed by including chronological age as a proxy covariate for maturation in the linear mixed models for CMJ recovery at 24 and 48 hours. This approach allows us to verify whether the main effects observed for microcycle intensity, ACWR, and age category remain robust when accounting for individual variability related to maturation.

To extend the evaluation of recovery dynamics beyond sensitivity analyses, we next examined the differential predictive ability of regression models for CMJ changes at 24 and 48 hours post-microcycle. This approach enables a quantitative assessment of how the combination of ACWR, training load, RPE, age, category, and microcycle type explains variance in neuromuscular performance, and highlights the relative contribution of each predictor over time.

Building on the results from the regression models, further analyses including ANOVA and bivariate correlations were conducted to clarify the relationships between training load variables and CMJ changes. These analyses provide insight into the time-dependent effects of workload metrics,

Table 7. Sensitivity analysis: inclusion of age as a proxy covariate for biological maturation in linear mixed models for CMJ at 24 h and 48 h post-microcycle

Timepoint	Variable	Coefficient (Coef.)	p-value	Interpretation
24 h	Microcycle MOD vs HIGH	3.839	<0.001	Moderate microcycles result in better recovery → significant effect
	ACWR	-4.284	<0.001	High ACWR reduces CMJ → significant effect
	Category U17 vs U16	4.646	<0.001	U17 recover better than U16 → significant effect
	Category U18 vs U16	8.780	<0.001	U18 recover even better → significant effect
	Age	-1.449	0.147	Not significant → age does not alter main conclusions
48 h	Microcycle MOD vs HIGH	4.066	<0.001	Microcycle effect maintained
	ACWR	-0.047	0.960	ACWR no longer significant → same pattern as original
	Category U17 vs U16	4.097	0.001	Age effect maintained
	Category U18 vs U16	8.004	0.000	Age effect maintained
	Age	-1.167	0.235	Not significant → robust

Coefficients from linear mixed models for the sensitivity analysis including chronological age as a proxy covariate for biological maturation. Models account for repeated measures per player (ID) and assess the effects of microcycle intensity (MOD vs HIGH), ACWR, and age category (U16-U18) on CMJ height at 24 and 48 hours post-microcycle. Including age shows that the main results remain robust, confirming that chronological age is an appropriate primary factor while accounting for individual variability related to maturation.

Table 8. ANOVA for the linear regression models predicting ΔCMJ_24h and ΔCMJ_48h

Outcome	Source	SS	df	MS	F	p
ΔCMJ_24h	Regression	2324	7	331.98	120.60	< .001
	Residual	1216	442	2.75	—	—
	Total	3540	449	—	—	—
ΔCMJ_48h	Regression	717.9	7	102.55	36.67	< .001
	Residual	1236.0	442	2.80	—	—
	Total	1953.8	449	—	—	—

Note. Les deux modèles M_1 incluent ACWR, Training_Load_AU, RPE_mean, Age, Category et Microcycle_Type.

the interdependence between ACWR and total load, and the consistency of individual recovery patterns across measurement timepoints.

Differential Predictive Ability of Neuromuscular Recovery Models

The ANOVA for the regression model predicting CMJ changes at 24 hours post-microcycle revealed that the full model was statistically significant ($F_{(7.442)}=120.60$, $p<.001$), with the regression sum of squares accounting for 2324.0 cm^2 of the total variance (3540.0 cm^2). The mean square for the regression (331.98) substantially exceeded the residual mean square (2.75), indicating a strong overall model fit. For CMJ changes at 48 hours post-microcycle, the regression model was also statistically significant ($F_{(7.442)}=36.67$, $p<.001$), with a regression sum of squares of 717.9 cm^2 out of a total variance of 1953.8 cm^2. Notably, the F-ratio for the 24-hour model was approximately 3.3 times higher than that observed at 48 hours, reflecting a markedly stronger predictive contribution of the independent variables at the earlier recovery timepoint. Residual mean squares were comparable between models (2.75 vs. 2.80), suggesting similar error variance despite substantial differences in explained variance.

When entered independently, ACWR remained a significant negative predictor of ΔCMJ_24h ($B = -2.79$, $SE = 0.64$, $p < .001$), indicating greater neuromuscular performance decrements at 24 h following higher acute-to-chronic workload ratios. In contrast, total training load entered alone was not associated with ΔCMJ_24h ($B = -0.00013$, $SE = 0.00044$, $p = .767$). Model performance indices were comparable, supporting the interpretation that ACWR captures a performance-relevant signal that is not explained by absolute load alone. Detailed results are presented in Table 8.

Table 9. Sensitivity analyses addressing collinearity between ACWR and total training load for ΔCMJ_24h

Model	Primary predictor	B ± SE	t	p
A	ACWR (no Training Load)	−2.786 ± 0.639	-4.36	< .001
B	Training Load (no ACWR)	−0.00013 ± 0.00044	-0.30	.767

Note. ΔCMJ_24h = CMJ_24h − CMJ_baseline. Les deux modèles ont été ajustés pour l'âge, la catégorie d'âge, le type de microcycle et RPE_mean. L'ACWR et la charge totale ont été inclus séparément afin de répondre à la colinéarité entre ces indicateurs.

Time-Dependent Predictors of Neuromuscular Recovery Following Training Microcycles

For CMJ changes at 24 hours post-microcycle, ACWR emerged as a significant negative predictor (B = −2.78, β = −0.29, t = −4.34, p < .001), indicating that higher acute-to-chronic workload ratios were associated with greater neuromuscular performance decrements. Age also demonstrated a significant negative effect (B = −1.15, β = −0.36, t = −3.30, p = .001). In contrast, neither training load (B = −0.000, p = .966) nor RPE (B = 0.21, p = .331) significantly predicted CMJ changes at this timepoint. Age category exerted a significant influence, with U17 (B = 1.44, t = 3.41, p < .001) and U18 (B = 3.00, t = 4.02, p < .001) players exhibiting smaller performance decrements compared with U16 players. Microcycle type was also a significant predictor (B = 3.33, t = 7.03, p < .001), indicating that moderate-load microcycles were associated with attenuated CMJ declines relative to high-load microcycles. It is important to note that the persistence of ACWR significance in regression models, coupled with the non-significance of absolute training load, must be interpreted in light of a statistical suppression effect related to the high multicollinearity between these two variables. Thus, these results should not be interpreted as demonstrating a strictly independent predictive value of ACWR. At 48 hours post-microcycle, the predictive pattern differed substantially. ACWR (B = −0.07, p = .911), training load (B = −0.000, p = .295), and RPE (B = 0.33, p = .132) were no longer significant predictors. Age remained significantly associated with CMJ changes (B = −0.82, β = −0.35, t = −2.33, p = .021). Regarding categorical variables, U18 players continued to exhibit significantly smaller performance decrements (B = 2.12, t = 2.81, p = .005), as did players exposed to moderate-load microcycles (B = 2.53, t = 5.30, p < .001). The effect of the U17 category approached, but did not reach, statistical significance at this timepoint (B = 0.83, t = 1.95, p = .052).

Relationship Between Training Load Variables and Changes in Countermovement Jump Performance

All bivariate correlations reached statistical significance (p < .001). A strong positive correlation was observed between ACWR and training load (r = 0.81, 95% CI [0.77, 0.84]). ACWR demonstrated a strong negative correlation with changes in CMJ performance at 24 h (r = −0.77, 95% CI [−0.80, −0.73]) and a moderate negative correlation at 48 h (r = −0.53, 95% CI [−0.60, −0.46]). Similarly, training load exhibited a strong negative correlation with CMJ changes at 24 h (r = −0.69, 95% CI [−0.74, −0.64]) and a moderate negative correlation at 48 h (r = −0.52, 95% CI [−0.59, −0.45]). A moderate positive correlation was found between CMJ changes at 24 h and 48 h (r = 0.65, 95% CI [0.60, 0.70]), indicating consistent individual recovery patterns across measurement time points. The strong association between ACWR and training load is expected because acute training load constitutes a component of the ACWR calculation. Therefore, these variables should not be regarded as statistically independent when interpreting analyses that include both measures.

Discussion

The aim of this longitudinal study was to document the evolution of neuromuscular performance, as measured by CMJ, in developing elite footballers subjected to different training load intensities and recovery periods.

Table 10. Standardized and unstandardized regression coefficients for predictors of countermovement jump changes at 24 h and 48 h post-microcycle

	Predictor	B	SE	β	t	p
Predictors of ΔCMJ_24h	Intercept	13.582	5.367	—	2.531	.012
	ACWR	-2.784	0.641	-0.286	-4.343	< .001
	Training Load (AU)	-0.000	0.000	-0.004	-0.043	.966
	RPE_mean	0.212	0.218	0.077	0.973	.331
	Category (U17)	1.444	0.423	—	3.414	< .001
	Category (U18)	3.004	0.747	—	4.018	< .001
	Microcycle (MOD)	3.327	0.473	—	7.034	< .001
Predictors of ΔCMJ_48h	Intercept	7.625	5.410	—	1.409	.159
	ACWR	-0.072	0.646	-0.010	-0.112	.911
	Training Load (AU)	-0.000	0.000	-0.124	-1.049	.295
	RPE_mean	0.331	0.219	0.162	1.507	.132
	Category (U17)	0.832	0.426	—	1.952	.052
	Category (U18)	2.116	0.753	—	2.809	.005
	Microcycle (MOD)	2.529	0.477	—	5.304	< .001

Legend. B = unstandardized regression coefficient; SE = standard error; β = standardized regression coefficient; t = t-statistic; ACWR = acute:chronic workload ratio; AU = arbitrary units; RPE = rating of perceived exertion; MOD = moderate-load microcycle; ΔCMJ_24h = change in countermovement jump height from baseline to 24 hours post-microcycle; ΔCMJ_48h = change in countermovement jump height from baseline to 48 hours post-microcycle. Reference categories: U16 for age category; HIGH for microcycle type. Standardized coefficients (β) are reported only for continuous predictors. Significance level set at p < .05.

Table 11. Pearson correlation coefficients between Acute Chronic workload ratio, training load, and changes in countermovement jump performance at 24h and 48h post-microcycle

Variables	n	Pearson's r	p	95% CI
ACWR – Training Load (AU)	450	0.807	< .001	[0.772, 0.837]
ACWR – ΔCMJ_24h	450	−0.766	< .001	[−0.802, −0.725]
ACWR – ΔCMJ_48h	450	−0.534	< .001	[−0.597, −0.464]
Training Load – ΔCMJ_24h	450	−0.693	< .001	[−0.739, −0.642]
Training Load – ΔCMJ_48h	450	−0.523	< .001	[−0.587, −0.453]
ΔCMJ_24h – ΔCMJ_48h	450	0.654	< .001	[0.597, 0.704]

Note. ACWR = acute:chronic workload ratio; AU = arbitrary units; ΔCMJ_24h = change in countermovement jump height from baseline to 24 h post-microcycle; ΔCMJ_48h = change in countermovement jump height from baseline to 48 h post-microcycle; CI = confidence interval; n = sample size. Negative correlation coefficients indicate that higher workload measures were associated with greater reductions in CMJ performance.

To provide clarity, we first summarize the key findings of our investigation. Three major findings emerged: (1) the identification of a critical window of neuromuscular fatigue at 24 h post-training, evidenced by a significant interaction between microcycle intensity and recovery time ($F_{(2, 214.53)}$ = 138.445, p < .001); (2) the predominant predictive role of ACWR in CMJ performance alterations at 24 h (β = -0.286, p < .001), but not at 48 h (β = -0.010, p = .911); and (3) the substantial modulating effect of age category, with U18 players demonstrating greater resilience to load-induced neuromuscular perturbations. These findings collectively provide a basis for a more detailed analysis of the underlying physiological mechanisms. The maximum deterioration in CMJ performance observed 24 h post-training (a decrease from 38.21 cm to 34.30 cm), followed by gradual but incomplete recovery at 48 h, is consistent with recent studies (Akyildiz et al., 2022; Silva et al., 2021). This observation highlights a critical decision point at which reductions in CMJ performance reflect an integrated alteration of the neuromuscular system, potentially involving dysfunction of the stretch-shortening cycle, central fatigue, and/or metabolic disturbances, although these mechanisms cannot be distinguished in the absence of direct mechanistic measurements. Furthermore, recovery beyond 48 h appears necessary for complete restoration of neuromuscular performance. Incomplete recovery at 48 h suggests that substantial training loads require more than 48 consecutive hours for full recovery. Central and peripheral fatigue mechanisms likely play a decisive role in this prolonged recovery process (Pinelli et al., 2025b). Next, we consider the influence of age and biological maturation on neuromuscular resilience. CMJ is a reliable indicator with a coefficient of variation of less than 5% (Gathercole et al., 2015). Our data quantify the magnitude of the neuromuscular deficit at 24 h (approximately 3.9 cm on average) and confirm that recovery remains incomplete at 48 h, supporting the use of CMJ as a monitoring tool with sufficient temporal sensitivity to guide training decisions. Additionally, the interaction between microcycle intensity and recovery kinetics underscores the complex dynamics of fatigue. The significant interaction between microcycle intensity and recovery kinetics (β = -1.072, p < .001) represents one of the major contributions of this study. Although our investigation relies on observational CMJ measures, the use of sophisticated statistical models allows the identification of key modulators of neuromuscular recovery. The combined application of linear mixed models and multiple regression analyses enables the isolation of the modulatory effects of microcycle intensity, ACWR, and chronological age on neuromuscular recovery. These analyses not only describe the temporal dynamics of fatigue but also support plausible physiological interpretations involving peripheral fatigue associated with muscle contractility and tendon elastic properties, together with central fatigue related to motor unit recruitment and corticospinal excitability. Moreover, the influence of biological maturation, particularly among U16-U18 players, indicates that pubertal development contributes to neuromuscular resilience and supports the integration of developmental status into training planning. Consequently, this study proposes an integrative conceptual framework linking training load, ACWR, chronological age, and neuromuscular responses, thereby providing practitioners with a scientific basis for individualized decision-making. Even without direct biomarker measurements, the longitudinal design and hierarchical analytical approach provide a physiologically grounded interpretation that supports the use of CMJ as an operational monitoring tool and informs preventive and adaptive strategies in elite football academies. High-load microcycles produced mean reductions in CMJ performance of approximately 5.15 cm at 24 h compared with moderate-load microcycles, reflecting a significant main effect of microcycle type. This effect did not differ across age categories, as indicated by the absence of a significant Category × Microcycle × Time interaction (p > .34). These findings emphasize the importance of training load magnitude in determining recovery dynamics. This dose-response relationship is consistent with conceptual models of cumulative fatigue (Malone et al., 2017b). The substantial differences between moderate- and high-load microcycles underline the importance of careful training planning (Field et al., 2021). The significant interaction further indicates that training load intensity determines not only the magnitude but also the duration of neuromuscular disruption, with direct implications for the scheduling of high-intensity training sessions. The operational and quantitative definition of microcycles adopted in this study strengthens the internal validity of the comparisons and reduces the interpretative ambiguity frequently associated with qualitative classifications of training load.

The significant increase in internal load (sRPE) and external load parameters (total distance and accelerations) during HIGH compared with MOD microcycles is consistent with periodization patterns reported in professional soccer. This confirms the relevance of session-specific metrics for capturing load-induced fatigue. The sensitivity of sRPE in reflecting these variations in training volume and intensity confirms its role as a robust indicator of overall training load, as highlighted by Nobari et al. (2022), who observed similar

fluctuations between preparation and competition periods. The clear differentiation in high-intensity acceleration metrics (>2 $m \cdot s^{-2}$ and >3 $m \cdot s^{-2}$) is particularly relevant. Accelerations are known to impose substantially greater metabolic and neuromuscular demands than running at a constant speed because of the eccentric nature of the associated muscle contractions. Therefore, high-intensity accelerations are critical determinants of residual fatigue. These findings corroborate those of Gualtieri et al. (2023), who showed that acceleration density during high-load microcycles is the principal determinant of residual fatigue observed at the end of the training week. Furthermore, the increase in total distance covered during the HIGH microcycle suggests an intentional manipulation of training volume, a classic strategy for stimulating physiological adaptations while remaining within the recommended ACWR range (0.8-1.3), in line with the recommendations of Qin et al. (2025b). This methodological clarity supports the interpretation that the observed differences are meaningful rather than artefactual. We now shift our focus to the predictive utility of ACWR. This clear distinction between the two microcycle types supports the methodological approach adopted to investigate recovery. As demonstrated by Morán-Navarro et al. (2017), the kinetics of neuromuscular recovery are directly dependent on the magnitude of accumulated external load, thereby explaining why HIGH microcycles may result in incomplete recovery at 48 h, whereas MOD microcycles are better tolerated. The ability of ACWR to predict changes in countermovement jump (CMJ) performance at 24 h, together with its strong correlation with total training load ($r = 0.807$), highlights the challenge of collinearity inherent in training load monitoring. As suggested by Gabbett et al. (2016), ACWR is mathematically dependent on acute workload, making it difficult to isolate its independent effect. Nevertheless, our results indicate that ACWR provides a more informative contextual indicator than acute workload alone for identifying immediate decrements in neuromuscular performance. This finding is consistent with Stapleton et al. (2021), who argued that the ratio provides information about the athlete's readiness that absolute workload alone cannot capture. However, its predictive ability diminishes during medium-term recovery. The attenuation of this predictive effect at 48 h represents an important finding of the present study. It suggests that although workload largely determines the initial fatigue response, the rate of recovery over the following 48 h is influenced predominantly by non-mechanical factors (Impellizzeri et al., 2019). Finally, we discuss age-related differences in neuromuscular resilience. Previous studies have also reported that markers of muscle damage and jumping performance are no longer associated with GPS-derived metrics after 48 h, suggesting that biological recovery processes, including sleep, nutrition, and individual variability, become the dominant determinants of recovery. This transition highlights the limitations of ACWR as a stand-alone tool for medium- and long-term training planning and supports its integration into a multimodal monitoring system. In the present study, ACWR was used as a contextual indicator of recent training load relative to the player's chronic workload, allowing the identification of athletes susceptible to short-term neuromuscular fatigue. Our findings demonstrate a significant association between ACWR and CMJ decrements at 24 h after the microcycle, whereas this relationship was no longer evident at 48 h. This pattern indicates that ACWR primarily reflects immediate fatigue rather than medium-term recovery. Its interpretation should therefore consider important methodological limitations, including its mathematical dependence on workload measures and its collinearity with total training volume. Consequently, ACWR should be regarded as a heuristic tool within a multimodal monitoring framework, complemented by direct measures of neuromuscular performance (CMJ), RPE, and indicators of age or biological maturation to guide individualized training load adjustments safely and effectively. Our sensitivity analysis further suggests that ACWR functions as a contextual filter. In elite soccer, where competition schedules are congested, identifying load-adaptation imbalance at 24 h is crucial for optimizing immediate recovery strategies. As highlighted by Moore (2016), residual neuromuscular fatigue following a high acute workload alters running mechanics and increases the risk of non-contact injury, supporting the use of ACWR as an early warning indicator rather than as a direct physiological predictor.

Although some observations confirm previously established effects of load intensity on CMJ, our study provides several original contributions. First, the longitudinal design with six measurements per player, combined with linear mixed model analyses, allows fine-grained and hierarchical characterization of fatigue and recovery dynamics, rarely addressed in the literature on young footballers. Second, the integration of ACWR as a contextual indicator, coupled with chronological age and estimated biological maturation, provides a predictive model of neuromuscular response capable of differentiating vulnerability between U16, U17, and U18 players. Third, precise quantification of effects at 24 and 48 hours post-microcycle, along with demonstration of partial recovery, offers novel practical and scientific insight, enabling individualized recommendations for training planning and overload prevention. Collectively, these elements provide our work with original value and scientific contribution beyond merely confirming previously established results.

Finally, we discuss age-related differences in neuromuscular resilience. U18 players consistently demonstrated superior CMJ performance (38.82 ± 3.29 cm) compared with U17 (36.27 ± 3.33 cm) and U16 (33.30 ± 3.53 cm) players. Although chronological age was a significant predictor ($\beta = -0.362$ at 24 h), it remains an imperfect proxy for biological maturation (Wenger & Csapo, 2025). The greater resilience observed in U18 players may be explained by several mechanisms, including increased musculotendinous stiffness, which enhances stretch-shortening cycle (SSC) efficiency (Katare et al., 2022), greater muscle cross-sectional area, which reduces mechanical stress on individual muscle fibers, improved neuromuscular coordination, and metabolic adaptations that facilitate recovery. These findings highlight the importance of integrating maturation indicators into training monitoring. Sensitivity analyses using chronological age as a proxy for biological maturation confirmed that the main effects of microcycle intensity, ACWR, and age category on CMJ recovery remained robust. Although chronological age itself was not a significant independent predictor in all models, the results support the theoretical importance of considering

biological maturation, particularly in players aged U16-U18. They further suggest that individual variability in maturation may influence neuromuscular responses, whereas the primary effects of training load and ACWR remain consistent across developmental stages. Biologically less mature athletes have been shown to be at greater risk of injury when exposed to training loads comparable to those experienced by their more mature peers (Birat et al., 2018). The greater neuromuscular resilience observed in U18 players therefore emphasizes the dominant influence of biological development on training load tolerance. As demonstrated by Birat et al. (2018), differences in maturation status within the same chronological age category can substantially influence creatine kinase responses and CMJ performance following maximal exercise. The greater muscle mass and increased musculotendinous stiffness associated with pubertal maturation may act as protective factors against structural damage induced by repeated accelerations. Likewise, the greater susceptibility of U16 and U17 players to neuromuscular disturbances is consistent with the findings of Clavel et al. (2022), who suggested that players undergoing peak height velocity (PHV) experience a period of "growth vulnerability," during which the neuromuscular system has difficulty adapting to rapidly increasing external loads. Consequently, ACWR and acute fatigue indicators should be interpreted with particular caution during these biological transition phases. The inability to distinguish the effects of training experience from those of biological maturation, acknowledged as a limitation of the present study, is also recognized in the current literature (Abbott et al., 2019). Abbott et al. (2019) reported that accumulated training volume (training age) and biological maturation interact to determine recovery capacity. Therefore, our findings support the adoption of bio-banding or, at a minimum, the systematic inclusion of biological maturation indicators, such as maturity offset, in athlete monitoring protocols to improve the predictive accuracy of fatigue models in elite youth footballers.

Moreover, the influence of extra-training factors should be acknowledged. Although this study focused on training workload, the variability in recovery trajectories observed, particularly at 48 h, suggests a predominant influence of extra-training factors. As pointed out by Nobari et al. (2022), even in controlled environments such as professional soccer academies, individual differences in sleep quality and psychological stress can alter the recovery kinetics of the autonomic nervous system independently of accumulated GPS-derived workload. Sleep, in particular, is a critical mediator of protein synthesis and glycogen replenishment, both of which are essential for neuromuscular recovery. Therefore, athlete monitoring should adopt a holistic approach that incorporates both training load and individual recovery profiles. The apparent homogeneity of academy training routines does not preclude individual metabolic variability. Silva et al. (2021) demonstrated that nutritional and hydration status directly influence the clearance of muscle damage markers, such as creatine kinase, which may explain why some players recover their CMJ performance within 48 h whereas others remain in a state of residual fatigue. Furthermore, the qualitative characteristics of training sessions, such as eccentric versus metabolically dominant content, introduce variability that global workload indicators (e.g., sRPE or total distance) may not adequately capture. Gualtieri et al. (2023) suggested that neuromuscular fatigue is more sensitive to the density of high-intensity actions than to overall training volume, reinforcing the importance of session content rather than workload magnitude alone. Finally, the lack of control for previous injury history represents an important latent variable. A history of muscle injury may permanently alter musculotendinous stiffness and motor activation patterns, making some athletes inherently more susceptible to acute increases in training load. This observation supports the implementation of holistic monitoring systems in which training load data are interpreted alongside wellness indicators and individualized recovery profiles, as recommended by Qin et al. (2025a), to improve clinical decision-making. Based on these findings, several practical recommendations can be proposed. First, the CMJ test should be performed routinely 24 h after high-load training sessions to identify players experiencing clinically relevant neuromuscular fatigue (R. J. Gathercole et al., 2015). Second, our correlational analyses suggest that an ACWR exceeding 2.0 is associated with greater reductions in CMJ performance. Although interventional studies are required to establish causal thresholds, maintaining ACWR below 2.0 appears to be a prudent practical strategy when combined with other indicators of training load and recovery. Third, at least 48 h of recovery should be scheduled following high-load microcycles, whereas recovery periods of up to 72 h may be more appropriate for U16 and U17 players (Field et al., 2021). Finally, for potentially less biologically mature players, particularly those in the U16 category and some U17 players, longer intervals between high-load exposures and/or adjustments to the volume and intensity of the most demanding training content should be considered without prescribing fixed percentage reductions. Numerical recommendations (e.g., 15–20%) reported in the applied literature should be regarded as provisional guidance until confirmed by interventional studies. Collectively, these recommendations support individualized training planning aimed at reducing injury risk while optimizing performance.

Conclusions

This longitudinal study highlights the existence of a critical window of neuromuscular fatigue at 24 hours post-microcycle, modulated by training load intensity and relative load context. The countermovement jump demonstrates a relevant temporal sensitivity for detecting short-term neuromuscular alterations in elite young footballers, with a maximal decrease in performance observed at 24 hours followed by partial recovery at 48 hours. The significant interaction between microcycle type and recovery time confirms that high-load microcycles induce more marked and prolonged neuromuscular disturbances compared to moderate microcycles. The acute/chronic load ratio emerges as a strong predictor of performance alterations at 24 hours, but loses its predictive capacity at 48 hours, highlighting the temporal complexity of neuromuscular recovery. U18 players showed greater neuromuscular resilience than the U16 and U17 categories, probably reflecting the influence of biological maturation status on load tolerance. These results underline the need for systematic monitoring of CMJ 24 hours after high-load microcycles, and for individualized

management according to developmental status. From an applied point of view, these results suggest the value of integrating CMJ as an operational monitoring tool to guide load adjustment decisions in real time, particularly in younger players. However, these recommendations are based on observational associations and require validation by rigorous interventional studies. Future research should incorporate validated indicators of biological maturation, extend observation windows beyond 48 hours, and incorporate mechanistic biomarkers to dissociate the contributions of central and peripheral fatigue.

Strengths, Limitations and Prospects

This study has several strengths, including its longitudinal design, the application of rigorous linear mixed models, a substantial dataset comprising 450 observations without missing values, and a standardized testing protocol (R. Gathercole et al., 2015). However, several limitations should be acknowledged, including the absence of blood biomarker measurements, the lack of standardized recovery protocols, and, most importantly, the use of chronological age rather than biological maturation status (Wenger & Csapo, 2025). Future research should prioritize (1) the integration of biological maturation into monitoring models (Wenger & Csapo, 2025) and (2) the development of real-time athlete monitoring systems. In the longer term, mechanistic studies incorporating biomarkers and neurophysiological techniques may help distinguish the relative contributions of peripheral and central fatigue, whereas randomized controlled trials comparing different load-modulation strategies could strengthen evidence-based practical recommendations (Field et al., 2021). An important limitation of the present study is the lack of direct assessment of biological maturation. Although chronological age categories are commonly used as a proxy for developmental status in applied settings, they do not adequately capture inter-individual variability in maturation. Future investigations should therefore incorporate validated indicators of biological maturation, such as age at peak height velocity or maturity offset, to better distinguish the respective contributions of chronological age and biological development to neuromuscular fatigue and recovery. Another methodological limitation is the high degree of multicollinearity between ACWR and total training load. This structural dependence, inherent to the formulation of ACWR, may produce suppression effects in regression analyses and limits the interpretation of ACWR as an independent predictor. Future studies should consider alternative analytical approaches, including separate regression models, hierarchical modeling, or the use of exponentially weighted workload metrics, to better differentiate the respective contributions of acute and chronic training load. A further limitation concerns the inability to estimate random slopes reliably for individual recovery trajectories. Although inter-individual variability in responses to training load is biologically plausible, the available data structure did not support stable estimation of random-slope models. Future studies including a greater number of measurement occasions and higher observation density per participant may permit more precise modeling of individual recovery trajectories. An additional limitation relates to the absence of explicit measurement and control of several potentially important confounding variables, including sleep quality, nutritional and hydration status, specific training session characteristics, match exposure during the microcycle, and previous injury history. Although these factors were partially standardized within the professional academy environment, they may nevertheless influence neuromuscular recovery and contribute to the inter-individual variability observed. Future research should incorporate these variables into multifactorial analytical models to improve understanding of the determinants of recovery in elite youth footballers. In summary, this study demonstrates that CMJ is a sensitive tool for detecting a critical window of neuromuscular fatigue 24 h after high training loads, with responses modulated by ACWR and age category. Its application in longitudinal athlete monitoring appears justified when interpreted within a contextualized, multimodal framework, while recognizing the limitations associated with biological maturation and other unmeasured confounding factors.

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Conflict of Interest

The authors declare no conflicts of interest.

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Вплив тренувального навантаження та часу відновлення на нервово-м'язову працездатність елітних юних футболістів

Валід Бузід[1ABCDE], Карла Лоуренсу[3,4,5ABCDE], Халаф Валід Халаф Діабат[6ABCDE], Омар Бен Ракаа[2ABCDE], Азіз Шокрі[1ABCDE], Азіз Елуїрді[1ABCDE], Мохамед Баркауї[1ABCDE]

[1] Перший університет Хасана
[2] Університет Хасана II в Касабланці
[3] Політехнічний інститут Візеу
[4] Університет Бейра Інтеріор
[5] Центр досліджень освіти та інновацій
[6] Університет Аль аль-Бейт

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

Реферат. Стаття: 16 с., 11 табл., 38 джерел.

Актуальність. Управління тренувальним навантаженням і відновленням у молодих елітних футболістів є важливим завданням для оптимізації спортивної результативності при одночасному обмеженні ризику розвитку нервово-м'язової

втоми. Вертикальний стрибок із контррухом (VJM) залишається пріоритетним показником нервово-м'язового стану, однак кінетика відновлення після мікроциклів контрастної інтенсивності у юних спортсменів досі недостатньо вивчена.

Мета. Дослідити вплив тренувального навантаження та часу відновлення на нервово-м'язову працездатність шляхом аналізу модулюючого впливу типу мікроциклу, вікової категорії та співвідношення гострого й хронічного тренувального навантаження (ACWR).

Матеріали та методи. У шестимісячному лонгітюдному дослідженні взяли участь 75 елітних футболістів чоловічої статі (U16–U18). Протокол передбачав оцінювання стрибка з контррухом (CMJ) до, а також через 24 год і 48 год після мікроциклів помірної та високої інтенсивності. Для аналізу основних ефектів і взаємодій використовували лінійні змішані моделі.

Результати. Виявлено статистично значущі ефекти типу мікроциклу ($F = 69.93$, $p < 0.001$), часу вимірювання ($F = 374.48$, $p < 0.001$) та ACWR ($F = 7.41$, $p = 0.007$). Мікроцикли високої інтенсивності спричиняли більш виражене зниження показників CMJ через 24 год ($\beta = -1.072$, $p < 0.001$), після чого через 48 год спостерігалося часткове відновлення. Встановлено сильний кореляційний зв'язок між ACWR і змінами показників CMJ через 24 год ($r = -0.766$, $p < 0.001$).

Висновок. Через 24 год після мікроциклу існує критичне «вікно» нервово-м'язової втоми, яке модулюється інтенсивністю тренувального навантаження та контекстом тренувального навантаження, що підтверджує доцільність систематичного моніторингу нервово-м'язового стану після мікроциклів високої інтенсивності.

Ключові слова: нервово-м'язова втома, стрибок із контррухом, тренувальне навантаження, співвідношення гострого й хронічного тренувального навантаження, юні футболісти, відновлення.

Information about the Authors:

Bouzid, Walid: walidbouzidphd@gmail.com; https://orcid.org/0009-0003-8531-7356; Sports Science Research Team, Institute of Sports Sciences, Hassan I University, Settat, Morocco.

Lourenço, Carla: cvieira@esev.ipv.pt; https://orcid.org/0000-0002-4128-069X; Polytechnic Institute of Viseu,Portugal, University of Beira Interior, Covilhã, Portugal, CI&DEI (Centre for Studies in Ed-ucation and Innovation), Portugal.

Khalaf Diabat, Khalaf Waleed: diabat.khalaf@aabu.edu.jo; https://orcid.org/0000-0001-6531-2396; Full-Time Lecturer with the Rank of Assistant Professor, College of Technical Education, Al al-Bayt University, Jordan.

Ben Rakaa, Omar: omarbenrakaa@gmail.com; https://orcid.org/0000-0002-2181-5247; Multidisciplinary Laboratory in Education Sciences and Training Engineering (LMSEIF). Sport Science Assessment and Physical Activity Didactic, Normal Higher School (ENS-C), Hassan II University of Casablanca, Morocco.

Chokri, Aziz: aziz.chokri@uhp.ac.ma; https://orcid.org/0000-0001-8357-3880; Sports Science Research Team, Institute of Sports Sciences, Hassan I University, Settat, Morocco.

Eloirdi, Aziz: aziz.eloirdi@uhp.ac.ma; https://orcid.org/0000-0003-1061-7787; Sports Science Research Team, Institute of Sports Sciences, Hassan I University, Settat, Morocco.

Barkaoui, Mohamed: mohamed.barkaoui@uhp.ac.ma; https://orcid.org/0000-0002-5209-1499; Sports Science Research Team, Institute of Sports Sciences, Hassan I University, Settat, Morocco.

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Original Scientific Articles. Training Effects and Experimental Design

The Effect of 6-Weeks of SAQ Training on the Speed and Agility Parameters of U-18 Female Soccer Players

Slamet Raharjo[1ABCD], Mahmud Yunus[1ABCD], Raja Mohammed Firhad Raja Azidin[2ACD] and Eggy Nur Arfiansyah[3BCD]

[1]State University of Malang
[2]Universiti Teknologi MARA
[3]Yogyakarta State University

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

Corresponding Author: Slamet Raharjo, e-mail: slamet.raharjo.fik@um.ac.id
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Abstract

Objectives. To determine whether a six-week Speed, Agility, and Quickness (SAQ) training programme improves linear sprint performance and change-of-direction ability in adolescent female soccer players.

Materials and Methods. This randomized controlled trial included 48 adolescent female soccer players (mean age: 17 years), who were randomly assigned to either an SAQ training group (n = 24) or a control group (n = 24). Both groups completed three training sessions per week over a six-week intervention period. Linear sprint performance was assessed using the 30-m sprint test, and change-of-direction ability was evaluated using the Illinois Agility Test. Measurements were performed before and after the intervention.

Results. No significant between-group differences were observed at baseline for any study variable (all $p > 0.05$). Following the intervention, significant group × time interactions were found for both 30-m sprint performance and Illinois Agility Test performance (both $p < 0.05$). Compared with the control group, the SAQ group demonstrated significantly greater improvements in sprint and agility performance. A modest but statistically significant improvement in 30-m sprint performance was also observed in the control group, whereas agility performance remained unchanged.

Conclusions. A six-week SAQ training programme effectively improves linear sprint performance and change-of-direction ability in adolescent female soccer players. Incorporating structured SAQ exercises into regular soccer training provides greater improvements in these performance characteristics than conventional soccer training alone and may therefore be recommended as an effective component of physical conditioning programmes for youth female soccer players.

Keywords: adolescent female soccer players, speed, agility and quickness, sprint performance, change-of-direction ability, soccer training.

Introduction

Soccer performance is determined by the ability to repeatedly execute high-intensity actions interspersed with periods of lower-intensity activity throughout a 90-minute match. Success in competitive play depends not only on technical and tactical proficiency but also on the capacity to accelerate, decelerate, sprint, rapidly change direction, and perform explosive sport-specific actions under conditions of accumulated fatigue (Stølen et al., 2005; Bangsbo, 2014). Consequently, modern conditioning programmes increasingly emphasise the development of neuromuscular qualities that enable players to sustain repeated high-intensity efforts during competition (Sporiš et al., 2011).

In women's soccer, the physical demands have increased substantially with the continuing professionalisation of the sport. Match play requires frequent accelerations, maximal and near-maximal sprints, multidirectional movements, jumping, tackling, and ball-related technical actions performed at varying intensities (Drust et al., 2007). Previous investigations have identified sprint performance, change-of-direction ability, agility, explosive lower-limb

power, and aerobic fitness as key determinants of successful performance in female players (Faude et al., 2012; Zouhal et al., 2021). These physical capacities are interrelated and require systematic training approaches capable of simultaneously improving movement efficiency and sport-specific performance (Buchheit et al., 2018; Horníková & Zemková, 2021).

Among contemporary conditioning methods, Speed, Agility, and Quickness (SAQ) training has gained considerable attention because it integrates linear sprinting, multidirectional movement patterns, acceleration, deceleration, coordination, and reactive motor tasks within a single training framework (Pearson, 2001). Rather than targeting isolated physical qualities, SAQ training aims to enhance the neuromuscular mechanisms underlying rapid movement execution, efficient transitions between movement patterns, and effective control of body position during high-speed actions (Trecroci et al., 2022). Such characteristics make this approach particularly suitable for intermittent team sports, where repeated changes in movement direction and velocity are fundamental components of match performance.

Growing evidence indicates that SAQ-based interventions can improve several performance-related variables in soccer players. Positive adaptations have been reported for sprint acceleration, maximal running speed, change-of-direction performance, reactive ability, and explosive power following structured training programmes lasting between six and twelve weeks (Jovanovic et al., 2011; Milanović et al., 2013; Azmi & Kusnanik, 2018; Formenti et al., 2021). Nevertheless, most available evidence has been obtained from male athletes or mixed populations, whereas comparatively few investigations have specifically examined highly trained female soccer players. Moreover, differences in physiological characteristics, neuromuscular function, and training adaptations suggest that findings derived from male cohorts cannot be directly generalised to female athletes (McKay et al., 2022).

Although previous studies have demonstrated beneficial effects of SAQ training in female youth soccer players (Mathisen & Pettersen, 2015), the available evidence remains limited with respect to intervention duration, competitive level, and regional training environments. Additional research is therefore warranted to clarify the effectiveness of short-term SAQ programmes implemented within regular training schedules for female players competing at the university level.

Accordingly, the purpose of this study was to examine the effects of a six-week SAQ training programme on sprint performance and agility in female soccer players. It was hypothesised that integrating SAQ training into the regular training programme would produce significant improvements in linear sprint performance and agility compared with conventional soccer training.

Materials and Methods

Participants

Forty-eight amateur female soccer players (mean ± SD: 17.4 ± 1.5 years) voluntarily participated in this randomized controlled trial. An a priori sample size calculation indicated that at least 17 participants were required to detect meaningful differences between groups with adequate statistical power. Eligible participants were required to be between 16 and 18 years of age, have accumulated a minimum of two years of competitive soccer experience, be free from musculoskeletal injury during the previous six months, and regularly participate in organized training and official competition.

Before enrolment, all participants received verbal and written information regarding the study objectives, experimental procedures, and potential risks. Written informed consent was obtained from each participant before data collection. The study protocol was approved by the Sports Science Ethics Committee of Malang State University (Approval No. 22.1.18/UN32.6.1/2025) and conducted in accordance with the principles of the Declaration of Helsinki.

Study Design

A parallel-group randomized controlled design was employed to determine the effects of a six-week Speed, Agility, and Quickness (SAQ) training programme on sprint and agility performance. Following baseline testing, participants were randomly assigned in a 1:1 ratio to either an experimental SAQ group (n = 24) or a control group (n = 24).

Physical performance was evaluated before and immediately after completion of the intervention using two standardized field tests: the 30-m linear sprint test and the Illinois Agility Test. The primary outcome variables were sprint time over 30 m and agility completion time.

Experimental Procedures

The intervention was conducted over six consecutive weeks on a regulation outdoor natural-grass soccer field (90 × 120 m). Training and testing sessions were scheduled between 15:30 and 17:30 h under the supervision of experienced soccer coaches holding continental coaching qualifications.

Prior to the experimental period, participants completed familiarization sessions to ensure consistent execution of all testing procedures and training drills. Soccer boots were worn during every training and testing session. Participants were instructed to maintain their habitual nutritional practices, daily routines, and regular physical activity outside the study in order to minimize the influence of external factors on training adaptations.

Training Intervention

Both groups completed three supervised training sessions per week in addition to their regular soccer practice. The experimental group performed a progressive SAQ programme specifically designed to develop acceleration, multidirectional speed, reactive agility, and movement coordination, whereas the control group completed conventional sprint and zigzag running exercises matched for overall training volume.

Training intensity increased progressively throughout the intervention, beginning at approximately 80% of maximal effort during Weeks 1–2, increasing to approximately 90% during Weeks 3–4, and reaching maximal intensity during Weeks 5–6. Coaches continuously monitored exercise

Table 1. Training program

Grup	Week 1-2 Intensity 80%	Week 3-4 Intensity 90%	Week 5-6 Intensity 100%
SAQ	Speed Wall Drill 3 Count–A Skip, A Run, and B Run COD Speed Hop Scotch Agility Ladder Drill	Speed Speed Ladder Drill Speed Training Band COD speed Agility Ladder Drill Reactive Agility Tictac Toe Game	Speed Speed Hurdle Drill COD speed Slalom Sprint Agility Hurdle Drill Reactive Agility Relay race game
Control Grup	Sprint 15m Zig-Zag Sprint	Sprint 20m Zig-Zag Sprint	Sprint 25m Zig-Zag Sprint
General Training	Passing Exercise Small Sided Game 4v4 5min x 2 (30 x 40m)	Passing Exercise Small Sided Game 4v4 with mini goal 5min x 2 (30 x 40m) Finishing drill	Passing Exercise Small Sided Game 4v4+3N 5min x 2 (30 x 40m) Finishing drill

Note: all groups did general training after the intervention exercises in each group.

execution to ensure that the prescribed intensity was achieved.

Each exercise consisted of three sets of four repetitions separated by 90 s of passive recovery, while a 3-min recovery interval was provided between different drills. After completion of the experimental or control intervention, both groups participated in identical soccer-specific training sessions that included technical exercises, tactical drills, small-sided games, and finishing practice. Consequently, the principal difference between groups was limited to the conditioning component of the training programme.

Performance Testing

30-m Sprint Test

Linear sprint performance was assessed using a maximal 30-m sprint test. Participants started from a stationary standing position immediately behind the starting line and were instructed to complete the distance as rapidly as possible. Sprint time was measured to the nearest 0.01 s using a digital stopwatch (CASIO HS-70W, Tokyo, Japan). Two maximal trials were performed with sufficient passive recovery between attempts, and the fastest performance was retained for statistical analysis.

Illinois Agility Test

Change-of-direction ability was evaluated using the standardized Illinois Agility Test. Participants completed the established running course beginning from the prescribed starting position before negotiating the sequence of directional changes around and between the cones until crossing the finish line. Performance time was recorded using an electronic timing system. Two trials were completed under identical testing conditions, and the shortest completion time was used for subsequent analyses.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics (Version 26.0; IBM Corp., Armonk, NY, USA). Descriptive statistics are presented as mean ± standard deviation.

Before inferential analyses, data distribution was examined using the Shapiro–Wilk test, whereas homogeneity of variance was assessed using Levene's test. Because measurements were obtained at only two time points (pre- and post-intervention), assessment of the sphericity assumption was unnecessary.

Intervention effects were evaluated using a two-way mixed-design analysis of variance (ANOVA) with one between-subject factor (group: SAQ vs. control) and one within-subject factor (time: pre vs. post). The interaction between group and time represented the principal outcome of interest. When appropriate, between-group differences following the intervention were examined using independent-samples t-tests. For variables violating the assumption of homogeneity of variance, the Mann–Whitney U test was applied.

Effect sizes were quantified using Hedges' g, whereas Cohen's d was reported where appropriate to facilitate interpretation of mean differences. Effect sizes were interpreted according to Hopkins et al. (2009) as trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.00–3.99), and nearly perfect (≥4.00). Statistical significance was established at $p < 0.05$.

Results

Baseline comparisons showed no significant differences between the SAQ and control groups for anthropometric characteristics or performance variables before the intervention (all $p > 0.05$), indicating comparable baseline characteristics. Following the six-week intervention, significant between-group differences were observed for both sprint and agility performance ($p < 0.05$) (Table 2).

Table 2. Descriptive statistics

Variables	SAQ	Control Grup	p-value
	M ± SD	M ± SD	
Height (cm)	154.7 ± 4.0	153.7 ± 4.1	0.998
Weight (kg)	52.3 ± 5.6	51.7 ± 5.4	0.998
BMI	21.9 ± 2.1	21.7 ± 2.0	0.998
Pre-test Sprint 30m (s)	5.7 ± 0.4	5.8 ± 0.4	0.727
Post-test Sprint 30m (s)	4.7 ± 0.3	5.7 ± 0.4	0.000*
Pre-test Illinois agility test (s)	19.1 ± 0.9	19.2 ± 0.9	0.695
Post-test Illinois agility test (s)	17.9 ± 1.1	19.1 ± 0.9	0.000*

Note:*significance p<0.05

Table 3. Inter-group analysis

Variables	Group	n	Pre-Test	Post-test	Independent-t	Group	Time
			M ± SD	M ± SD		p-value	Partial η^2
Sprint 30 m (s)	SAQ	24	5.7 ± 0.4	4.7 ± 0.3	0.001*	0.001*	0.79
	CG	24	5.8 ± 0.4	5.7 ± 0.4			
Illinois Agility (s)	SAQ	24	19.1 ± 0.9	17.9 ± 1.1	0.000*	0.001*	0.64
	CG	24	19.2 ± 0.9	19.1 ± 0.9			

Note: *significance p<0.05

Sprint Performance

A significant group × time interaction was observed for the 30-m sprint (p = 0.001, partial η^2 = 0.79), indicating that changes in sprint performance differed between the experimental and control groups (Table 3). Within-group analysis demonstrated a significant reduction in sprint time in the SAQ group after the intervention (p = 0.001), whereas only a small improvement was observed in the control group (p = 0.049). Post-intervention comparisons confirmed significantly faster sprint performance in the SAQ group than in the control group (p = 0.001).

Agility Performance

For the Illinois Agility Test, a significant group × time interaction was also identified (p = 0.001, partial η^2 = 0.64) (Table 3). Within-group analysis revealed a significant reduction in completion time in the SAQ group (p = 0.001), whereas no statistically significant change was observed in the control group (p = 0.102). Between-group comparisons at post-test demonstrated significantly better agility performance in the SAQ group than in the control group.

Table 4. Group analysis

Variables	Group	n	Pre vs Post	Percentage of improvement Δ%	Hedges' g
Sprint 30m (s)	SAQ	24	0.001*	17.5	2.7
	CG	24	0.049*	1.7	0.3
Illinois Agility (s)	SAQ	24	0.001*	6.2	1.2
	CG	24	0.102	0.5	0.1

Note: *significance p<0.05

The magnitude of performance improvements was greater in the SAQ group than in the control group (Table 4). Sprint time improved by 17.5% in the SAQ group compared with 1.7% in the control group, corresponding to a very large effect size (Hedges' g = 2.7). Similarly, Illinois Agility Test performance improved by 6.2% in the SAQ group (Hedges› g = 1.2), whereas only minimal changes were observed in the control group.

Discussion

The present randomized controlled study investigated the effects of a six-week Speed, Agility, and Quickness (SAQ) training programme integrated into regular soccer practice in young amateur female players. The principal finding was that participants who completed the SAQ intervention demonstrated significantly greater improvements in sprint performance and multidirectional agility than those following conventional training alone. These findings indicate that incorporating structured SAQ exercises into routine soccer practice provides an effective stimulus for enhancing physical qualities that are directly associated with match performance.

The improvements observed in the experimental group appear to be primarily related to the specificity of the training stimulus. The SAQ programme combined acceleration drills, multidirectional running, resisted sprinting, agility ladder exercises, hurdle drills, and rapid transition tasks, requiring repeated execution of explosive movements under progressively increasing intensity. Such training conditions are known to improve movement efficiency by enhancing intermuscular coordination, motor-unit recruitment, and the rate of force development during high-speed actions. Since the participants had not previously undertaken a systematic SAQ programme, the introduction of these novel neuromuscular stimuli may have accelerated the early adaptive response, contributing to the substantial improvements observed after only six weeks of training.

Particular attention should be given to the improvement in 30-m sprint performance. Although the magnitude of change exceeded that commonly reported in longitudinal studies involving trained athletes, several factors may explain this response. The players had competitive experience but limited exposure to structured speed-oriented conditioning. Consequently, exercises such as wall drills, resisted sprinting, agility ladders, and hurdle coordination drills likely provided a sufficiently novel overload stimulus to optimise sprint mechanics and movement efficiency. Nevertheless, because large improvements over a relatively short intervention should be interpreted cautiously, future investigations using larger samples and fully automated electronic timing systems are required to confirm the reproducibility of these findings.

The present results are generally consistent with previous studies reporting positive effects of SAQ training on sprint performance and change-of-direction ability in soccer players (Jovanovic et al., 2011; Milanović et al., 2013; Anwer et al., 2021). However, the current study extends existing evidence by focusing specifically on adolescent female soccer players, a population that remains underrepresented in the literature. Given documented sex-related differences in neuromuscular characteristics and movement biomechanics, training recommendations should increasingly rely on evidence obtained from female athletes rather than extrapolating findings from male cohorts.

From a physiological perspective, the observed adaptations are consistent with the neuromuscular responses

expected following explosive movement training. Repeated accelerations, decelerations, cutting manoeuvres, and rapid changes of direction stimulate the stretch-shortening cycle, increase motor-unit synchronization, improve intermuscular coordination, and enhance the rate of force development. These adaptations reduce ground-contact time during sprinting while improving force transmission during rapid directional changes, thereby contributing to faster linear running and more efficient multidirectional movement. Previous research has similarly highlighted the importance of these mechanisms for improving high-speed athletic performance (Baechle & Earle, 2008; Radnor et al., 2018; Sun et al., 2025).

Beyond statistical significance, the present findings also have practical relevance. In soccer, successful performance frequently depends on the ability to repeatedly accelerate, decelerate, and rapidly reposition in response to continuously changing tactical situations. Improvements in linear sprint capacity may increase the ability to reach loose balls, create offensive space, and recover defensively, whereas enhanced multidirectional agility facilitates more efficient execution of technical and tactical actions performed under time pressure. Consequently, simultaneous improvements in sprinting and agility may provide a meaningful competitive advantage during repeated high-intensity phases of match play.

An important feature of the intervention is its high degree of movement specificity. Unlike traditional conditioning programmes that often develop endurance and strength separately, the SAQ approach integrates sprinting, directional changes, coordination, balance, and reactive movement patterns within a single training session. Such an integrated stimulus closely reflects the movement demands of competitive soccer and may therefore promote greater transfer of training adaptations to on-field performance. These observations support previous recommendations advocating a greater emphasis on multidirectional speed development within long-term soccer training programmes.

Several limitations should be acknowledged. First, the sample consisted exclusively of young amateur female soccer players from a single competitive level, which limits the generalizability of the findings to other age groups and playing standards. Second, potentially influential factors such as menstrual cycle phase, previous injury history, and biological maturation were not incorporated into the experimental design. Third, although the study demonstrated significant improvements in performance variables associated with athletic development, it did not evaluate injury incidence or biomechanical risk factors during competition. Future studies should therefore include larger multicentre samples, longer intervention periods, biomechanical analyses, and prospective injury surveillance to further clarify both the mechanisms and long-term practical significance of SAQ training.

In conclusion, the findings demonstrate that integrating a structured six-week SAQ programme into regular soccer training represents an effective strategy for improving sprint performance and multidirectional agility in adolescent female players. Because the programme requires relatively simple equipment and can be readily incorporated into routine practice, it provides coaches and strength and conditioning specialists with a practical, evidence-based approach for enhancing movement quality during high-intensity match situations.

Conclusions

A six-week Speed, Agility, and Quickness (SAQ) training programme integrated into regular soccer practice produced meaningful improvements in sprint performance and multidirectional agility in adolescent female soccer players. The findings indicate that SAQ training provides a more effective stimulus for developing high-intensity movement capabilities than conventional conditioning alone. Given its practical feasibility and minimal equipment requirements, SAQ training may be recommended as an effective component of physical preparation programmes for youth female soccer players. Future studies should verify these findings in larger cohorts and examine whether the observed performance gains are maintained over longer training periods and translate into improved competitive performance and reduced injury risk.

Ethics Approval

The study protocol was reviewed and approved by the Sports Science Ethics Committee of Malang State University (Approval No. 22.1.18/UN32.6.1/2025). All procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki.

Informed Consent

Written informed consent was obtained from all participants prior to their enrolment in the study.

Data Availability Statement

The datasets generated during the current study are not publicly available because of ethical and privacy restrictions.

AI Transparency Statement

Artificial intelligence-assisted tools were used exclusively to improve the linguistic quality of the manuscript. The authors retained full responsibility for the study design, data analysis, interpretation of the findings, and the final content of the manuscript.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Вплив шеститижневої програми тренувань швидкості, спритності та швидкості реагування (SAQ) на показники швидкості та спритності футболісток віком до 18 років

Сламет Рахарджо[1ABCD], Махмуд Юнус[1ABCD], Раджа Мохаммед Фірхад Раджа Азідін[2ACD], Еггі Нур Арфіансьях[3BCD]

[1]Державний університет Маланга
[2]Університет технологій MARA
[3]Державний університет Джок'якарти

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

Реферат. Стаття: 7 с., 4 табл., 21 джерело.

Мета. Визначити, чи покращує шеститижнева програма тренування швидкості, спритності та швидкості реагування (SAQ) показники лінійного спринту та здатності до зміни напрямку руху в дівчат-підлітків, які займаються футболом.

Матеріали та методи. У рандомізованому контрольованому дослідженні взяли участь 48 дівчат-підлітків, які займаються футболом (середній вік – 17 років). Учасниць випадковим чином розподілили на групу SAQ-тренувань (n = 24) та контрольну групу (n = 24). Обидві групи тренувалися тричі на тиждень протягом шести тижнів. Лінійну швидкість оцінювали за допомогою тесту бігу на 30 м, а здатність до зміни напрямку руху – за допомогою тесту спритності Іллінойса (Illinois Agility Test). Вимірювання проводили до та після завершення програми втручання.

Результати. На початку дослідження між групами не виявлено статистично значущих відмінностей за жодним із досліджуваних показників (усі $p > 0,05$). Після завершення програми встановлено статистично значущу взаємодію факторів «група × час» як для результатів бігу на 30 м, так і для тесту спритності Іллінойса (в обох випадках $p < 0,05$). Порівняно з контрольною групою учасниці групи SAQ продемонстрували значно більше покращення показників швидкісного бігу та спритності. У контрольній групі також відзначено незначне, але статистично значуще покращення результатів бігу на 30 м, тоді як показники спритності залишилися без змін.

Висновки. Шеститижнева програма SAQ-тренувань ефективно покращує показники лінійного спринту та здатності до зміни напрямку руху в дівчат-підлітків, які займаються футболом. Включення структурованих SAQ-вправ до регулярного тренувального процесу забезпечує більш виражене покращення цих фізичних якостей порівняно зі звичайними футбольними тренуваннями, тому може бути рекомендоване як ефективний компонент програм фізичної підготовки юних футболісток.

Ключові слова: дівчата-підлітки, які займаються футболом, швидкість, спритність і швидкість реагування (SAQ), спринтерська швидкість, здатність до зміни напрямку руху, футбольне тренування.

Information about the Authors:

Raharjo, Slamet: slamet.raharjo.fik@um.ac.id; https://orcid.org/0000-0002-0708-867X; Departement of Sport Science, State Univeristy of Malang, Malang, Indonesia.

Yunus, Mahmud: mahmud.yunus.fik@um.ac.id; https://orcid.org/0000-0001-8677-3837; Departement of Sport Science, State Univeristy of Malang, Malang, Indonesia.

Raja Azidin, Raja Mohammed Firhad: firhad@uitm.edu.my; https://orcid.org/0000-0003-4770-2870; Faculty of Sport Science and Recreation, Universiti Teknologi MARA, Selangor, Malaysia.

Arfiansyah, Eggy Nur: eggynur.2024@student.uny.ac.id; https://orcid.org/0009-0000-5338-1597; Departement of Sport Science, Yogyakarta State University, Yogyakarta, Indonesia.

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Physical and Sports Activities as a Tool for Inclusion: Exploring Physiological and Psychosocial Benefits

Emma Saraiello[1ABD], Francesca Latino[2ABCD], Giulia Amato[1BCD], Maria Giovanna Tafuri[3ABC]

[1]University of Naples "Parthenope"
[2]University of Salento
[3]Pegaso University

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

Corresponding Author: Francesca Latino, e-mail: francesca.latino@unisalento.it
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Abstract

Objectives. The main objective of the study is to promote the development of fundamental motor skills and social inclusion in primary school through the implementation of an inclusive educational intervention based on motor and sports activities.

Materials and Methods. The study employed a quasi-experimental design with an experimental group and a control group. A total of 80 fifth-grade primary school students participated in the study (40 in the experimental group and 40 in the control group), including 10 students with Special Educational Needs (SEN), with a mean age of 10.4 ± 0.5 years. The experimental group participated in a structured motor activity intervention. Fundamental motor skills were assessed using the TGMD-3, perceived inclusion was measured using the PIQ, and behaviours during activities were recorded through systematic observation. Assessments were conducted at pre-test (T0), post-test (T1), and follow-up (T2).

Results. The results showed significantly greater improvements in the experimental group than in the control group in fundamental motor skills, perceived inclusion, active participation, cooperation, and peer interactions. Observational data also confirmed higher-quality relational dynamics in the group that received the intervention.

Conclusions. In light of the findings, the structured motor intervention may produce positive effects on both the development of motor competencies and inclusive processes in primary school, simultaneously promoting motor learning, social participation, and educational inclusion, including among students with SEN.

Keywords: inclusion, fundamental movement skills, cooperative learning, special educational needs (SEN).

Introduction

In the context of primary school, motor activity represents a privileged tool for the development of fundamental motor skills and for the promotion of social and relational competences; indeed, basic motor skills such as running, jumping, throwing, and catching constitute the prerequisite for active participation in games and sports activities throughout life (Sasayama et al., 2025). In this regard, beyond motor development, a central aspect of motor activity is represented by the inclusive dimension; school-based motor activity in fact does not represent only a context of physical learning, but also and above all a social environment capable of creating peer relationships, a sense of belonging, and participation.

In this context, students with Special Educational Needs (SEN) are at greater risk of exclusion and reduced participation in physical education, highlighting the need for inclusive, flexible, and adapted teaching approaches that enable meaningful engagement for all learners (Haegele & Sutherland, 2015; Gazali et al., 2025; Jariono et al., 2025). Inclusive physical education provides a pedagogical framework that promotes equitable access to learning opportunities regardless of students' physical, cognitive, sensory, or socio-cultural characteristics and encourages active participation through appropriately designed learning environments (Lieberman et al., 2020; Jariono et al., 2025). Within this framework, motor activities can simultaneously foster the development of fundamental motor competence and promote social participation, cooperation, and a sense of belonging, transforming physical education into an inclusive learning environment that supports both individual development and collective well-being (Boke et al., 2025; Haegele & Sutherland, 2015).

Within this perspective, inclusive physical education should be understood as a reciprocal process in which all students actively contribute to the creation of an inclusive learning environment, rather than as an approach focused solely

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on adapting activities for students with Special Educational Needs (SEN) (Haegele & Sutherland, 2015). Accordingly, the present intervention was designed by integrating Cooperative Learning strategies and the principles of Universal Design for Learning (UDL), both of which have been recognised as effective pedagogical approaches for promoting meaningful participation, peer interaction, and equitable access to learning in physical education (Lieberman et al., 2020; Boke et al., 2025). Within the UDL framework, instructional adaptations are incorporated into lesson design from the outset, reducing the stigma associated with differentiated activities and creating learning environments in which all students can participate according to their individual abilities (Lieberman et al., 2020). Consistent with this perspective, recent evidence indicates that inclusive sport-based educational programmes can enhance students' sense of belonging, relational well-being, and active participation within the school community (Gravino et al., 2026).

Based on these pedagogical principles, the present intervention was designed using a flexible and cooperative approach in which task adaptation, simplified rules, and differentiated participation opportunities were integrated to create an inclusive learning environment where every student could actively contribute according to individual abilities (Lieberman et al., 2020; Boke et al., 2025; Gazali et al., 2025). Bocce was selected as the core activity because its simple rules, low physical demands, and high adaptability make it particularly suitable for inclusive physical education, allowing students with different levels of motor competence to participate meaningfully while promoting both motor learning and positive peer interaction (Gravino et al., 2026). Moreover, the game requires movement control, precision, eye–hand coordination, and motor planning, while remaining easily adaptable to different ability levels, making it an appropriate educational tool for heterogeneous school groups. Recent evidence also suggests that structured motor interventions combining cognitive engagement with adaptable motor tasks can enhance executive functions and facilitate active participation among students with diverse learning needs (Latino et al., 2025a).

Despite the growing interest in inclusive physical education, the available literature still indicates a limited number of experimental studies that simultaneously examine the effects of adapted traditional games, such as bocce, on both fundamental motor competence and socio-relational outcomes in authentic school settings involving students with Special Educational Needs (SEN) (Gazali et al., 2025; Jariono et al., 2025; Gravino et al., 2026). Therefore, the present study aimed to evaluate the effectiveness of a structured inclusive bocce programme in improving fundamental motor skills and perceived social inclusion among primary school pupils, including students with SEN. Specifically, the study examined changes in fundamental motor skills assessed using the Test of Gross Motor Development-3 (TGMD-3), perceived inclusion measured using the Perceptions of Inclusion Questionnaire (PIQ), and behavioural indicators of participation, cooperation, and peer interaction obtained through structured systematic observation by comparing the experimental and control groups.

Materials and Methods

Study Design

The didactic-motor intervention was structured in a regular primary school setting and aimed to promote the development of fundamental motor skills and foster inclusive peer dynamics. Specifically, the study adopts a longitudinal quasi-experimental design with a non-equivalent control group and included three assessment time points: pre-test (T0), post-test (T1), and follow-up (T2) conducted three months after the intervention in order to obtain a comprehensive evaluation both of the immediate effects and of the temporal stability of the proposed intervention. In addition, in order to strengthen methodological validity and to achieve a deeper understanding of the impact of the intervention, the study was structured using a mixed-method approach, combining standardized quantitative measures with qualitative indicators of inclusive behaviour through structured systematic observation, conducted by two independent observers, in order to also detect behavioural and socio-relational dimensions during the activities.

Participants

The study sample consisted of 80 fifth-grade primary school students and was divided into two groups: an experimental group (n = 40) undergoing a structured program of motor activities based on inclusive bocce; and a control group (n = 40) who carried out the usual, non-structured and non-adapted curricular motor activities. The mean age of the sample was 10.4 ± 0.4 years, consistent with the relevant school level; the sample was also composed of 42 males (52.5%) and 38 females (47.5%), and 10 students with Special Educational Needs (SEN) were present, equally distributed between the two groups. All participating students were regularly enrolled in primary school and regularly took part in the motor activities provided by the school curriculum, while students with clinical or motor conditions that could prevent safe participation in the proposed activities were excluded from the study. Prior to the start of the study, informed consent was obtained from parents or legal guardians, and all procedures were conducted in accordance with the ethical principles of educational research.

Procedure

The total duration of the intervention was 16 weeks, articulated into 2 weekly sessions lasting 60 minutes each, for a total of 32 motor sessions and 32 total hours of activity, which were carried out in a school setting during physical education lessons, in a natural and inclusive environment. Each session was organized according to a standardized structure for the experimental group, while in parallel the control group participated in the usual curricular motor activities provided by the school program, without exposure to the structured protocol based on inclusive bocce. The study protocol was designed according to principles of inclusive and adapted teaching, including adjustments such as reducing throwing distances, varying materials (weight and size of the bocce balls), visual and demonstrative supports, and peer tutoring strategies to promote full participation of students, including those with Special Educational Needs (SEN), while preserving the educational value of the motor task.

Measures

Measurements were conducted at three time points: pre-intervention (T0), post-intervention (T1), and follow-up (T2) three months after the intervention. The study included intra-group (paired-samples t-tests) and inter-group (independent-

samples t-tests) comparisons in order to evaluate the impact of the inclusive bocce program on motor and inclusive outcomes and adopted a multi-method approach, integrating quantitative and qualitative tools in order to obtain a comprehensive assessment of the effects and in addition to statistical significance, Cohen's d effect sizes were computed to assess the practical relevance of the observed differences.

Among the instruments, the Test of Gross Motor Development-3 (TGMD-3) was used in order to assess fundamental motor skills at the three time points: T0, T1, and T2. The test allows a standardized evaluation of movement quality through specific observational criteria organized into two main domains:

- *Locomotor skills:* running, galloping, hopping, standing long jump, and side sliding, which reflect the ability to move the body through space;
- *Object control skills:* overhand throw, catch, kick, dribble, and strike with an implement, which measure hand–eye coordination and control of moving objects.

Another instrument used was the Perceptions of Inclusion Questionnaire (PIQ), administered at the three time points T0, T1, and T2 in a simplified Likert format ranging from 1 to 5, with higher scores indicating greater perceived inclusion, suitable for the participants' age. This is a standardized questionnaire that explores specific dimensions such as (i) sense of belonging to the class group, (ii) participation in activities, (iii) peer relationships, and (iv) perceived social acceptance.

Finally, throughout the duration of the intervention, a structured systematic observation was conducted by two independent observers. The observed variables were (i) active participation; (ii) peer interaction; (iii) cooperation; (iv) rule compliance. For each variable, a structured observational grid with a predefined rating scale was used, and inter-observer reliability was calculated using Cohen's Kappa, with values ranging between 0.82 and 0.91, indicating a high level of agreement.

Intervention

The intervention was designed according to a progressive model of inclusive motor education, structured into four phases aimed at the gradual development of fundamental motor skills and socio-relational competences in order to promote inclusion. Approximately one week before the start of the 16-week program, participants were invited to a dedicated introductory meeting during which the project, its objectives, and the procedures of the activities were presented. Prior to the start of the inclusive protocol, both groups were administered the TGMD-3 and PIQ pre-tests; administration was conducted according to standardized and identical procedures for both groups in order to ensure the internal validity of the research design and the comparability of the results. In addition, throughout the entire duration of the educational intervention, systematic observation of the activities was carried out in order to ensure control of the implementation of the experimental didactic protocol and to monitor its quality.

Phase 1: Familiarisation and motor literacy (Weeks 1–4)

The first phase was dedicated to the introduction of the game of bocce and to the development of basic motor skills in order to promote familiarisation with materials and rules of the game, and in this phase the focus was mainly placed on inclusion through targeted didactic adaptations aimed at ensuring the participation of all pupils.

Specifically, adaptations of the task, materials, and teaching context were implemented, such as reducing throwing distance, progressively simplifying rules, using high-visibility and facilitating materials, as well as methodological strategies based on motor demonstration, simplified instructions, and peer support. A particular strategy used was visual cueing, which consists of the use of structured visual stimuli to guide the execution of the motor gesture, in order to facilitate task comprehension and reduce cognitive load. The present intervention included the use of this strategy through the teacher's motor demonstrations, modeling, directional visual signals, and spatial indications, which supported students in the correct execution of the throw.

Specifically, the intervention involved, through the game of bocce, the development of basic hand–eye coordination, the acquisition of correct throwing postures, and the promotion of active participation and engagement of all pupils, through specific activities characterized by free short-distance throws, simplified individual games, and guided exercises with teacher demonstration; in this regard, the practical demonstration of the gesture allowed pupils to observe the correct motor sequence and guided repetition facilitated the progressive acquisition of the motor pattern.

Phase 2: Consolidation of motor skills (Weeks 5–8)

The focus of the second phase was the consolidation of fundamental motor skills; in particular, the activities were structured in order to promote improvement in throwing accuracy, force control, and direction. Motor pathways aimed at developing these competences were proposed, and participants worked in rotating heterogeneous pairs, with particular attention to the distribution of students with SEN, in order to observe and promote cooperative interactions, natural peer tutoring, and processes of active inclusion. Specifically, the activities included throws at progressive distances, exercises with targets of different sizes, pair games, and initial forms of structured non-competitive competition. In this phase, peer tutoring was used as a structured inclusive strategy, promoting peer support, including for students with SEN.

Phase 3: Cooperation and structured play (Weeks 9–12)

The third phase was oriented toward the development of cooperative dynamics and the organisation of group play in order to promote peer cooperation, the development of team-game strategies, and increasingly autonomous rule management. Specifically, the activities in this phase included mixed-team games with immediate feedback, game situations with common goals, and rotation of assigned roles such as captain, coordinator, motor gesture observer, and feedback facilitator, which were structured to ensure the active participation of all students, regardless of ability level. The intervention included inclusive adaptations based on task differentiation, simplification of instructions, and enhancement of individual strengths, promoting cooperative dynamics and equitable access to motor and relational success. This approach therefore allowed the promotion of

peer scaffolding processes and observational learning, and in this phase a significant increase in active participation and social interactions was observed.

Phase 4: Generalisation and advanced inclusive play (Weeks 13–16)

In this final phase, the highest level of inclusion, cooperation, and active participation was observed. The activity was dedicated to the generalisation of acquired competences and the strengthening of inclusive dynamics in order to promote the consolidation of motor skills, autonomy in regulated play, always ensuring full participation of all students, including those with SEN. Specifically, the activities included structured bocce matches with full rules, student-led free play, autonomous team management, and cooperative learning situations without continuous direct teacher intervention, in order to foster collaboration among participants and individual autonomy. The program was therefore developed according to a didactic progression of increasing difficulty, moving from simplified individual activities to structured and cooperative game situations, with inclusive adaptations systematically integrated to ensure the active participation of all students, including those with Special Educational Needs (SEN). At the end of the intervention, both groups (experimental and control) were administered the TGMD-3 and PIQ post-tests using standardized procedures identical to those used in the initial assessment phase.

Results

Test of Gross Motor Development-3 (TGMD-3)

In the total TGMD-3 scores, no significant differences were found between the experimental group and the control group at baseline (T0) ($p > 0.05$); this finding suggests a substantial initial homogeneity of the sample ($d = 0.08$).

The experimental group, involved in the inclusive bocce program, showed a progressive improvement in scores from pre-test to follow-up (Table 1), and the analysis of the overall change revealed an average increase of approximately 13.8 points in the experimental group, compared to an increase of 4.1 points in the control group.

Table 1. Mean TGMD-3 scores (Mean ± SD)

Group	T0 (Pre-test)	T1 (Post-test)	T2 (Follow-up)
Experimental group	52.40 ± 6.10	63.85 ± 6.45	66.20 ± 6.30
Control group	51.90 ± 6.25	55.10 ± 6.40	56.05 ± 6.55

The paired t-test analysis showed a significant increase between T0 and T1 ($t = -8.34$; $p < 0.001$; $d = 1.82$) and between T0 and T2 ($t = -9.12$; $p < 0.001$; $d = 2.23$) in the experimental group, while in the control group a more limited improvement was observed ($t = -2.11$; $p = 0.041$; $d = 0.65$).

Regarding the analysis of the TGMD-3 subdimensions, in the experimental group more evident improvements were recorded in object control skills, with an increase of 24.5%, compared to an improvement of 18.2% observed in locomotor skills. In the control group, instead, the improvements were more limited, with increases of 7.8% in object control skills and 6.1% in locomotor skills. Finally, at post-intervention (T1), the between-group comparison using independent-samples t-test also showed significant differences in favour of the experimental group ($t = 6.17$; $p < 0.001$; $d = 1.36$), differences which were also confirmed at follow-up ($t = 7.03$; $p < 0.001$; $d = 1.58$).

Perceptions of Inclusion Questionnaire (PIQ)

Regarding perceived inclusion, PIQ scores at baseline (T0) showed comparability between the two groups, as no significant differences were observed ($p > 0.05$).

The PIQ results showed a progressive increase in the experimental group across the three assessment points compared to the control group (Table 2).

Table 2. Mean PIQ scores (Mean ± SD)

Group	T0 (Pre-test)	T1 (Post-test)	T2 (Follow-up)
Experimental group	3.10 ± 0.60	4.20 ± 0.50	4.40 ± 0.50
Control group	3.00 ± 0.50	3.20 ± 0.60	3.40 ± 0.60

Therefore, the paired t-test analysis showed significant differences in the experimental group between T0 and T1 ($t = -7.02$; $p < 0.001$; $d = 1.99$) and between T0 and T2 ($t = -8.17$; $p < 0.001$; $d = 2.36$), while in the control group the changes did not reach statistical significance ($p > 0.05$) with only a small-to-moderate improvement observed over time (T0–T2: $d = 0.72$). In addition, the between-group comparison using independent-samples t-test revealed significant differences in favour of the experimental group both at post-intervention (T1) ($t = 7.88$; $p < 0.001$; $d = 1.81$) and at follow-up (T2) ($t = 8.26$; $p < 0.001$; $d = 1.81$). Furthermore, the analysis of the individual dimensions of the questionnaire showed the most consistent improvements in participation in activities and sense of belonging to the group, followed by peer relationships and perceived social acceptance.

Structured systematic observation

Throughout the entire intervention period, systematic observation was conducted by two independent observers; inter-observer reliability showed Cohen's Kappa values ranging from 0.82 to 0.91, indicating a high level of agreement between raters. In the experimental group, a progressive increase was observed in active participation, peer interaction, cooperation, and rule compliance over the sessions; these changes were more evident in the second half of the intervention, while in the control group the observed variations were minimal and less systematic.

Discussion

The present study analysed the effects of a 16-week inclusive bocce programme on the development of fundamental motor skills and perceived inclusion among fifth-grade primary school students, including students with Special Educational Needs (SEN). The findings demonstrated significant improvements in the experimental group across both motor competence (TGMD-3) and socio-relational

outcomes (PIQ), which were further supported by systematic behavioural observations. The concurrent enhancement of motor competence and perceived inclusion suggests that the inclusive bocce intervention influenced not only motor performance but also the broader social and relational dimensions of participation, confirming that appropriately designed inclusive physical education programmes can simultaneously promote motor development and meaningful social engagement (Lieberman et al., 2020; Boke et al., 2025). These improvements were accompanied by moderate to large effect sizes, indicating that the observed changes were not only statistically significant but also educationally meaningful. The parallel increase in TGMD-3 and PIQ scores further suggests a close relationship between the development of fundamental motor competence and active social participation. This interpretation is consistent with previous evidence indicating that greater motor competence enhances children's confidence, participation in group activities, and opportunities for positive peer interaction (Ulrich, 2013; Salaj & Masnjak, 2022; İdareci & Yarımkaya, 2025). Likewise, students who perceive themselves as more competent in motor tasks are generally more willing to engage in collaborative activities, strengthening interpersonal relationships and fostering a stronger sense of belonging within the group, particularly in inclusive educational settings (Haegele & Sutherland, 2015; Lieberman et al., 2020). Consequently, the present findings suggest that the inclusive bocce programme effectively supported both motor learning and social inclusion, creating learning conditions that actively engaged students with SEN alongside their typically developing peers, consistent with current recommendations for inclusive physical education practice (Jariono et al., 2025; Gazali et al., 2025). Regarding the observed improvements in fundamental motor skills, these findings may be explained by the progressive structure of the intervention. The familiarisation phase likely reduced fear of making mistakes, increased task engagement, and facilitated the gradual acquisition of movement skills through an adapted and supportive learning environment, which has been recognised as a key component of successful inclusive motor learning programmes (Lieberman et al., 2020; Jariono et al., 2025).

Therefore, during the initial phase of the programme, exposure to simple, progressively structured, and highly accessible motor tasks likely facilitated the development of basic coordinative prerequisites, particularly locomotor skills and fundamental object-control movements, before advancing to more complex motor tasks (Lieberman et al., 2020; Jariono et al., 2025). Such a progressive instructional approach has been recognised as an effective strategy for stabilising fundamental movement patterns and promoting the transfer of motor skills across different task contexts (Ulrich, 2013). This interpretation is consistent with the present findings, as object-control skills showed the greatest improvement, likely because bocce requires repeated execution of precise throwing actions involving eye-hand coordination, movement accuracy, and force regulation, all of which represent core components assessed by the TGMD-3 (Ulrich, 2013).

Regarding the PIQ results, the significant increase in perceived inclusion observed in the experimental group suggests that the intervention positively influenced students' social participation and sense of belonging within the physical education environment. This finding is consistent with previous research demonstrating that structured, cooperative, and adaptable learning environments promote meaningful participation of all students, regardless of their abilities, while reducing barriers to inclusion (Holland et al., 2023; Lieberman et al., 2020; Haegele & Sutherland, 2015). The cooperative nature of bocce activities, which encourages shared goal achievement, peer interaction, and mutual support, may have further contributed to these positive social outcomes, in agreement with recent evidence highlighting the educational value of collaborative learning strategies in inclusive physical education (Boke et al., 2025). Furthermore, the cognitive activation associated with regular motor practice may have indirectly supported students with Special Educational Needs by improving attention, behavioural self-regulation, and engagement in learning activities (Latino et al., 2025b). These mechanisms are consistent with contemporary adaptive physical education approaches, which emphasise that appropriately modified motor tasks and inclusive instructional strategies facilitate both educational participation and successful social integration of students with SEN (Jariono et al., 2025; Gazali et al., 2025).

The selection of bocce as the intervention activity was based on its non-invasive, flexible, and easily adaptable characteristics, which make it particularly suitable for inclusive physical education settings. These features likely reduced barriers to participation by enabling students with different levels of motor competence to contribute meaningfully to shared game situations, thereby strengthening their sense of belonging and promoting positive peer interactions (Lieberman et al., 2020; Haegele & Sutherland, 2015; Gazali et al., 2025). Furthermore, the incorporation of team-based activities and cooperative learning tasks created opportunities for peer support, shared responsibility, and reciprocal learning, which are recognised as essential components of effective inclusive pedagogical practice (Boke et al., 2025). Such cooperative experiences may have contributed not only to the development of fundamental motor skills but also to broader educational outcomes, including communication, behavioural self-regulation, respect for rules, and social responsibility, which are considered key objectives of contemporary adaptive physical education programmes for students with Special Educational Needs (Jariono et al., 2025; İdareci & Yarımkaya, 2025).

These findings may also be interpreted through the perspective of Bandura's (1977) Social Learning Theory, which proposes that motor and social behaviours are acquired through observation, imitation, modelling, and social reinforcement. Within the inclusive bocce programme, students were provided with frequent opportunities to observe peers, imitate successful movement strategies, receive immediate feedback, and learn collaboratively in authentic game situations. Such learning conditions are consistent with contemporary evidence indicating that peer modelling and cooperative interaction enhance both motor learning and social participation in inclusive physical education settings (Lieberman et al., 2020; Boke et al., 2025). Furthermore, the systematic observational data support this interpretation, demonstrating greater cooperation and active participation in the experimental group than in the control group. Pair- and small-group activities likely facilitated reciprocal modelling, shared problem-solving, and mutual encouragement, thereby contributing not only to the acquisition of motor skills but also to the development of cooperative behaviours, communication skills, and positive peer relationships (Haegele & Sutherland, 2015; Boke et al., 2025).

The final generalisation phase enabled students to apply the motor and social competences acquired during the programme more autonomously in increasingly complex and less structured game situations. From an educational perspective, this phase is particularly important because it promotes the consolidation of learned motor patterns and facilitates the transfer of acquired skills to novel and authentic movement contexts (Ulrich, 2013). Gradually reducing instructional support while increasing students' autonomy is consistent with contemporary inclusive pedagogical approaches, which emphasise independent participation and the functional application of acquired competences across different learning environments (Lieberman et al., 2020; Jariono et al., 2025).

During the final generalisation phase, the highest level of perceived inclusion (PIQ) was observed, suggesting that increasing autonomy and active participation strengthened students' sense of belonging within the group. This finding further supports the view that inclusive physical education programmes should progressively empower students to participate independently while maintaining meaningful peer interaction (Haegele & Sutherland, 2015; Lieberman et al., 2020). Particularly noteworthy was the active involvement of students with Special Educational Needs, whose successful participation was facilitated by the methodological adaptations incorporated throughout the programme. These findings are consistent with current evidence indicating that appropriately adapted learning environments enable students with SEN to participate successfully alongside their peers while enhancing both educational and social outcomes (Jariono et al., 2025; Gazali et al., 2025).

Limitations

Despite these encouraging findings, several limitations should be acknowledged. First, the quasi-experimental design and the absence of full randomisation limit the strength of causal inferences. Second, although the statistical analyses adequately addressed the study objectives, the use of a unified longitudinal analytical approach, such as linear mixed models or mixed ANOVA, would have provided a more comprehensive evaluation of changes over time while accounting for within-subject variability. Future studies employing randomised controlled designs, larger samples, and advanced longitudinal statistical models are warranted to confirm and extend the present findings.

Conclusion

The inclusive bocce program proved effective in improving both fundamental motor skills and perceived inclusion in primary school students. The progressive structure of the intervention and the integration of cooperative and inclusive strategies appear to represent key elements for the success of the program, even in the presence of students with SEN. Therefore, the results of the present study support the effectiveness of bocce as an inclusive educational tool within primary school. From a pedagogical perspective, the study highlights how simple yet structured motor activities can represent a privileged context for promoting the development of fundamental motor skills, active participation, and cooperation among students with different ability levels.

Ethics Approval

The study was approved by the Ethics Committee of the University of Naples Parthenope (DiSMMeB, Prot. No. 16716/2026). 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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Фізична та спортивна діяльність як засіб інклюзії: вивчення фізіологічних і психосоціальних переваг

Емма Сараєлло[1ABD], Франческа Латіно[2ABCD], Джулія Амато[1BCD], Марія Джованна Тафурі[3ABC]

[1] Університет Неаполя «Партенопе»

[2] Університет Саленто

[3] Університет Пегасо

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

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Мета. Основною метою дослідження було сприяти розвитку базових рухових навичок і соціальної інклюзії в початковій школі шляхом упровадження інклюзивного педагогічного втручання, заснованого на руховій та спортивній діяльності.

Матеріали та методи. Дослідження виконано за квазіекспериментальним дизайном із експериментальною та контрольною групами. У дослідженні взяли участь 80 учнів п'ятих класів початкової школи (40 в експериментальній та 40 у контрольній групі), серед яких було 10 учнів з особливими освітніми потребами (ООП); середній вік учасників становив 10,4 ± 0,5 року. Учні експериментальної групи брали участь у структурованому педагогічному втручанні, заснованому на руховій діяльності. Базові рухові навички оцінювали за допомогою тесту TGMD-3, рівень сприйняття інклюзії визначали за опитувальником PIQ, а поведінку учнів під час занять реєстрували шляхом систематичного спостереження. Оцінювання проводили до початку втручання (T0), після його завершення (T1) та під час віддаленого контрольного обстеження (T2).

Результати. Результати засвідчили статистично значуще більші покращення в експериментальній групі порівняно з контрольною за показниками базових рухових навичок, сприйняття інклюзії, активної участі, співпраці та взаємодії з однолітками. Дані систематичного спостереження також підтвердили вищу якість міжособистісної взаємодії в групі, яка брала участь у педагогічному втручанні.

Висновки. Отримані результати свідчать, що структуроване педагогічне втручання, засноване на руховій діяльності, може позитивно впливати як на розвиток рухових компетентностей, так і на інклюзивні процеси в початковій школі, одночасно сприяючи навчанню рухових дій, соціальній участі та освітній інклюзії, зокрема учнів з особливими освітніми потребами.

Ключові слова: інклюзія, базові рухові навички, кооперативне навчання, особливі освітні потреби (ООП).

Information about the Authors:

Saraiello, Emma: esaraiello@gmail.com; https://orcid.org/0000-0002-8783-6112; Department of Medical, Human Movement and Well-Being Sciences, University of Naples "Parthenope", 80100 Naples, Italy.

Latino, Francesca: francesca.latino@unisalento.it; https://orcid.org/0000-0003-0302-6145; Department of Biological and Environmental Sciences and Technologies, University of Salento, 73100 Lecce, Italy.

Amato, Giulia: giulia.amato@uniparthenope.it; https://orcid.org/0009-0004-4383-175X;

Department of Medical, Human Movement and Well-Being Sciences, University of Naples "Parthenope", 80100 Naples, Italy.

Tafuri, Maria Giovanna: mariagiovanna.tafuri@unipegaso.it; https://orcid.org/0009-0008-5835-1846; Department of Literary, Linguistic and Philosophical Studies, Pegaso University, 80143 Naples, Italy.

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