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REVIEW ARTICLE

Adapted pedagogical strategies in inclusive physical education for students with special educational needs: a systematic review

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

Abstract

Background and Study Aim Adapted physical activity (APA) and inclusive physical education (IPE) strategies aim to enhance the inclusion of students with special educational needs (SEN). These approaches are essential for ensuring equitable and active participation in physical education classes. This study examines the impact of adapted pedagogical strategies in physical education for students with SEN, identifying key factors that promote their inclusion, engagement, and physical development.

Material and Methods A systematic review was conducted using academic databases (Scopus, Web of Science, ERIC) to collect empirical studies published between 2000 and 2024. The eligibility criteria included experimental, observational, and qualitative studies evaluating adapted teaching strategies in physical education.

Results The findings indicate that adapting physical activities, implementing inclusive pedagogical models, and utilizing specific teaching resources are essential for fostering inclusion. Approaches such as co-teaching and peer tutoring have been particularly effective in enhancing student engagement and socialization. However, challenges persist, including inadequate infrastructure and insufficient teacher training.

Conclusions Adapted pedagogical strategies play a critical role in the inclusion and development of students with SEN. Further research and implementation of these strategies are necessary to ensure truly inclusive and equitable physical education for all students.

Keywords: educational adaptations, adapted sports, inclusive teaching, inclusive approach, school inclusion.

Introduction

Research on adapted physical activity (APA) and inclusive pedagogical strategies in physical education (IPE) has been expanding rapidly, with an increasing focus on fostering inclusivity and supporting the holistic development of students with special educational needs (SEN). These approaches are crucial for promoting active and equitable participation in physical education classes while addressing the specific needs of each student.

Recent studies have identified various effective strategies and interventions, particularly emphasizing the adaptation of physical activities [1], the implementation of inclusive teaching models [2,3], and the use of appropriate teaching resources [4]. Inclusive educational practices in APA highlight the importance of differentiated and personalized instruction to meet the diverse needs of students [5]. For instance, adapting physical activities for overweight students has demonstrated positive outcomes in enhancing engagement and promoting equity in the classroom [1].

In addition, teachers' perceptions of the inclusion of students with disabilities play a significant role in shaping the strategies adopted and determining their effectiveness [6]. APA focuses on adapting physical activities to enhance accessibility and provide benefits for individuals with physical, intellectual, or sensory impairments. A recent systematic review has emphasized the importance of regular, structured physical education programs in improving motor, cognitive, and social skills in preschool children [7]. These programs include targeted activities designed to develop fundamental motor skills, which are essential for engaging in more complex physical tasks [8]. Moreover, APA has demonstrated positive effects on participants' mental health, including stress reduction and improved self-esteem [9,10]. APA-based interventions, such as adapted sports, also contribute to the development of social skills and the strengthening of interpersonal relationships, which are essential for the social inclusion of students with SEN [11].

Adapted teaching strategies in IPE are diverse and include collaborative support models, specialized communication methods, activity modifications, and the use of adapted teaching resources [4]. One study identified four key components for the inclusion of students with special educational needs in physical education classes: support models and collaborative work, communication methods and instructional strategies, activity adaptations, and

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the use of teaching materials and resources [12]. Co-teaching and peer tutoring have been shown to be effective approaches for fostering inclusion. These models facilitate direct interaction between students with and without disabilities, encouraging mutual learning and socialization [13,14]. The use of both verbal and non-verbal communication, along with demonstrations, is essential for helping students understand and engage in physical activities. Teachers adjust their communication methods to accommodate the specific needs of their students [15]. Modifications to rules, spaces, and materials are also crucial for ensuring full participation. For example, using balls with bells for visually impaired students or adjusting distances and time constraints for students with physical limitations can significantly enhance accessibility [16].

Despite significant advances, several challenges persist, particularly regarding inadequate infrastructure, insufficient in-service teacher training, and limited resources. It is essential to develop educational policies and training programs that enhance inclusion and accessibility in physical education classes [17,18]. Teachers must be equipped with the necessary skills to implement effective teaching strategies and foster an inclusive learning environment that accommodates the needs of all students [19]. Regardless of training, the presence of students with different disabilities in the classroom can lead to feelings of pedagogical incompetence among teachers [20] or, conversely, a sense of confidence based on their prior experience or medical background [21]. Additionally, a well-informed school and family community plays a crucial role in fostering a culture of respect and support for all students [22]. Although inclusive pedagogical strategies in physical education are gaining traction, challenges remain in their effectiveness, implementation, and adaptation to the specific needs of students with special educational needs (SEN). This often results in varying levels of participation in physical and sports activities [23].

Numerous studies have identified various pedagogical approaches that contribute to the inclusion of students with special educational needs in physical education. Research has demonstrated that adapted teaching strategies, such as co-teaching, peer tutoring, and the modification of activities, significantly enhance student engagement, socialization, and overall participation. However, challenges remain, particularly in ensuring the effective implementation of these strategies, addressing infrastructure limitations, and providing adequate teacher training. The diversity of disabilities further complicates the development of universally applicable methods, highlighting the need for a more structured and evidence-based approach to inclusive physical education.

Given these findings, this study aims to systematically analyze the impact of inclusive pedagogical strategies in physical education for students with special educational needs, identifying best practices while also examining existing obstacles to formulate recommendations for truly effective and equitable inclusion.

Methodology

Information sources

Relevant literature for this systematic review was retrieved from three major academic databases: Scopus (n = 102), Web of Science (n = 112), and ERIC (n = 30). These databases were selected for their extensive coverage of peer-reviewed research in education, physical activity, and health sciences. The search included randomized controlled trials, quasi-experimental studies, observational studies, and qualitative research focusing on adapted pedagogical strategies in inclusive physical education.

Search strategy

The search strategy for this systematic review was designed using a combination of carefully selected keywords and Boolean operators to maximize the relevance of retrieved studies. The search focused on studies addressing the inclusion of students with special educational needs in school-based physical education activities. The following keyword combinations were used:

- (“Adapted Physical Activity” OR “Inclusive Physical Education” OR “Physical Education and Disabilities” OR “Adapted Sports” OR “Para-sports” OR “Disability Inclusion in Physical Education” OR “Co-teaching in Physical Education” OR “Physical Fitness in Disability” OR “Disability and Physical Activity” OR “School Adaptation in Physical Education” OR “Adapted Physical Activity Intervention” OR “Disabilities and Sports Participation” OR “Inclusive Teaching Strategies” OR “Physical Education and Intellectual Disability” OR “Visually Impaired Students in Physical Education” OR “Hearing Impaired Students in Physical Education” OR “Disability Rehabilitation in Physical Education” OR “Social Acceptance and Inclusion in PE” OR “Boccia in Physical Education” OR “Wheelchair Basketball in Physical Education”)
- AND (“Disabilities” OR “Intellectual Disability” OR “Physical Disability” OR “Sensory Impairment” OR “Health Impairments” OR “Developmental Disabilities” OR “Special Needs” OR “Educational Intervention” OR “Physical Fitness” OR “Physical Activity” OR “Health-related Physical Fitness” OR “Sport Rehabilitation” OR “Peer Tutoring” OR “Physical Education Teachers” OR “Special Education”)

- AND ("Inclusion" OR "Participation" OR "Cooperative Teaching" OR "Co-teaching" OR "School Inclusion" OR "Barriers to Physical Activity" OR "Inclusive Curriculum" OR "Adaptation in PE" OR "Inclusive Pedagogies" OR "Attitude Change" OR "Social Inclusion")
- AND ("Randomized Controlled Trial" OR "Case Study" OR "Survey" OR "Intervention Study" OR "Qualitative Study" OR "Mixed Methods Study" OR "Cross-sectional Study").

To refine the results, searches were restricted to peer-reviewed articles published between 2000 and 2024 in English and Spanish. Additional filters were applied to include only empirical studies, such as randomized controlled trials, intervention studies, and qualitative research.

Eligibility criteria

The inclusion criteria for this systematic review were defined to ensure the selection of studies that provide empirical evidence on adapted teaching strategies in physical education for students with special educational needs, including motor, psychological, intellectual, and sensory disabilities, as well as disabling illnesses.

Studies were eligible for inclusion if they met the following criteria:

1. Study focus: Evaluated adapted pedagogical strategies in inclusive physical education.
2. Study design: Included randomized controlled trials, quasi-experimental studies, observational studies, or qualitative research.
3. Outcome measures: Reported data on student participation, physical fitness, social inclusion, or the impact of interventions on student development.
4. Sample size: Included a minimum of X participants (to be specified based on methodological standards).
5. Publication type: Published in peer-reviewed academic journals.
6. Language and time frame: Published in English or Spanish between 2000 and 2024.

The following exclusion criteria were applied:

- Non-peer-reviewed studies, including conference abstracts, dissertations, and reports.
- Studies that did not explicitly assess the impact of adapted teaching strategies in physical education.
- Medical or rehabilitation-focused studies that did not involve an educational context.
- Theoretical papers or reviews without empirical data.

Data extraction

Data extraction in this systematic review follows a structured and standardized approach to ensure consistency and accuracy. The following key information will be extracted from each included study:

1. Study identification: Full reference details (author, year, journal).
2. Study design: Type of study (randomized controlled trial, quasi-experimental study, observational study, qualitative research).
3. Study population:
   - Type of disability (motor, psychological, intellectual, sensory, or disabling illness).
   - Age of participants.
4. Intervention details: Description of the adapted pedagogical strategy used in inclusive physical education.
5. Outcome measures:
   - Student participation in physical education.
   - Changes in physical performance.
   - Levels of social inclusion.
   - Student and teacher attitudes toward inclusive education.

A standardized data extraction form will be used to ensure uniformity and minimize errors.

Assessment of study methodology

The methodological quality of the selected studies is assessed using standardized evaluation tools to ensure the reliability of this systematic review. Different study designs are evaluated using appropriate frameworks:

1. Randomized controlled trials (RCTs) are assessed using the Cochrane Risk of Bias Tool, which identifies potential biases at different stages, including participant selection, intervention allocation, blinding procedures, and outcome reporting.
2. Observational studies are evaluated using the Newcastle-Ottawa Scale (NOS), which assesses methodological quality based on participant selection, group comparability, and outcome assessment.
3. Qualitative studies are analyzed using the Critical Appraisal Skills Programme (CASP), which examines study design, data collection methods, researcher reflexivity, and credibility of findings.

Each included study undergoes a structured evaluation process to determine its methodological rigor and risk of bias.

Results

The results of this section are structured around three main areas of analysis. Firstly, the identification of studies via academic databases is highlighted, along with the process of searching for and selecting relevant work. Secondly, the socio-demographic characteristics of the studies are examined, with sample profiles such as age, gender and geographical location being analysed. Finally, a synthesis of the studies is provided, analysing their objectives, the methodologies employed and the main results obtained, thus offering an overview of the scientific and significant contributions.

Identification and selection of studies

The study selection process is summarized in Figure 1, illustrating the identification, screening, and final inclusion of studies in this systematic review. As shown in Figure 1, after removing duplicates from the 244 studies initially retrieved from Scopus, Web of Science, and ERIC, a total of 224 unique records remained. The initial screening process excluded 150 records, followed by an eligibility assessment of 74 reports, of which 47 were eliminated for various reasons. Ultimately, 27 studies met the inclusion criteria and were selected for this systematic review, ensuring methodological rigor and relevance.

Table 1 presents a summary of the included studies, outlining key characteristics such as authors, year of publication, original article title, country, participant demographics, sport practiced, type of disability studied, measured variables, participants' grade level, and study quality assessment.

Table 2 provides a synthesis of the studies included in the systematic review, detailing their objectives, methodologies, intervention or adaptation strategies, key findings, conclusions, and recommendations. Additionally, it highlights the added value of each study in contributing to the understanding of inclusive pedagogical strategies in physical education.

Discussion

The findings of this review highlight a range of inclusive pedagogical strategies that enhance the participation and well-being of students with motor disabilities. These approaches facilitate equitable and meaningful engagement in physical education by addressing both physical and psychosocial well-being. Specifically, the adaptation of didactic equipment and instructional strategies has been shown to improve self-esteem and confidence in students with motor disabilities [24].

An inclusive systemic approach, characterized by active collaboration among teachers, administrative staff, and educational communities, is essential for establishing sustainable and supportive learning environments [32]. Furthermore, the integration of adapted sports, including Paralympic disciplines

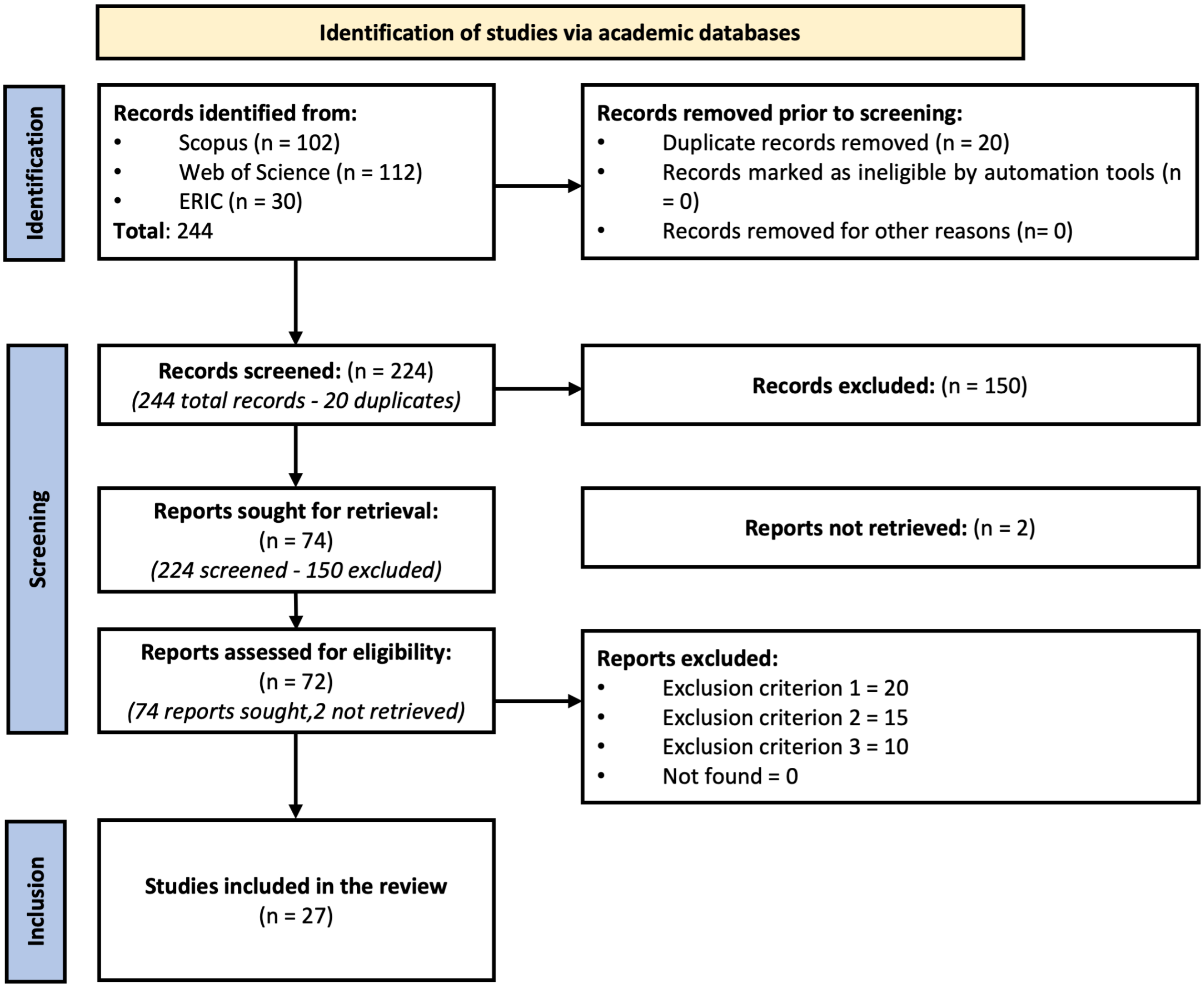

Figure 1. Flowchart of the systematic review

Table 1. Socio-demographic characteristics of studies

Reference Number	Title of Article	Country	Participants	Sport Practiced	Type of Disability	Variables Measured	Educational Level	Study Quality
[24]	Adapted Physical Activity: Overcoming Diversity Through Physical Education and Sports	USA, UAE	Mixed disability group (motor, intellectual, sensory)	Inclusive PE programs	Motor	Inclusion index, participation rate, instructional adaptation effectiveness	Not school-based (recreational setting)	Moderate (NOS: 5/9)
[25]	Boccia as an Adapted and Sensitizing Sport in Physical Education in Secondary Education	Spain	28 secondary school students (ages 14–16, mixed gender)	Boccia	Intellectual	Attitudes, values education, skill improvement	Secondary education	High (NOS: 7/9)
[26]	Co-teaching and School Physical Education: Interventions Aimed at the Inclusion of Students with Disabilities	Brazil	3 teachers and their students in public schools	General physical education activities	Intellectual	Collaboration, communication, inclusion outcomes	Middle school	Moderate (NOS: 5/9)
[13]	Co-teaching in Physical Education: A Strategy for Inclusive Practice	USA	High school students with and without disabilities	Physical education activities	Intellectual	Teacher collaboration, student engagement	High school	High (Cochrane RoB: Low risk)
[27]	Does Adapted Physical Activity-Based Rehabilitation Improve Mental and Physical Functioning? A Randomized Trial	Norway	246 adults with chronic disabilities	Rehabilitation exercises	Disabling diseases	Mental and physical functioning, self-efficacy, pain reduction	Not school-based (rehabilitation setting)	High (Cochrane RoB: Low risk)
[28]	Education Intervention Using Para-Sports for Athletes with High Support Needs to Improve Attitudes Towards Students with Disabilities in Physical Education	Spain	88 sixth-grade students (approx. 11 years old)	Boccia and Goalball	Sensory	Attitudes, acceptance of adaptations, inclusiveness	Primary education	High (NOS: 8/9)
[29]	Effectiveness of an Adapted Physical Activity Intervention on Health-Related Physical Fitness in Adolescents with Intellectual Disability: A Randomized Controlled Trial	Hong Kong	57 adolescents (ages 12–18, overweight or obese, mild or moderate ID)	Moderate aerobic and resistance exercises	Intellectual	Cardiorespiratory fitness, flexibility, muscular strength	Secondary education	High (Cochrane RoB: Low risk)
[30]	Evaluation of the Barriers to the Practice of Physical and Sport Activities in Spanish Adolescents	Spain	324 adolescents (ages 12–17, gender-balanced sample)	General physical activities	Psychological	Self-concept, motivation, social support, compatibility with tasks	Secondary education	Moderate (NOS: 6/9)

Table 1. Continued.

Reference Number	Title of Article	Country	Participants	Sport Practiced	Type of Disability	Variables Measured	Educational Level	Study Quality
[11]	How to Promote Inclusion in Physical Education Classes? Adaptation as a Path	Brazil	Not applicable (essay-based study)	General physical activities	Motor	Barriers, teaching strategies, adaptation practices	All educational levels	Moderate (CASP: Qualitative assessment)
[31]	Inclusion of Children With Disabilities in Physical Education in Zimbabwean Primary Schools	Zimbabwe	24 teachers, primary school level	General physical activities	Disabling Diseases	Teacher practices, social relationships, adapted instruction	Primary	High
[32]	Inclusion of Students With Disabilities in Physical Education: The Crossroads of Systemic Coherence	Chile	135 students observed in 3 schools	General physical activities	Motor	Teacher training, infrastructure, community involvement	Elementary and middle school	High (NOS: 8/9)
[33]	Inclusion of Students With Physical Disabilities and Other Health Impairments	USA	Not specified	General physical activities	Motor and disabling diseases	Adaptation strategies, health outcomes	All educational levels	Moderate (NOS: 6/9)
[34]	Influence of Organized vs. Non-Organized Physical Activity on School Adaptation Behavior	Romania	80 adolescents (aged 14, divided into 3 groups)	Organized physical activities	Intellectual and psychological	School behavior, sensorimotor coordination	Secondary education	High (NOS: 7/9)
[35]	Modifying Physical Activities for Maximizing Learning Opportunities	Finland	4 PE teachers, 4 special educators	General physical activities	Sensory and intellectual	Teaching strategies, collaboration outcomes	All educational levels	High (CASP: Qualitative assessment)
[36]	Organizational Basics of Inclusive Education and Training Process for Karate Athletes With Disabilities	Ukraine	10 athletes (aged 14–20)	Karate	Motor	Physical fitness, motor skills	Not school-based (sports training)	Moderate (NOS: 5/9)
[37]	Participation of People Living With Disabilities in Physical Activity: A Global Perspective	Canada	Global population (no specific characteristics detailed)	General physical activities	All (physical, mental, sensory, intellectual)	Physical activity prevalence, cardiovascular fitness, musculoskeletal fitness	Not school-based (global population study)	High (NOS: 9/9)
[16]	Pedagogies for Inclusion of Junior Primary Students With Disabilities in PE	Australia	3 primary school PE teachers, junior primary students	General physical activities	Motor	Teacher attitudes, pedagogical practices, environmental modifications	Primary education	Moderate (NOS: 6/9)

Table 1. Continued.

Reference Number	Title of Article	Country	Participants	Sport Practiced	Type of Disability	Variables Measured	Educational Level	Study Quality
[14]	Peer Tutoring: Meeting the Demands of Inclusion in Physical Education Today	USA	Not specified	General physical activities	Intellectual	Learning outcomes, social inclusion	All educational levels	High (NOS: 8/9)
[38]	Promoting Social Acceptance and Inclusion in Physical Education	USA	Not specified	General physical activities	Psychological	Social interactions, teacher strategies	Middle school	High (NOS: 7/9)
[39]	School Physical Education and Disabled Students: What About Paralympic Sports?	Brazil, Portugal	1 disabled student, 44 non-disabled students, 1 teacher	Paralympic sports	Motor	Identity recognition, disability awareness	High school	Moderate (NOS: 6/9)
[40]	Students' Perspectives on Wheelchair Basketball in Mainstream and Special Schools	Germany	19 students (10 boys, 9 girls, ages 13–16)	Wheelchair basketball	Motor	Social inclusion, enjoyment, perceived challenges	Secondary education	Moderate (NOS: 6/9)
[15]	Successful Strategies for the Inclusion of Visually Impaired Students in Physical Education Classes	Brazil	1 PE teacher, 2 visually impaired students (1 boy, 1 girl)	General physical education	Sensory	Teaching strategies, guidance, and safety	Primary education (grades 1–5)	High (NOS: 7/9)
[41]	Learning Strategies and Inclusion of Students With Low Vision in Physical Education Classes	Brazil	2 students, 2 teachers	General physical education	Sensory	Strategy usage, inclusion indicators	Elementary education	Moderate (NOS: 6/9)
[22]	Strategies for Teaching Visually Impaired Students: The Curriculum Proposal of São Paulo State	Brazil	Not specified	General physical education	Sensory	Strategy effectiveness, resource adaptations	Secondary education	Moderate (NOS: 6/9)
[42]	The Impact of Adapted Physical Education on Physical Fitness of Students With Intellectual Disabilities: A Three-Year Study	Taiwan	44 students (average age: 15.9), mild to severe ID	Adapted physical education (varied activities)	Intellectual	BMI, muscular strength, endurance, flexibility, cardiovascular fitness	Secondary education	High (NOS: 8/9)
[9]	Young Para-Athletes Display More Hedonic Well-Being Than People With Disabilities Not Taking Part in Competitive Sports	Multi-country (Europe)	1,208 participants (58.4% male, average age ~17, 70.3% para-athletes)	Various para-sports (Para-athletics, Para-swimming, Wheelchair basketball, etc.)	Psychological	Hedonic well-being, life satisfaction, anxiety, vitality	Not school-based (competitive sports setting)	High (NOS: 9/9)

Table 2. Synthesis of the Studies: Objectives, Methodologies and Key Results

Reference Number	Objective	Methodology	Intervention / Adaptation Strategy	Key Results	Conclusion / Recommendations	Added Value of This Study
[24]	Exploring strategies to include physical activity among individuals with special needs in inclusive environments.	Qualitative	Instructional modifications, adaptive equipment	The APA is an effective method for improving both physical and psychosocial well-being. It enhances pride in physical achievements, body image, and self-confidence. Inclusive environments and adapted equipment facilitate participation for individuals with disabilities.	Pedagogical modifications and open approaches are essential to promote inclusion and equal participation for all.	Highlights practical adaptations for inclusiveness.
[25]	Evaluate the impact of Boccia on attitudes toward disabilities in secondary education.	Quantitative	Boccia sessions and inclusive tournaments	A significant improvement in students' attitudes toward disability was observed after participating in Boccia activities. Most students perceived Boccia as a sensitizing sport rather than a tool for motor skill development.	Boccia fosters inclusion but requires broader promotion.	Highlights the role of adapted sports in inclusive education.
[26]	Analyze the feasibility of co-teaching strategies to support inclusion.	Qualitative	Co-teaching practices	Collaborative teaching methodologies effectively promote the inclusion of students with disabilities in mainstream education. Key factors for success include effective communication, joint lesson planning, and shared instructional responsibilities.	Co-teaching is feasible but requires structured planning.	Provides a model for collaborative teaching in inclusive settings.
[13]	Explore co-teaching roles to support inclusion.	Qualitative	Co-teaching framework	Co-teaching fosters an inclusive classroom culture by addressing students' individual needs and capabilities. Success depends on mutual trust and respect between teachers. Positive peer relationships play a fundamental role in learning and contribute to knowledge acquisition.	Emphasizes collaborative teaching as a strategy for inclusion.	Highlights the benefits of co-teaching in inclusive PE.
[27]	Evaluate the effects of adapted physical activity-based rehabilitation.	Quantitative (Randomized Controlled Trial)	4-week APA rehabilitation program	APA-based rehabilitation significantly improves physical and mental functioning. Increased self-efficacy and motivation contribute to these improvements, while pain and fatigue levels also decrease.	Promotes APA as an effective rehabilitation strategy.	Provides evidence-based support for APA in rehabilitation.
[28]	Evaluate the impact of para-sports awareness programs on attitudes toward disabilities.	Quantitative	Para-sports awareness program, including multimedia and simulation exercises	Significant improvement in attitudes toward disability, particularly in the acceptance of adaptations in sports practice. These positive attitudes remained stable five weeks after program completion.	Para-sports awareness programs effectively improve attitudes toward disabilities.	Highlights para-sports as tools for inclusiveness in primary education.

Table 2. Continued.

Reference Number	Objective	Methodology	Intervention / Adaptation Strategy	Key Results	Conclusion / Recommendations	Added Value of This Study
[29]	Assess the impact of a 9-month adapted physical activity program on physical fitness.	Quantitative (RCT)	Structured aerobic and resistance training sessions	Significant improvements in cardiorespiratory fitness and flexibility. No significant changes in muscular strength and endurance. The intervention group showed a mean increase of 413.6 meters in the 9-minute run/walk test compared to the control group.	Supports the implementation of extended APA programs to enhance fitness and well-being.	Provides a framework for long-term fitness programs for adolescents with ID.
[30]	Identify perceived barriers to physical activity among adolescents.	Quantitative	Questionnaire-based study on barriers	Significant gender differences in self-perception and motivation, with girls reporting lower levels than boys. Older students (ages 15–16) exhibited higher self-perception, motivation, and social support. No significant gender- or age-based differences were found regarding task incompatibility.	Highlights the need for targeted interventions based on gender and age.	Explores psychosocial barriers to sports participation.
[11]	Discuss adaptations to promote inclusion in PE.	Qualitative	Adaptations in curriculum, environment, and teaching strategies	A comprehensive approach is necessary to create an inclusive educational environment. Adaptations should be implemented across multiple areas, including curriculum, learning tasks, teaching strategies, assessment methods, and communication.	Encourages teacher training and curriculum reforms.	Proposes practical adaptation frameworks for inclusive PE.
[31]	Explore inclusive practices in PE for children with disabilities.	Qualitative	Teacher interviews, document analysis, non-participant observations	The key practices identified include a comprehensive understanding of the children, the fostering of positive teacher-student and student-student relationships, the provision of support for collaborative structures, and the adaptation of instruction. Teachers demonstrated a positive attitude towards inclusion, despite the challenges presented by factors such as class size and the lack of specialist support.	Stresses the need for capacity building and policy support.	Baseline for future studies on inclusive practices.
[32]	Understand the systemic coherence needed for inclusive practices in PE.	Qualitative (Case Studies)	Collaborative community efforts, curriculum flexibility	Inclusive strategies must align with the specific educational context. Key factors include teacher commitment, collaboration between educators and school management, effective communication within the educational community and governmental levels, proper resource allocation, and the role of teachers as primary agents for inclusive learning.	Emphasizes the need for teacher training and resource allocation for inclusivity.	Illustrates the systemic requirements for implementing inclusive education.

Table 2. Continued.

Reference Number	Objective	Methodology	Intervention / Adaptation Strategy	Key Results	Conclusion / Recommendations	Added Value of This Study
[33]	Identify strategies to include students with physical disabilities in PE.	Qualitative	Adapting physical activities to students' needs	Successful inclusion depends on three key factors: well-trained educators, supportive environments, and collaboration among professionals. The use of authentic assessment methods and continuous adaptation of teaching strategies is essential in addressing students' unique needs.	Promotes individualized adaptations in PE.	Provides detailed, disability-specific strategies for inclusive physical education.
[34]	Compare the effects of organized and non-organized PA on school behavior.	Quantitative	Organized after-school programs	Organized physical activity, supervised by a trainer, significantly improves school inclusion, motor skills, and psychological well-being. Adolescents engaged in structured PA exhibit lower levels of psychoticism, neuroticism, and school-related anxiety compared to those in non-organized or no physical activities.	Advocates structured PA as a means to support students with disabilities.	First study to compare the effects of organized vs. non-organized PA on school behavior.
[35]	Explore inclusive strategies in PE from educators' perspectives.	Qualitative (Case Studies)	Modifying activities, collaboration frameworks	PE and special educators demonstrated a willingness to adapt rules, equipment, and the environment to support inclusive practices. However, traditional independent roles among these educators often hinder collaboration. The study highlights the need for cooperative structures and a shared vision of inclusive teaching to effectively address diversity in PE.	Supports collaborative strategies for inclusive PE.	Introduces the TREE model as a framework for inclusive strategies.
[36]	Evaluate the impact of inclusive karate programs on physical development.	Quantitative	Inclusive karate training program	The inclusive karate training program significantly improved the physical abilities of athletes with disabilities. Key improvements included a 73.1% increase in flexibility(Sit and Reach Test), 2.3% increase in power (Standing Long Jump), and 33.4% enhancement in strength endurance (Abdominal Crunches). However, speed (60-meter run) remained unchanged.	Inclusive sports programs effectively enhance physical development in athletes with disabilities.	Highlights martial arts as a means of inclusion in adapted physical activity.
[37]	Provide an overview of the benefits and policies promoting physical activity among people living with disabilities.	Meta-Analysis	Policy-driven promotion of physical activity	People living with disabilities (PLWD) are 16–62% less likely to meet physical activity guidelines and face higher risks of inactivity-related health conditions. Physical activity significantly benefits cardiovascular and musculoskeletal fitness, reduces cardiometabolic risk factors, and improves mental health.	Advocates for stronger global policies to promote inclusion in physical activity.	Establishes a global context for physical activity disparities among people with disabilities.

Table 2. Continued.

Reference Number	Objective	Methodology	Intervention / Adaptation Strategy	Key Results	Conclusion / Recommendations	Added Value of This Study
[38]	Discuss strategies to improve social acceptance in inclusive PE.	Qualitative	Social inclusion strategies, teacher modeling	Effective inclusive practices in PE require understanding students' needs, building support networks, and incorporating modifications and accommodations. Teachers should model positive attitudes, create supportive learning environments, and use peer tutoring to enhance social interactions. These strategies foster social acceptance and inclusion, enabling students to succeed physically, cognitively, and socially.	Highlights the importance of teacher training and modeling for social inclusion.	Focuses on the social aspects of inclusion in PE.
[39]	Investigate the role of Paralympic sports in PE as a tool for inclusion.	Qualitative	Integration of Paralympic sports into the curriculum	A 5-week Paralympic sports uniting PE allowed a disabled student to express their identity and challenge normative PE practices. The unit raised disability awareness among non-disabled students but was often viewed as an awareness strategy rather than a fundamental right for disabled students. Integrating Paralympic sports fosters equity and disability identity recognition.	Encourages broader integration of Paralympic sports in PE curricula.	Links sports participation to disability identity recognition.
[11]	Analyze strategies used by PE teachers for students with hearing impairment.	Qualitative	Peer tutoring, communication aids	The study identified five key strategies for including students with hearing impairments in PE: Prior Strategies, Aid Strategies through a Peer Tutor, Strategies for Teaching the Activity, Strategies Arising from Student Response or Action, and Strategies for Communication. These approaches enhanced teaching effectiveness, student functionality, and respect for individual characteristics and needs.	Promotes the use of multiple strategies to support inclusive education.	Provides a specific focus on hearing impairments in PE settings.
[40]	Explore student perspectives on wheelchair basketball.	Qualitative	Inclusive basketball curriculum	Mainstream school students viewed wheelchair basketball positively but perceived sitting in a wheelchair as a limitation. Special school students had a more positive outlook on wheelchair use. The study highlights wheelchair basketball's potential to foster inclusion and understanding, though special school students face barriers to joining wheelchair basketball clubs.	Encourages the use of wheelchair sports as a tool for inclusive education.	Combines perspectives from both mainstream and special school students.

Table 2. Continued.

Reference Number	Objective	Methodology	Intervention / Adaptation Strategy	Key Results	Conclusion / Recommendations	Added Value of This Study
[15]	Identify and describe successful strategies for school inclusion of visually impaired students.	Qualitative-descriptive	Specific physical activities, educational adaptations, physical assistance, feedback	The study identified 22 successful strategies for including students with visual impairments in PE classes, categorized into five types: Previous Strategies, Strategies for Teaching the Activity, Strategies for Guidance and Mobility, Strategies Arising from Student Action, and Strategies for Safety. These strategies created favorable conditions for the participation of all students in the same activities.	Strategies have successfully created conditions conducive to the inclusion of students with and without disabilities.	Provides detailed, practical strategies for the inclusion of visually impaired students in PE.
[41]	Investigate teaching strategies for including low-vision students in PE.	Qualitative (Case Study)	Visual aids, modified rules	Both students with visual impairments felt included and actively participated in PE activities. Key strategies used by teachers included verbal instructions, activity demonstrations, rule modifications, and task-based teaching styles. Despite positive attitudes toward inclusion, teachers did not systematically plan strategies and resources.	Supports the structured implementation of strategies for inclusion.	Focuses on low vision as a unique inclusion challenge in PE.
[22]	Plan strategies and adaptations for visually impaired students.	Qualitative	Resource planning, tactile materials	Ten teaching strategies and four new resources were developed to include students with visual impairments in PE classes. Key strategies included verbal instructions, Braille materials, peer tutoring, real object demonstrations, and rule modifications.	Emphasizes the need for resource development to support inclusive education.	Connects theoretical approaches to practical curriculum implementation.
[42]	Examine the effect of APE on fitness and associations over a three-year period.	Quantitative (Longitudinal study)	Structured APE curriculum including Bocce, Basketball, and Track & Field	An adapted physical education (APE) program significantly improved muscular strength, endurance, and cardiovascular fitness in adolescents with intellectual disabilities over three years. However, there was limited success in improving body composition and flexibility.	Encourages tailored long-term fitness programs for adolescents with ID.	Highlights long-term fitness trends among APE participants.
[9]	Compare hedonic well-being of para-athletes and non-athletes with disabilities.	Quantitative (Survey study)	Competitive para-sports participation	Para-athletes exhibited higher well-being across all domains compared to individuals with disabilities not engaged in competitive sports. Those with acquired disabilities reported lower well-being. Participation in wheelchair basketball, para-athletics, and para-swimming was linked to higher well-being, whereas wheelchair rugby was associated with lower well-being.	Advocates for para-sports as a means to enhance well-being in disabled populations.	Provides large-scale evidence on the well-being benefits of para-sports.

such as wheelchair basketball, serves a dual purpose: raising awareness among able-bodied students and providing a platform for self-expression and confidence-building among students with disabilities [39, 40].

To accommodate the diverse educational needs of students, teaching-learning programs must remain flexible, incorporating personalized pedagogical practices and adapted assessment methods. Studies confirm that customized instructional strategies, such as peer tutoring and modified assessment criteria, contribute to more inclusive physical education settings [11, 16, 28].

Trained teachers, safe inclusive environments, collaborative pedagogical practices contribute to a transformative physical education that generates positive individual and collective educational outcomes for students with motor disabilities [33, 36, 37]. Inclusion has progressed through adapted teaching strategies that compensate for physical limitations while ensuring access to physical activity [43]. Studies indicate that assistive technologies, including sports wheelchairs and support devices, facilitate active participation in modified sports [44]. Adapting game rules, using specialized equipment, and implementing targeted modifications have also been effective in enhancing inclusion [45]. An individualized approach that considers the specific abilities of each student is fundamental to fostering meaningful participation [46]. Furthermore, training teachers in differentiated instructional strategies is crucial to ensuring that students with motor disabilities benefit from an inclusive learning environment [20]. Continuous interaction between teachers, students, and parents plays a key role in assessing and adjusting teaching practices, allowing for more effective management of inclusiveness in physical education [47].

The present study has shown that inclusive strategies for sensory disabilities, particularly the implementation of awareness-raising programs using multimedia exercises and simulations, lead to lasting improvements in attitudes toward sensory disabilities and greater acceptance of educational adaptations [28]. While special educators are willing to adapt game rules, sports equipment, and physical activity settings to support inclusion, overcoming the challenges related to their professional independence remains crucial. Establishing collaborative pedagogical structures and fostering a shared vision of inclusive teaching enables a more effective response to pedagogical diversity [35].

Despite the well-documented benefits of physical activity for cardiovascular and mental health, participation remains insufficient among students with sensory disabilities [42]. To address this gap, public policies should actively promote greater engagement in physical education and sports [37]. Additionally, strengthening collaboration between special educators and physical education teachers is essential for developing effective instructional strategies tailored to the specific needs of these students [48].

For hearing-impaired students, inclusion can be supported through strategies such as peer tutoring and communication aids, which enhance the effectiveness of inclusive teaching [11]. The integration of sign language into physical education instruction has been widely explored as a method for improving accessibility for deaf students [49, 50]. Tactile adaptations and audible signaling devices also play a crucial role in facilitating participation in physical activities for students with hearing impairments [49].

Similarly, visually impaired students benefit from orientation and safety strategies, as well as specific modifications to physical activities [15]. Resources such as Braille didactic materials further support their inclusion in physical education settings [22]. Recent adaptations in inclusive teaching have focused on sensory aids and multimodal instructional supports, integrating both visual and auditory cues to enhance learning [51]. For example, adapting verbal instructions by incorporating pictograms and explanatory videos helps visually impaired students better understand physical activities [52].

Research on the psychological aspects of inclusion in physical education and sports highlights significant differences in self-esteem, motivation, and well-being depending on gender, age, and type of disability [30]. However, no gender- or education-level-based differences were found in task incompatibility. Regarding participation in physical activity, studies indicate that people with disabilities are less likely to meet physical activity recommendations, despite its well-documented benefits for cardiovascular, musculoskeletal, and mental health [37]. Additionally, inclusive strategies in physical education, such as understanding students' needs and establishing support networks, play a key role in fostering social inclusion and acceptance [38]. Finally, para-athletics has been shown to enhance the well-being of adolescent girls with disabilities, particularly when compared to those who do not engage in competitive sports. However, the impact varies by discipline, with wheelchair rugby being associated with lower well-being [9].

Students with psychological disabilities, including behavioral and emotional disorders, benefit from educational approaches that foster a safe and respectful environment [53]. Research indicates that behavior management techniques and strategies for promoting emotional regulation are essential for effective inclusion in physical education [54]. For example, the positive behavioral approach has been shown to encourage student participation in physical activities [55]. Additionally, relaxation and mindfulness techniques, when integrated into physical education sessions, help reduce anxiety and improve student attention [56, 57]. The implementation of cooperative games and group activities further contributes to enhancing self-esteem and social skills [58]. Creating a trusting and supportive environment, where students feel valued, plays a critical role in fostering their engagement [59]. Finally, the need for individualized strategies to adapt activities to students' emotional and behavioral fluctuations has been emphasized, ensuring their full participation in physical education [46].

The existing literature on the inclusion of students with intellectual disabilities in physical education and sports highlights the benefits of targeted pedagogical interventions across multiple domains, including attitudes and physical abilities [25]. Studies have reported significant improvements in students' attitudes toward disability following participation in boccia activities, emphasizing the sport's role in promoting educational values and equal opportunities [60]. Collaborative teaching methods, such as joint planning and effective communication between teachers, have been shown to enhance the inclusion of students with disabilities in mainstream schools [26]. Research also confirms that co-teaching, based on mutual trust and respect between educators, facilitates inclusion by addressing students' individual needs [13]. Participation in organized physical activities has been linked to improved school inclusion and psychological well-being in adolescents, reducing psychoticism and neuroticism [34]. Additionally, studies emphasize the role of cooperative structures and a shared vision in overcoming barriers to inclusive physical education [35]. Adapted physical education programs have been shown to significantly improve muscle strength, endurance, and cardiovascular fitness in adolescents with intellectual disabilities [42]. However, research indicates that while aerobic and resistance training sessions improve cardiorespiratory health and flexibility, they do not lead to significant gains in muscular strength [29].

A needs-based pedagogical approach enhances satisfaction, motivation, and well-being among students with intellectual disabilities by simplifying instruction while promoting meaningful peer integration [61]. Structured teaching strategies, including simplified motor tasks and the use of clear, repeated instructions, support the successful participation of these students in physical activities [62]. Additionally, students with intellectual disabilities benefit from cooperative learning, peer learning, ability grouping, extended visual aids, and curriculum differentiation, all of which enhance their learning experience and participation in physical education [63]. Further adaptations include designing low-complexity exercises and gradually increasing difficulty as students' skills develop [64]. To foster social interaction and engagement, adapted physical education programs should incorporate peer-supported physical education and group activities, which have been shown to be effective in improving participation and social integration [65]. Modified team sports and structured group activities are particularly beneficial for students with intellectual disabilities [66]. Moreover, establishing a stable and predictable learning environment enhances students' ability to focus and actively participate in physical activities, making it a critical factor for success [53].

Inclusive strategies in physical education are essential to ensuring the participation of all students, regardless of their disability. Effective inclusive teaching practices rely on a thorough understanding of students' educational needs and the adaptation of learning environments [38]. These strategies involve strong support networks (including psychological, medical, and paramedical resources), learning-friendly environments, and peer tutoring, all of which contribute to enhanced social interaction [39]. Beyond promoting social inclusion, these approaches support academic, social, and professional success for students with disabilities [38]. Furthermore, ongoing adaptation of teaching methods, authentic assessments, and interdisciplinary collaboration allow educators to meet the specific educational and medical needs of students [33]. Co-teaching has also been identified as a key pedagogical approach in fostering an inclusive classroom culture [13, 26]. By combining the expertise of multiple educators, co-teaching enables greater personalization of instruction, accommodating the diverse learning needs of students [13, 26]. Finally, studies have demonstrated that adapted sports activities, such as Boccia, foster positive shifts in students' attitudes toward disability, reinforcing values of equality and inclusion [60].

Inclusive physical education requires adapted teaching strategies for students with disabling illnesses. Research indicates that assistive technologies, such as wearable health devices, enhance physical activity levels by providing real-time data, improving chronic disease management, and promoting treatment compliance [67]. These technologies offer instant access to accurate health information, enabling students to take an active role in their treatment, which contributes to better fitness and overall well-being [67]. Another essential strategy is the adaptation of learning environments, including modifications to sports equipment, which facilitate the participation of students with disabling illnesses in physical activities [16]. Additionally, differentiated pedagogical approaches, incorporating individualized adjustments to physical activity programs, have been shown to increase student engagement [46]. Beyond physical modifications, psychological support from teachers and peers, along with accessible sports facilities, plays a significant role in boosting confidence and motivation among students with disabling illnesses, encouraging their sustained participation in physical exercise [68]. Finally, studies emphasize that teacher training on how to support students with special needs is a critical factor in ensuring the success of inclusive strategies [20].

The findings of this review emphasize the critical role of adapted pedagogical strategies in fostering inclusive and equitable physical education for students with special educational needs. While various approaches, such as co-teaching, peer tutoring, assistive technologies, and differentiated instruction, have demonstrated positive impacts on student engagement, physical development, and social inclusion, persistent challenges remain. Infrastructure limitations, gaps in teacher training, and disparities in resource availability continue to hinder the full implementation of inclusive practices. Addressing these challenges requires a multifaceted approach, combining policy development, professional training, and cross-sector collaboration to ensure sustainable and effective inclusion in physical education. The discussion in this review highlights the importance of refining and adapting inclusive pedagogical strategies to meet the diverse and evolving needs of students with disabilities, ultimately contributing to a more inclusive educational framework.

Limitations and Future Directions

This study has several limitations. First, the majority of studies included in this review rely on qualitative methodologies, which may limit the generalizability of findings. Second, most of the selected studies originate from developed countries, potentially overlooking the challenges and contexts faced in developing countries. Additionally, the diversity of disabilities studied and the range of educational interventions employed make direct comparisons between studies difficult. Future research should incorporate quantitative and mixed-method approaches to enhance result validity and facilitate broader generalization. Expanding the scope to include studies from developing countries would provide a more comprehensive perspective on the challenges and solutions related to inclusion in physical education. Moreover, longitudinal studies are needed to examine the long-term effects of adapted pedagogical strategies on student participation, physical performance, and social inclusion. Finally, technological innovations, such as assistive devices and digital platforms, present promising opportunities to enhance the accessibility and effectiveness of inclusive pedagogical interventions.

Conclusions

This systematic review highlights the importance of adapted pedagogical strategies in promoting the inclusion of students with special educational needs (SEN) in physical education. The findings indicate that adapting physical activities, implementing inclusive pedagogical models, and utilizing specific teaching resources are essential for ensuring active and equitable participation among students. Inclusive approaches, such as co-teaching and peer tutoring, have been shown to enhance student engagement and socialization for both students with and without disabilities.

Despite these advancements, challenges persist, particularly regarding inadequate infrastructure, insufficient in-service teacher training, and limited resources. To address these barriers, it is essential to develop educational policies and training programs that support inclusion and accessibility in physical education. Additionally, collaboration among teachers, administrative staff, and educational communities plays a key role in fostering inclusive and sustainable learning environments.

Finally, adapted pedagogical strategies in physical education have a significant impact on student inclusion, active participation, and physical and social development. Continued research and implementation of these strategies are essential to ensure truly inclusive and equitable physical education for all students.

Conflict of interests

The authors declare that there is no conflict of interests.

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ORIGINAL ARTICLE

The effect of a 4-week plyometric training exercise on specific physical fitness components in U21 novice volleyball players

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Abstract

Background and Study Aim Plyometric training is widely utilized to improve athletic performance by increasing explosive power, speed, and agility. Despite extensive research on its benefits for professional athletes, there is a lack of empirical studies investigating how plyometric exercise training influences specific fitness components in novice volleyball players. This study aimed to investigate the impact of a 4-week plyometric training program on particular physical fitness components in novice volleyball players under 21 years of age.

Material and Methods This study involved 40 novice volleyball players under 21 years of age (M = 19.28 ± 0.93 years). Participants were randomly assigned to an experimental group (n = 20), which engaged in an organized 4-week plyometric training program, or a control group (n = 20), which adhered to their conventional training schedule. Performance in lateral cone hops, burpees, squat jumps, box jumps, and a 40-meter sprint was evaluated through pre- and post-test assessments. Data were analyzed using paired and independent samples t-tests, with a significance threshold of $p < 0.05$.

Results The results showed substantial enhancements in all assessed training metrics for the experimental group relative to the control group. Significant improvements were noted in lateral cone hops, squat jumps, and sprint performance. The results indicate that short-term plyometric training markedly improves specific fitness components essential for volleyball performance.

Conclusions A four-week plyometric training program significantly enhances particular fitness components in U21 novice volleyball players. These findings underscore the need to include plyometric exercises in training programs to improve athletic performance. Future studies should investigate the long-term effects and adaptations across various levels of athletes.

Keywords: plyometric training, volleyball, physical fitness, exercise training

Introduction

The utilization of the plyometric method in the preparation of athletes, including volleyball players, has garnered significant attention from numerous authors. Plyometric exercises entail explosive movements that focus on a quick muscular stretch followed by a vigorous contraction [1, 2]. This training method is advantageous for improving speed, strength, and dexterity in players, rendering it crucial for sports [3, 4, 5]. Research demonstrates that plyometric activities can substantially enhance athletic performance by augmenting muscle strength, refining balance and coordination, and improving cardiovascular fitness [6, 7, 8, 9]. Moreover, various studies indicate that athletes participating in plyometric training exhibit significant enhancements in explosive power, correlating with elevated performance levels in competitions [10, 11, 12]. The components of physical fitness are essential for athletic performance, and plyometric training is fundamental for enhancing these qualities. Despite extensive research on the benefits of plyometric

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exercises for athletic performance, there is limited empirical evidence regarding its targeted effects on specific components of physical fitness, particularly among novice volleyball players in the under-21 (U21) category.

Plyometric training is an efficient method that stresses the musculotendinous unit [13, 14] and improves vertical jump height [15, 16, 17], as noted by Silva et al. [1], who documented enhancements ranging from 4.7% to 15% with bodyweight exercises, including countermovement, depth, and squat jumps. This training technique markedly improves neuromuscular coordination by activating the neural system and refining the stretch-shortening cycle (SSC), which entails an immediate transition from muscle extension to contraction [11, 18]. Plyometric training also develops flexibility [19, 20], augments the storage of elastic energy in muscles [21, 22], engages additional muscle units [23, 24], increases neuronal firing frequency [25], and improves joint proprioception [26, 27]. Multiple studies validate the advantages of integrating plyometrics into strength training programs, emphasizing enhancements in proprioception, acceleration, leg strength, muscle power, and jumping performance [28, 29, 30]. Consequently, a study by Huang et al. [11] underscores the significance of plyometric workouts in attaining optimal athletic performance when combined with structured strength training.

For volleyball players, the capacity to execute forceful jumps is essential for performing skills such as spiking and blocking [31, 32, 33]. Research indicates that athletes participating in plyometric training exhibit significant enhancements in explosive power, correlating with elevated performance levels in competitions [10, 20, 34]. Furthermore, athletes exhibiting greater explosive power have demonstrated a 20% increase in competition performance, underscoring the need for specialized training [35, 36]. A carefully developed plyometric exercise program may increase neuromuscular efficiency, enabling athletes to produce greater ground reaction forces and accelerate more rapidly on the court [27, 34]. Hence, incorporating progressive workouts into a training regimen helps athletes build a solid foundation of strength, speed, and agility, ultimately translating into better on-court performance [37, 38]. Through gradual progression and careful attention to technique, players can safely improve their athletic capabilities and prepare for the demands of the sport [20, 30].

Consequently, integrating progressive workouts into a training routine aids athletes in establishing a robust foundation of strength, speed, and agility, which eventually enhances on-court performance [24, 36]. By applying gradual improvements and maintaining precise dedication to technique, athletes can securely enhance their physical abilities and prepare themselves for the demands of the sport [30, 39].

Previous studies have primarily focused on experienced or elite athletes, neglecting how plyometric training might influence physical fitness development in novice athletes who are still in the early stages of their performance trajectory. Additionally, there is a lack of studies employing short-term intervention programs, such as a 4-week plyometric training regimen, to evaluate their effectiveness on volleyball-specific physical fitness attributes. Hence, this study bridges the gap by investigating the effects of a 4-week plyometric training program on targeted physical fitness components specifically in U21 novice volleyball players. Unlike existing research, this study focuses on a relatively underexplored population and employs a condensed training duration, offering insights into the feasibility and efficiency of short-term plyometric interventions. Furthermore, the study emphasizes volleyball-specific physical fitness components, contributing valuable knowledge to the optimization of training protocols for novice athletes in this sport.

Methods and Materials

Participants

The participants in this study were volleyball players with at least two years of experience in sports participation. The study involved 40 volleyball players aged 19 to 21 years (M = 19.28, SD = 0.93) who were recruited for this investigation. The inclusion criteria included: (1) the player had to be under 21 years old, (2) at least one to two years of sports experience, and (3) no reported injuries in the last three months. Individuals with disabilities, immunocompromised conditions, or a history of cardiovascular difficulties were excluded from testing due to their unique health needs. The detailed characteristics of the participants are shown in Table 1.

Procedure

This study adhered to ethical guidelines prior to the commencement of the experiment. All participants were notified of the study's objective, and informed consent was obtained from every participant. Additionally, the researchers explained the benefits of the study to the institution, community, and its contribution to scientific knowledge. Moreover, respondents were notified that the data obtained would no longer be used in any subsequent or secondary research. Withdrawal of respondents' participation in the study would not have any adverse effects on their relationships with the involved researchers or research organizations, nor would it affect their contributions to any future services or current programs. In order to maintain the anonymity and confidentiality of the respondents,

Table 1. Characteristics of the participants

Group	Experimental M ± SD	Control M ± SD	Total M ± SD
Age (years)	19.30 ± .84	19.25 ± 1.02	19.28 ± .93
Height (cm)	168.10 ± 4.16	169.13 ± 3.64	168.62 ± 3.95
Weight (kg)	47 ± 1.14	46.70 ± 1.03	46.85 ± 3.95
BMI (kg/m^2)	16.66 ± .82	16.35 ± .95	16.51 ± .89

their identities and names were withheld throughout the data collection, analysis, and reporting of the study's findings. Due to the aforementioned conditions, respondents were permitted to withdraw from the study at any time or request a debriefing. All respondents' information was securely protected in accordance with the Data Privacy Act of 2012.

Each participant completed a brief questionnaire regarding their personal information and history of sports-related injuries. No participants were rejected from the study, as none exhibited issues that justified exclusion based on the results. An experimental design incorporated pre- and post-assessments to evaluate athletic performance. The control group received standard basic training program instructions, whereas the experimental group engaged in a 4-week plyometric training program aimed at improving player performance through targeted fitness components. Plyometric training exercises were performed to assess the athletes' fitness and improvement in physical performance: (1) lateral cone hops, (2) burpees, (3) squat jumps, (4) box jumps, and (5) 40-meter sprints. Subsequently, novice volleyball players from both groups engaged in a 4-week plyometric workout routine under similar conditions, encompassing facility usage and environmental factors.

Execution of Plyometric Training Exercise

Lateral Cone Hops:

a. Target fitness components: Agility and lateral power.
b. Benefits: Enhances quick lateral movements essential for volleyball, improving agility and balance. Develops lower-body explosive power and responsiveness.
c. Execution: Place a cone on the ground and assume a stance to one side with your feet shoulder-width apart. Slightly bend your knees, adopting an athletic posture while engaging your core. Propel yourself with both feet to leap laterally over the cone, focusing on elevation and distance. Gently land on the balls of your feet on the other side, maintaining a slight bend in your knees. Quickly reset and return to the initial position.

Burpees:

a. Target fitness components: Full-body strength and explosive power.
b. Benefits: Integrates aerobic and anaerobic components, enhancing overall conditioning and power production. Excellent for improving endurance in extended matches.
c. Execution: Begin in a standing position with your feet shoulder-width apart. Assume a squat position, placing your hands flat on the ground in front of you. Propel your feet backward into a plank position, ensuring your body maintains a straight alignment from head to heels. Quickly bring your feet back toward your hands. Execute an explosive vertical jump, extending your arms overhead. Descend gently and promptly proceed to the subsequent repetition.

Squat Jump:

a. Target fitness components: Explosive power, strength, and vertical jump ability.
b. Benefits: Strengthens the quadriceps, hamstrings, and glutes while increasing vertical leap, which is essential for blocking and spiking.
c. Execution: Stand with your feet shoulder-width apart. Lower into a squat position, keeping your chest upright and knees behind your toes. Explode upward, jumping as high as possible. Land softly, immediately lowering into the next squat to repeat.

Box Jump:

a. Target fitness components: Explosive power, coordination, and strength.
b. Benefits: Boosts vertical jump, reflexes, and muscle coordination. Practicing safe landings builds confidence for game situations.
c. Execution: Position yourself in front of a solid box or platform. Stand with your feet shoulder-width apart, bend your knees, and swing your arms back to generate momentum. Explode upward and propel yourself forward, landing gently on the box with both feet. Assume an upright position, then descend carefully, stepping down one foot at a time. Repeat for the specified number of repetitions.

Sprint (40-meter dash):

a. Target fitness components: Speed, acceleration, and endurance.
b. Benefits: Develops quick bursts of speed necessary for reaching the ball and covering

the court. Improves overall reaction time and cardiovascular fitness.

c. Execution: Start by standing with your weight on the balls of your feet and your back straight. As you move forward, take long strides and pump your arms simultaneously. Maintain a slight forward lean and engage your core to stay balanced. Run as fast as you can for the given distance. Slow down gradually to avoid sudden stops.

Training program. Participants were randomly allocated into two groups: the experimental group (n = 20) and the control group (n = 20). The training intervention lasted four weeks, comprising three sessions per week for the volleyball players. The experimental group engaged in a plyometric workout program, whereas the control group maintained their standard training schedule. Pre-training and post-training assessments were administered before and after the execution of the training program. Before the test protocols, participants engaged in a familiarization session to prevent any issues during testing. All tests were performed in a covered court under appropriate conditions, at least 24 hours after the previous training session or match. Participants were instructed to wear similar athletic apparel during the testing periods. Measurements were conducted concurrently at the same time of day over three testing sessions to mitigate the impact of daily variations on the chosen parameters. Participants received recommendations regarding nutrition and rest during the training and testing phases to minimize any potential factors that could influence the study outcomes. Table 2 provides information about the applied training program.

Statistical Analysis

The data were analyzed using SPSS version 20. Descriptive statistics, including the mean, frequency, and standard deviation, were used to analyze quantitative data. The normality of the data was evaluated using the Shapiro-Wilk test. It was observed that the data exhibited a normal distribution. Within-group pre- and post-test scores were analyzed using a paired samples t-test, and inter-group differences were evaluated using an independent samples t-test. The significance level was established at $p < 0.05$. Upon reviewing the table, it is evident that the experimental and control groups exhibit comparable descriptive statistics.

Results

The pre-test results displayed in Table 3 reveal no statistically significant differences between the experimental and control groups across all evaluated plyometric exercises, including lateral cone hops, burpees, squat jumps, box jumps, and sprints ($p > 0.05$). The absence of notable differences indicates that the two groups were equivalent in their baseline plyometric performance prior to the intervention. Such comparability is essential in experimental research, as it guarantees that any detected post-test differences can be attributed to the intervention rather than pre-existing discrepancies. This finding corroborates the randomized group allocation and reinforces the reliability of subsequent analyses.

The results of the independent samples t-test for these comparisons are presented in Table 4. The results illustrate notable improvements in the post-test plyometric exercise scores of the experimental group relative to the control group across all five plyometric exercises. The experimental group attained markedly superior scores in lateral cone hops ($t = 14.399$, $p < 0.001$) and squat jumps ($t = 17.199$, $p < 0.001$) compared to the control group. The results indicate the efficacy of the 4-week plyometric training program in improving specific fitness components essential for volleyball performance. The findings suggest that systematic plyometric workouts can improve physical competency, providing evidence-based advice for physical education and sports training.

The findings demonstrate that both the

Table 2. Plyometric training program

Week	Plyometric Exercise Program	Sets	Reps	Rest	Duration
1-2	Lateral Cone Hops Burpees Squat Jump Box Jump Sprint	2	8	180 seconds	30-40 minutes
3-4	Lateral Cone Hops Burpees Squat Jump Box Jump Sprint	3	12	180 seconds	30-40 minutes

Table 3. Pre-test scores for both experimental and control groups

Movement Patterns	Group	N	M	SD	t-value	p-value
Lateral Cone Hops	Experimental	20	5.400	0.821	-1.815	0.077
	Control	20	5.850	0.745		
Burpees	Experimental	20	5.300	1.031	0.128	0.899
	Control	20	5.250	1.410		
Squat Jump	Experimental	20	4.700	0.657	-1.013	0.318
	Control	20	4.950	0.887		
Box Jump	Experimental	20	4.850	0.671	-1.217	0.231
	Control	20	5.150	0.875		
Sprint	Experimental	20	5.050	0.759	0.841	0.406
	Control	20	4.850	0.745		

Table 4. Post-test scores for both experimental and control groups

Movement Patterns	Groups	N	M	SD	t-value	p-value
Lateral Cone Hops	Experimental	20	9.450	0.686	14.399	< .001
	Control	20	6.500	0.607		
Burpees	Experimental	20	13.050	1.572	3.260	0.002
	Control	20	11.700	0.979		
Squat Jump	Experimental	20	9.550	0.510	17.199	< .001
	Control	20	6.500	0.607		
Box Jump	Experimental	20	9.050	0.686	12.034	< .001
	Control	20	6.600	0.598		
Sprint	Experimental	20	8.250	1.209	2.904	0.006
	Control	20	7.400	0.503		

experimental and control groups exhibited substantial improvements in their physical fitness performance from pre-test to post-test (Table 5). The experimental group, which participated in an adapted plyometric training program, showed significantly greater improvements in all measured plyometric exercises, including lateral cone hops ($M = 4.050$, $p < 0.001$), burpees ($M = 7.750$, $p < 0.001$), squat jumps ($M = 4.850$, $p < 0.001$), box jumps ($M = 4.200$, $p < 0.001$), and sprints ($M = 3.200$, $p < 0.001$). The mean differences in performance gains were consistently greater in the experimental group compared to the control group, underscoring the efficacy of plyometric training in enhancing the physical fitness of novice volleyball players. This highlights the necessity of incorporating specialized training programs to enhance athletic performance, especially among young volleyball players.

Discussion

The aim of the study was to evaluate the effects of a 4-week plyometric training program on specific physical fitness components in under-21 novice volleyball players. The findings demonstrated significant improvements in performance across specific fitness components (i.e., power, strength, agility, coordination, balance, and speed), with statistically significant differences ($p < 0.01$) observed between pre-test and post-test results. The experimental group showed a notable increase in all measured components, reinforcing the effectiveness of plyometric training in enhancing volleyball-specific fitness. This study emphasizes the efficacy of a short training program designed for novice volleyball players, in contrast to prior research that focused on elite athletes or extended training periods (e.g., six to eight weeks) [3, 14]. Our findings suggest that even a 4-week program can yield measurable improvements, filling a gap in research on beginner-level training interventions. This study included a variety of plyometric exercises (e.g., lateral cone hops, burpees, squat jumps, box jumps, and sprints), each aimed at developing specific physical attributes. Although previous research frequently highlights improvements in vertical jump [30, 38], the results of this study illustrate

Table 5. Paired sample t-test of scores in the experimental and control groups of volleyball players

Variable	Group	Pre-Test M ± SD	Post-Test M ± SD	Mean Difference M	t-value	p-value
Lateral Cone Hops	Experimental	5.400 ± .821	9.450 ± .686	4.050	19.176	< .001
	Control	5.850 ± .745	6.500 ± .607	.650	2.942	.008
Burpees	Experimental	5.30 ±1.031	13.050 ±1.572	7.750	-17.358	< .001
	Control	5.250 ± 1.410	11.700 ± .979	6.450	16.962	< .001
Squat Jump	Experimental	4.700 ±v.657	9.550 ± .510	4.850	29.108	< .001
	Control	4.950 ± .887	6.500 ± .607	1.550	7.339	< .001
Box Jump	Experimental	4.850 ± .671	9.050 ± .686	4.200	10.514	< .001
	Control	5.150 ± .875	6.600 ± .598	1.450	5.900	< .001
Sprint	Experimental	5.050 ± .759	8.250 ± 1.209	3.200	18.685	< .001
	Control	4.850 ± .745	7.400 ± .503	2.550	16.616	< .001

that plyometric training can enhance several fitness elements essential for volleyball performance.

Our findings align with research confirming the benefits of plyometric training for power and jump performance [11, 40, 41]. The improvements in squat jumps and box jumps support the idea that plyometric exercises enhance lower-body explosiveness, which is crucial for spiking and blocking [26]. Additionally, the significant gains in agility and speed observed in this study are consistent with previous research indicating that structured plyometric training enhances reaction time and movement efficiency [7, 11, 42]. Although research has examined plyometric training in soccer and basketball [5, 7], volleyball requires distinct movement patterns, including lateral agility and explosive jumps. The study findings indicate that the selected exercises effectively target these volleyball-specific demands, making this study particularly relevant to the sport. The study's findings corroborate previous research, demonstrating that the plyometric training program significantly enhanced jumping performance in the experimental group compared to the control group. Plyometric exercises, whether performed with or without external weights, have been widely recognized for their effectiveness in improving explosive power, strength, and sprint performance [42, 43, 44]. Notably, the inclusion of burpees in the training regimen contributed to overall strength and physical endurance, enabling athletes to sustain peak performance for prolonged periods [28, 45, 46]. Given their high-intensity nature and the engagement of multiple muscle groups simultaneously, burpees facilitate improvements in muscular strength, endurance, and cardiovascular fitness. Consequently, players develop greater stamina and the ability to maintain optimal performance levels during high-intensity gameplay.

Furthermore, the results revealed significant improvements in key physical fitness components, such as speed and coordination, among novice volleyball players. Speed and coordination exercises contributed to enhanced reaction times and improved movement efficiency on the court, thereby elevating both offensive and defensive performance [2, 33, 47]. The integration of these exercises into a volleyball training program not only enhances individual performance but also strengthens overall team dynamics. Players develop a heightened ability to anticipate opponents' movements, execute precise actions, and transition seamlessly between plays, contributing to a more cohesive and effective team strategy. These enhancements align with prior studies indicating that plyometric training improves neuromuscular efficiency and muscle activation patterns [27, 41]. By fostering better motor control and explosive power, such training directly benefits volleyball-specific movements, such as jumping, quick lateral shifts, and sudden accelerations [4, 26].

The structured nature of the training program, which incorporated progressive increments in sets and repetitions, allowed athletes to adapt gradually and safely, reinforcing the importance of systematic load progression in athletic training. This progressive approach not only optimized performance gains but also minimized the risk of injury. Collectively, the improvements observed in agility, power, strength, coordination, and speed highlight the comprehensive benefits of plyometric training for volleyball players. Enhanced physical capabilities translate into more efficient execution of volleyball-specific skills, leading to superior individual performance, improved team cohesion, and an increased likelihood of success in competitive settings. Additionally, these physical gains contribute to injury prevention, prolong athletic careers, and establish a solid foundation for future training advancements. Thus, the study underscores the efficacy of plyometric training in developing the critical physical attributes necessary for volleyball performance. By systematically integrating plyometric exercises into training programs, coaches and athletes can achieve significant improvements in athleticism, facilitating higher levels of performance while ensuring long-term physical development.

Notwithstanding the substantial findings, this study presents several limitations that warrant consideration. The short duration of the intervention, restricted to four weeks, may not adequately reflect the long-term impacts of plyometric exercise on physical fitness components. The sample size was limited and confined to novice volleyball players aged 19–21, thus constraining the generalizability of the findings to other age demographics, skill levels, and sports disciplines. Furthermore, the study failed to account for individual differences in fitness levels, training history, or program adherence, which could have impacted the outcomes. Ultimately, the study depended exclusively on performance-based metrics, omitting biomechanical or physiological evaluations that would have offered more profound insights into the mechanisms underlying the reported enhancements. Future research ought to prioritize extended studies with larger and more diverse groups to enhance comprehension of the long-term impacts of plyometric exercise. Moreover, investigating the effects of diverse plyometric training protocols, encompassing differences in intensity, frequency, and exercise selection, may yield more tailored recommendations for athletes. Integrating biomechanical and physiological evaluations could enhance the comprehension of plyometric training's impact on performance and its role in mitigating injury risk.

Conclusions

The results of this study indicate that a 4-week plyometric training program markedly improves essential physical fitness attributes, such as agility, speed, power, strength, coordination, and balance, in novice volleyball players aged 19 to 21. The experimental group demonstrated significant enhancements in performance metrics, including lateral cone hops, squat jumps, box jumps, and sprints, relative to the control group, underscoring the effectiveness of specific plyometric activities. These findings highlight the need to integrate plyometric training into volleyball training programs to enhance athletic performance and equip players for the sport's dynamic requirements. This study establishes a basis for subsequent research by highlighting the significance of organized plyometric exercise in cultivating fundamental fitness characteristics. It also emphasizes topics for further exploration, including the long-term effects of plyometric exercise, its applicability across diverse age groups and skill levels, and the influence of varying training intensities and durations. Additionally, this study serves as a practical reference for developing evidence-based training routines to improve athletic performance and mitigate injury risk in volleyball and other sports.

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Conflict of interests

The authors declare that there is no conflict of interests.

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ORIGINAL ARTICLE

The effect of long-term high-intensity workouts improving physical fitness in adolescent males

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

Abstract

Background and Study Aim The combination of a sedentary lifestyle with low physical activity contributes to reduced quality of life and can be a cause of death. Changing a sedentary lifestyle habit, such as increasing physical activity, is a form of prevention against the emergence of health problems. This study aimed to investigate the impact of long-term high-intensity workouts on enhancing physical fitness in adolescent males.

Material and Methods The study included 25 male adolescents aged 19-23 years who were university students residing in Malang. The participants were randomly assigned to one of two groups: K1 (control group; n = 12) or K2 (high-intensity workout group; n = 13). The high-intensity workout intervention was administered three times per week for eight weeks. Physical fitness components, including VO_2max, speed, agility, strength, and flexibility, were measured twice: before and after the intervention. The data were analyzed via an independent samples t-test with a 5% significance level.

Results Significant improvements in VO_2max, strength, speed, and agility were observed in the high-intensity workout group (K2), while no significant changes occurred in the control group (K1). Mean ΔVO_2max between K1 and K2 (0.13±0.56 to 4.49±1.18 mL/kg/min, p=0.001), Δspeed (-0.02±0.05 to -0.21±0.15 s, p=0.001), Δagility (0.03±0.21 to -0.56±0.26 s, p=0.001), Δstrength (1.50±2.02 to 8.85±1.82 kg, p=0.001), and Δflexibility (0.98±2.16 to 1.82±0.66 cm, p=0.219).

Conclusions This study revealed evidence of the effect of high-intensity workout interventions on improving physical fitness components but not on flexibility improvement, likely due to the strength- and endurance-focused nature of the training program.

Keywords: high-intensity workout, healthy lifestyle, adolescent males, physical fitness.

Introduction

Sedentary lifestyles and the rapid pace of urbanization are primary contributors to the increasing prevalence of physical inactivity [1]. This decline in physical activity is a major public health concern, as it significantly affects overall well-being and increases the risk of various chronic diseases. The World Health Organization (WHO) defines a sedentary lifestyle as any waking behavior characterized by an energy expenditure of ⩽ 1.5 METs (metabolic equivalents) while sitting or lying down [2]. This lifestyle has been identified as a leading cause of reduced quality of life and increased mortality rates [3]. Park et al. [4] reported that a sedentary lifestyle is associated with numerous adverse health outcomes, including a higher risk of mortality, cardiovascular disease, cancer, metabolic disorders, osteoporosis, and cognitive decline. Furthermore, prolonged sedentary behavior has been linked to an increased likelihood of developing type 2 diabetes and reduced bone density [5]. Globally, physical inactivity is responsible for approximately 6% of all deaths [6], with up to 81% of individuals failing to meet the WHO's recommended physical activity levels [7]. This inactivity is particularly concerning because it accelerates physiological aging and contributes to muscle deterioration [8]. However, research indicates that shifting from inactivity to regular physical activity could prevent up to 5.3 million deaths annually [9].

Physical activity is defined as any bodily movement produced by skeletal muscles that requires energy expenditure. The WHO recommends that adults engage in at least 150 minutes of moderate-intensity physical exercise per week or 75 minutes of high-intensity exercise, with each session lasting between 20 and 60 minutes [2]. Similarly, the American College of Sports Medicine (ACSM) suggests resistance training with 8 to 12 repetitions for each major muscle group at an intensity ranging from 40% to 80% of one repetition maximum (RM), depending on the individual's fitness level [10]. A rest period of two

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to three minutes between sets is recommended for adequate recovery [11]. Among various training methods, circuit training has gained popularity due to its efficiency in improving multiple fitness components simultaneously [12]. High-intensity circuit training, in particular, has been recognized as a safe and effective approach for enhancing physical fitness [13]. This form of training engages both the cardiorespiratory and musculoskeletal systems, making it a comprehensive workout strategy. Previous studies have demonstrated that circuit training improves key health parameters, including cardiorespiratory endurance, muscular strength, and body composition [14].

Among adolescents, physical inactivity is especially concerning. This period is crucial for musculoskeletal development and metabolic health, emphasizing the importance of establishing active habits early in life [15]. While extensive research supports the benefits of regular exercise, there remains a gap in the literature regarding the long-term effects of structured high-intensity workouts on adolescent males' physical fitness. Most existing studies focus on general physical activity or moderate-intensity exercise, leaving uncertainties about the physiological adaptations induced by prolonged high-intensity training in this demographic.

High-intensity circuit training has been shown to enhance muscle strength, muscle mass, and bone density. However, the optimal exercise dose required to maximize physical fitness adaptations remains underexplored. Therefore, this study aims to investigate the effects of long-term high-intensity workouts on improving physical fitness in adolescent males.

Materials and Methods

Participants

A total of 25 adolescent males meeting the following criteria were selected for participation: aged 19–22 years, normal body mass index, normal blood pressure, normal heart rate, normal body temperature, and normal oxygen saturation. All selected respondents were confirmed to have no history of chronic diseases (including diabetes mellitus, heart disease, hypertension, or respiratory problems). Additionally, selected respondents were also confirmed not to have consumed alcohol, smoked, or had a history of consuming alcohol or tobacco in the last five years, and not to have taken medication regularly. The selection of participants was carried out using a consecutive sampling technique, and the division into groups was carried out randomly. The participants were randomly assigned to one of two groups: K1 (control group; n = 12) or K2 (high-intensity workout group; n = 13). All procedures conducted in this study were approved by the Research Ethics Commission of Universitas Negeri Malang (KEP UM) (No.4.07.2/UN32.14.2.8/LT/2024).

Study Design

High-intensity Workout Protocol

The high-intensity workout regimen was conducted three times per week over ten weeks, for a total of 30 sessions. The workout consisted of six stations: jumping jacks, running in place, zig-zag running, squat thrusts, downline drifting, and dot-wave drill training. Each session lasted 25–30 minutes, with active rest intervals of 30–60 seconds between stations. Heart rate was monitored throughout the intervention via a Polar H10 Heart Rate Sensor. Details of the high-intensity workout protocol are presented in Table 1.

Data collection procedure

Data were collected by administering physical fitness tests at two time points: pre-intervention (0 weeks) and 24 hours after the intervention (10 weeks). The tests were conducted at the same time of day on both occasions. Maximal oxygen uptake (VO_2max) was assessed via the multistage 20-meter shuttle run test (20 mMSFT) [16]. Strength was measured with a Back & Leg Dynamometer [17], whereas speed was evaluated using a 30-Meter Sprint Test [18]. Agility was assessed via the Shuttle Run Fitness Test [16], and flexibility was measured using the sit-and-reach flexibility test [19]. All instruments used in this research had been validated by several previous studies [16, 17, 18, 19].

Statistical Analysis

The data were analyzed using SPSS software version 20. The normality and homogeneity of the data were assessed using the Shapiro–Wilk test and Levene's test. All data that were normally distributed and had homogeneous variance were analyzed using paired samples t-tests and independent samples t-tests. A paired samples t-test was applied to evaluate differences in physical fitness within each group, whereas an independent samples t-test was used to compare differences between the groups. Meanwhile, data that were not normally distributed were analyzed using the Wilcoxon signed-rank test and the Mann-Whitney U test. Effect size evaluation was implemented using Cohen's d. Statistical significance was determined at a p-value of ≤ 0.05.

Results

Based on the study results, the analysis showed that the overall data on the characteristics of the research subjects in the two groups did not show any significant differences ($p \geq 0.05$). Details of the analysis results can be seen in Table 2. Meanwhile, details of the analysis results for physical fitness components, including VO_2max, strength, speed, agility, and flexibility, can be seen in Figure 1 and Table 3.

Table 1. Details of the High-Intensity Workout Protocol

Group	Frequency	Intensity	Duration	Type of Exercises	Warm-up	Cooldown
High-intensity workout training						
Week 1–2	3 times per week for 10 weeks	Work-rest ratio 1:1	4 sets with active rest intervals of 60 seconds between stations and a rest period of 3 minutes between sets	Circuit training (jumping jacks, running in place, zig-zag running, squat thrusts, downline drifting, and dot-wave drill training)	Dynamic stretching for 5 minutes	Running at alow intensity (50% HRmax) for 5 minutes
Week 3–4	3 times per week for 10 weeks	Work-rest ratio 1:0.5	4 sets with active rest intervals of 30 seconds between stations and a rest period of 2 minutes between sets	Circuit training (jumping jacks, running in place, zig-zag running, squat thrusts, downline drifting, and dot-wave drill training)	Dynamic stretching for 5 minutes	Running at alow intensity (50% HRmax) for 5 minutes
Week 5–6	3 times per week for 10 weeks	Work-rest ratio 1:1	5 sets with active rest intervals of 60 seconds between stations and a rest period of 3 minutes between sets	Circuit training (jumping jacks, running in place, zig-zag running, squat thrusts, downline drifting, and dot-wave drill training)	Dynamic stretching for 5 minutes	Running at alow intensity (50% HRmax) for 5 minutes
Week 7–8	3 times per week for 10 weeks	Work-rest ratio 1:0.5	5 sets with active rest intervals of 30 seconds between stations and a rest period of 2 minutes between sets	Circuit training (jumping jacks, running in place, zig-zag running, squat thrusts, downline drifting, and dot-wave drill training)	Dynamic stretching for 5 minutes	Running at alow intensity (50% HRmax) for 5 minutes
Week 9–10	3 times per week for 10 weeks	Work-rest ratio 1:1	6 sets with active rest intervals of 30 seconds between stations and a rest period of 2 minutes between sets	Circuit training (jumping jacks, running in place, zig-zag running, squat thrusts, downline drifting, and dot-wave drill training)	Dynamic stretching for 5 minutes	Running at alow intensity (50% HRmax) for 5 minutes
Control	10 weeks without training intervention					

These findings confirm that both groups had similar physiological profiles at baseline, ensuring that any observed improvements in physical fitness resulted from the intervention rather than pre-existing differences (Table 2).

There were significant differences between pre- and post-intervention values in the high-intensity workout group (K2) for VO_2max ($p = 0.001$; effect size (ES): 1.937), strength ($p = 0.001$; ES: 0.922), speed ($p = 0.001$; ES: 0.958), agility ($p = 0.001$; ES: 1.997), and flexibility ($p = 0.001$; ES: 0.603) (Figure 1). Meanwhile, in the control group (K1), no significant differences were observed in VO_2max, strength, speed, agility, or flexibility between pre- and post-intervention measurements (all $p \geqslant 0.05$) (Figure 1).

The results indicate that the high-intensity workout group (K2) experienced significant improvements in all measured physical fitness components, including VO_2max, strength, speed, agility, and flexibility, following the intervention (Table 3). In contrast, no significant changes were

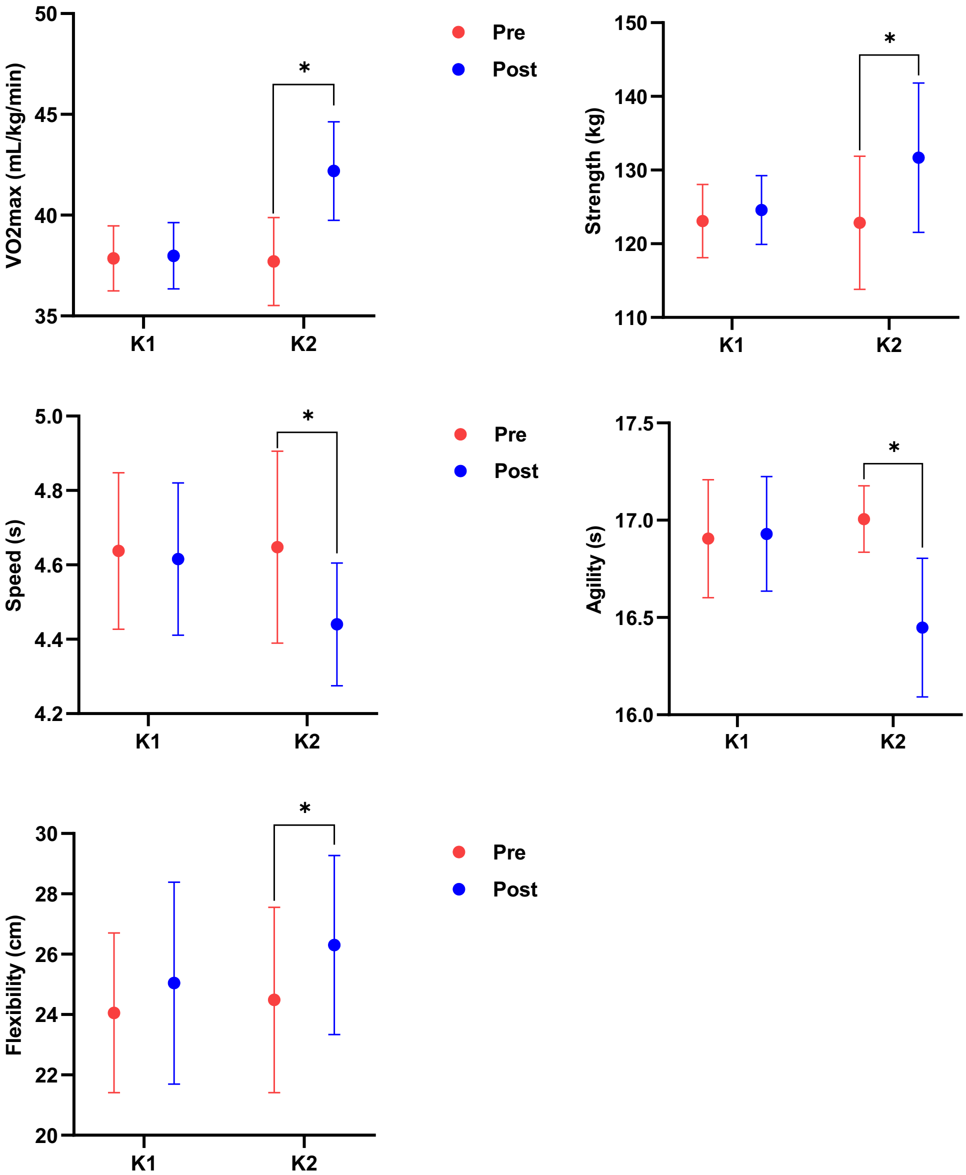

Figure 1. Pre- and post-intervention physical fitness assessment for each group. Significant difference in pre ($p \leqslant 0.001$). Data are presented as means ± SDs. The p-value was evaluated using a paired samples t-test.

observed in the control group (K1). These findings suggest that structured high-intensity training is an effective approach for enhancing multiple aspects of physical performance in adolescent males.

Discussion

This study aimed to evaluate the impact of long-term high-intensity workouts on physical fitness in adolescent males. The primary finding was that this intervention significantly improved VO_2max, strength, speed, and agility, although it did not enhance flexibility. These results align with previous research demonstrating the efficacy of high-intensity exercise in enhancing overall fitness levels [20]. Lee et al. [21] reported that high-intensity circuit training effectively improves multiple fitness components by simultaneously engaging the cardiovascular and musculoskeletal systems.

The improvement in VO_2max observed in this study can be attributed to cardiovascular adaptations, including increased stroke volume, enhanced capillary density, and improved oxygen utilization by skeletal muscles. High-intensity workouts induce repeated cardiovascular stress, which stimulates myocardial hypertrophy and increases cardiac efficiency, leading to improved oxygen delivery during exercise [22]. Similarly, the observed strength and speed improvements are likely driven by neuromuscular adaptations, such as greater motor unit recruitment, enhanced intramuscular coordination, and increased muscle fiber activation, contributing to higher force production and improved movement efficiency [23]. The improvements in agility may be associated with enhanced neuromuscular control and proprioceptive adaptation, which are crucial for rapid directional

Table 2. General characteristics of the study subjects

Parameters	Group	n	Mean	Std. Deviation	p-value
Age (years)	K_1	12	21.42	1.45	0.762
	K_2	13	21.23	1.59	
Height (m)	K_1	12	1.74	0.06	0.758
	K_2	13	1.75	0.04	
Body weight (kg)	K_1	12	63.67	4.31	0.846
	K_2	13	64.00	4.14	
Body Mass Index (kg/m^2)	K_1	12	20.98	0.65	0.867
	K_2	13	20.93	0.81	
Systolic blood pressure (mmHg)	K_1	12	117.08	3.61	0.715
	K_2	13	117.62	3.59	
Diastolic blood pressure (mmHg)	K_1	12	75.33	3.12	0.940
	K_2	13	75.23	3.61	
Heart rate (bpm)	K_1	12	62.92	2.75	0.722
	K_2	13	63.39	3.71	
Body temperature (°C)	K_1	12	36.68	0.39	0.819
	K_2	13	36.72	0.48	
Oxygen saturation (%)	K_1	12	97.67	1.07	0.793
	K_2	13	97.54	1.33	

K_1: Control group; K_2: High-intensity workout group. The p-value was evaluated using an independent samples t-test.

changes and acceleration.

Despite these positive effects, flexibility did not show significant changes, likely due to the nature of high-intensity workouts, which predominantly emphasize strength and power rather than joint range of motion. Unlike stretching-based training, high-intensity circuits do not prioritize prolonged muscle elongation, which is necessary to improve flexibility [24]. Future research should explore whether incorporating dynamic stretching or mobility exercises into high-intensity programs could lead to enhanced flexibility outcomes.

High-intensity exercise is widely recognized for its ability to improve physical fitness and overall health. When performed in group settings, high-intensity exercise can also provide social engagement opportunities for individuals with sedentary lifestyles. Participating in group workouts allows individuals to interact with others who share similar goals of improving fitness and health [25].

Allen et al. [26] demonstrated that high-intensity exercise conducted over a 9-week period effectively reduced waist circumference in sedentary individuals, which was attributed to increased adenosine triphosphate (ATP) consumption by skeletal muscles, leading to the activation of adenosine monophosphate-activated protein kinase (AMPK). AMPK plays a crucial role in mobilizing fat from adipose tissue, thereby reducing fat storage, particularly in the abdominal region [27]. Furthermore, a decrease in waist circumference is often associated with improved flexibility, a key component of physical fitness.

High-intensity training is also known to increase VO_2max levels. Research indicates that high-intensity exercise performed over a 5-week period can significantly increase VO_2max [28], and sessions lasting 30 minutes have shown notable improvements in VO_2max [29]. This effect is due to the activation of the sympathetic nervous system during high-intensity exercise, which regulates muscle contractions and neuromuscular efficiency [30]. Such activation leads to an increase in heart volume and efficiency, enhancing plasma volume and myocardial contractility, which in turn lowers resting heart rate (HR) [31]. Additionally, improved musculoskeletal efficiency allows for more effective oxygen utilization, contributing to increased VO_2max and overall fitness [32].

High-intensity exercise can increase the production of free radicals and potentially cause muscle damage. Muscle damage may result from inflammation triggered by oxidative stress [33], which can lead to mitochondrial membrane damage and a decrease in mitochondrial biogenesis [34]. Recent studies have suggested that low- to moderate-intensity exercise can also induce oxidative stress, highlighting that both exercise volume and a weakened antioxidant defense system are key contributors to exercise-induced oxidative stress [35]. This finding contrasts with earlier research suggesting that high-intensity

Table 3. Results of the physical fitness analysis for each group

Parameters	Group	n	Mean±Std. Deviation	p-value	Effect Size
Pre-VO_2max (mL/kg/min)	K_1	12	37.86±1.61	0.838	0.083
	K_2	13	37.70±2.19		
Post-VO_2max (mL/kg/min)	K_1	12	37.99±1.65	0.000	2.011
	K_2	13	42.19±2.45[b]		
Δ-VO_2max (mL/kg/min)	K_1	12	0.13±0.56	0.000	4.721
	K_2	13	4.49±1.18[b]		
Pre-Flexibility (cm)	K_1	12	24.06±2.65	0.713	0.149
	K_2	13	24.49±3.07		
Post-Flexibility (cm)	K_1	12	25.04±3.35	0.329	0.401
	K_2	13	26.31±2.97		
Δ-Flexibility (cm)	K_1	12	0.98±2.16	0.219	0.525
	K_2	13	1.82±0.66		
Pre-Strength (kg)	K_1	12	123.08±4.98	0.935	0.031
	K_2	13	122.85±9.03		
Post-Strength (kg)	K_1	12	124.58±4.68	0.036	0.901
	K_2	13	131.69±10.13[a]		
Δ-Strength (kg)	K_1	12	1.50±2.02	0.000	3.822
	K_2	13	8.85±1.82[b]		
Pre-Speed (s)	K_1	12	4.64±0.21	0.915	0.042
	K_2	13	4.65±0.26		
Post-Speed (s)	K_1	12	4.62±0.21	0.028	0.942
	K_2	13	4.44±0.17[a]		
Δ-Speed (s)	K_1	12	-0.02±0.05	0.001	1.699
	K_2	13	-0.21±0.15[b]		
Pre-Agility (s)	K_1	12	16.91±0.30	0.323	0.411
	K_2	13	17.01±0.17		
Post-Agility (s)	K_1	12	16.93±0.29	0.001	1.468
	K_2	13	16.45±0.36[b]		
Δ-Agility (s)	K_1	12	0.03±0.21	0.000	2.496
	K_2	13	-0.56±0.26[b]		

K_1: Control group; K_2: High-intensity workout group. [a]Significant difference in the control group ($p \leqslant 0.05$). [b]Significant difference in the control group ($p \leqslant 0.001$). The p-value was evaluated using an independent samples t-test.

exercise might significantly reduce oxidative stress [36]. Other studies have demonstrated that regular exercise can enhance the body's antioxidant system, increase physiological resilience, and mitigate oxidative stress [37].

Our findings indicate that high-intensity training can reduce oxidative stress following exercise and enhance physical fitness, as evidenced by improvements in speed, agility, muscle strength, and VO_2max. This effect is likely due to the adaptive nature of exercise, which stimulates muscle adaptation and increases antioxidant levels to counteract oxidative stress, thereby improving mitochondrial function [38].

This study has several limitations that should be considered when interpreting the findings. First, the focus on adolescent males limits the generalizability of the results to other age groups and genders. Physiological responses to high-intensity training may differ due to hormonal fluctuations, muscle composition, and metabolic rates, which were not accounted for in this study. Future research should include a more diverse sample to determine whether similar adaptations occur across different populations.

Additionally, this study primarily assessed physical fitness components (strength, speed, agility, VO_2max, and flexibility) without incorporating biomolecular parameters, which limits the understanding of the underlying physiological mechanisms. High-intensity training induces hormonal, mitochondrial, and oxidative stress adaptations, which were not measured in this study. Future research should integrate biochemical markers, such as oxidative stress indicators and inflammatory cytokines, to provide a more comprehensive perspective on these physiological effects.

Another limitation is the lack of flexibility improvement, which may be due to the training regimen emphasizing strength and endurance over joint mobility. Incorporating dynamic stretching or mobility-focused exercises in future protocols may address this gap.

Moreover, external factors such as nutrition, recovery strategies, and prior fitness levels were not strictly controlled, potentially introducing variability in the results. Future studies should implement more rigorous controls on these variables to enhance the validity and applicability of the findings.

Conclusions

The results of this study demonstrate that high-intensity workouts conducted over 10 weeks significantly improved key physical fitness components, including VO_2max, strength, speed, and agility, compared to the control group. These findings suggest that structured high-intensity training can be an effective strategy for enhancing athletic performance in adolescent males, making it a potential recommendation for sports training programs and school-based physical education curricula. However, no significant improvement in flexibility was observed in the high-intensity workout group compared to the control group. This outcome may be attributed to the nature of high-intensity exercises, which primarily target cardiovascular endurance and muscular strength rather than flexibility. Additionally, the training regimen used in this study did not incorporate specific flexibility-enhancing exercises, such as static or dynamic stretching routines. Future research should explore whether integrating flexibility-focused exercises into high-intensity training protocols could lead to more comprehensive fitness benefits.

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Conflict of Interest

he authors declare that they have no conflicts of interest regarding this study.

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ORIGINAL ARTICLE

Evaluating the effectiveness of a virtual reality-based training method for basic scuba diving skills

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

Abstract

Background and Study Aim Traditional scuba diving training often faces challenges in creating a safe and effective environment for beginners. Virtual reality (VR) technology offers a more interactive simulation to improve basic diving skills before participants dive into the real environment. This study aims to analyze the effectiveness of VR-based training methods compared to traditional training methods in improving basic diving skills in beginners.

Material and Methods This study used a two-group pretest-posttest experimental design, with 64 university students (aged 17-19 years) randomly divided into an experimental group (n = 32) and a control group (n = 32). The experimental group attended scuba diving training using VR, while the control group received traditional training involving classroom sessions and pool exercises. For 12 weeks, the experimental group also received 60 minutes of scuba diving training once a week. Diving skills were measured before and after the intervention using a basic diving skills test. Data analysis was aided using SPSS 26.

Results The Wilcoxon test results showed that there was a significant effect between the pretest and posttest in both groups ($p = 0.000$), which means that both the control group and the experimental group had improved diving skills after the intervention. The posttest results showed that the experimental group had a significant improvement in diving skills (mean = 95) compared to the control group (mean = 75) with $p < 0.05$. Mann-Whitney U analysis showed a significant difference between the two groups ($Z = -6.756$, $p < 0.05$), indicating that the VR method was more effective than the traditional method.

Conclusions VR-based training was shown to be more effective in improving basic diving skills than traditional methods. The use of this technology can be an innovative alternative in scuba diving training programs for beginners.

Keywords: virtual reality, scuba diving, diving training, basic skills, learning technology

Introduction

Scuba diving is an activity that requires complex technical skills, including buoyancy control, breathing coordination, and adaptation to the underwater environment. Conventional training for divers usually involves practical sessions in swimming pools or open water with experienced instructors [1]. However, traditional training methods have limitations, such as limited accessibility, high costs, and safety risks for novice divers [2]. In addition, unfavorable environmental conditions, such as bad weather or low visibility, can also hinder the training process [3]. Therefore, technology-based training methods, such as virtual reality, have been developed as a more effective alternative to improving basic diving skills.

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Virtual reality technology allows for the simulation of underwater environments that closely resemble real conditions. It is already utilized across multiple sectors, including education, training, sports, and healthcare [4]. Virtual reality has been used in various fields of sports and physical rehabilitation to improve individuals' motor and cognitive skills [5]. In the context of scuba diving training, virtual reality can help novice divers understand basic concepts, such as buoyancy control and breathing management. It even helps with underwater navigation without the risks inherent in live training in open water [6].

The main problems in scuba diving training are the risk of accidents due to lack of experience, inability to manage underwater stress, and lack of understanding of effective breathing techniques [7]. In addition, the instructor's limitation in supervising each individual during training in a real environment is a factor that can affect the effectiveness of learning. Therefore, the development of virtual reality-based training methods is a potential solution to overcome these obstacles. Virtual reality not only provides an opportunity for divers to practice independently and repeatedly without risk, but also allows for the use of data analysis to evaluate their skill development [8, 9, 10].

Several studies have demonstrated the effectiveness of virtual reality in water sports training. For example, in studies on diver training, virtual reality was shown to significantly improve conceptual understanding and motor skills compared to traditional methods [2, 11, 12]. In addition, the application of virtual reality in training swimmers has also been shown to help optimize movement patterns, as well as improve spatial awareness and body coordination [3]. Thus, the integration of virtual reality in scuba diving training is expected to provide similar benefits, especially in improving basic skills for novice divers.

The novelty of this study lies in the empirical evaluation of the effectiveness of virtual reality in improving basic scuba diving skills compared to traditional methods. This study not only explores the advantages of virtual reality technology in training [13, 14], but also highlights the challenges of its implementation, including technical, economic, and psychological factors that may affect learning success. Therefore, this research has high significance in providing new insights for the development of safer, more efficient, and accessible scuba diving training methods.

Furthermore, this study also sought to identify key factors that influence success, especially in learning in virtual reality-based scuba diving training, including cognitive aspects, motor skills, and participants' risk perception [4]. In addition, this research is expected to contribute to the development of a more adaptive and technology-based training curriculum, aimed at increasing the accessibility and effectiveness of training for prospective divers from various backgrounds.

Nevertheless, there are still some challenges in the application of virtual reality for scuba diving training, such as technological limitations in simulating the real physical effects of diving, the need for sophisticated hardware, and relatively high development costs [15, 16]. Therefore, this study aims to evaluate the effectiveness of virtual reality-based training methods in improving basic scuba diving skills and compare them with conventional training methods, as well as identify solutions to improve the wider application of virtual reality in scuba diving training.

Materials and Methods

Participants

This study used a random sampling technique to determine the distribution of the control group (CG) and the experimental group (EG). Each participant from a population of 64 students (aged 17–19 years) had an equal chance of being included in one of the two groups.

The randomization process was conducted using a software-assisted simple random sampling method or the lottery method, so that the distribution of participants in the two groups was not influenced by any subjective factors. Using this method, 32 students were randomly placed in the control group (CG), which underwent conventional scuba diving training, while the other 32 students were placed in the experimental group (EG), which underwent virtual reality-based training. This approach ensures that the initial characteristics of the participants in both groups are balanced, so that differences in the results obtained can be more accurately attributed to the treatment provided rather than to other uncontrolled factors.

Table 1. Research Population

No.	Group	Total
1	Experimental Group (EG)	32 Students
2	Control Group (CG)	32 Students

Research Design

This research is a quantitative study with an experimental study approach [17]. This research design used a two-group pretest and posttest design, namely an experimental group that received virtual reality-based training and a control group that received traditional training. Each group consisted of 32 participants randomly selected from a population of novice divers. The population and sample of this study were adult individuals who had never attended scuba diving training before. The sample was randomly drawn and divided into two groups (virtual reality group and traditional group), with 32 participants each.

Research Procedure

The experimental group (EG) underwent scuba diving training using a virtual reality (VR) system powered by the Blu software, which provided an immersive underwater simulation experience. The VR training incorporated motion-tracked hand controllers to simulate equipment handling, real-time breathing feedback, and interactive underwater navigation scenarios. Each session lasted 60 minutes, conducted twice per week for 12 weeks, following a structured progression from basic breathing exercises to advanced underwater orientation and emergency response drills. Meanwhile, the control group (CG) participated in traditional scuba diving training, which included theoretical classroom sessions covering diving safety, equipment handling, and breathing techniques, followed by practical pool exercises. The training schedule was designed to match the VR group's exposure, with 60-minute sessions held twice a week over 12 weeks.

After completing the training, both groups were assessed using the CMAS One-Star Diver Standard, which evaluates key scuba diving skills, including breathing techniques, equipment handling, and underwater orientation. Breathing skills were assessed based on participants' ability to use the scuba regulator properly, regulate breathing, and manage underwater stress. Equipment handling evaluation focused on the correct handling and adjustment of diving gear, such as mask clearing, regulator recovery, and buoyancy control. Underwater orientation assessment measured participants› navigation skills, spatial awareness, and ability to maintain neutral buoyancy while following a designated dive path. The assessment was conducted by certified CMAS diving instructors, who used a standardized scoring rubric to evaluate participants› accuracy, efficiency, and confidence in performing each skill.

Additionally, a questionnaire was administered to collect participants' perceptions of their learning experience, engagement, and confidence levels post-training [18]. To further enhance participants' comfort in aquatic environments, both groups also took part in scuba diving training once a week for 60 minutes over 12 weeks, which included basic water adaptation exercises to improve familiarity and ease in underwater settings.

Statistical Analysis

After the data from the sample were collected, they were analyzed using descriptive statistical analysis techniques. In descriptive statistical analysis, the goal is to find the highest value, lowest value, average, median, and mode, as well as standard deviation. Before testing the research hypothesis, it is necessary to conduct a preliminary test. The results of this testing aim to improve the accuracy of the analysis. For this reason, a data normality test was conducted in this study.

Before moving on to the t-test, a key assumption must be met: the analyzed data must be normally distributed. If not, a non-parametric test will be used. This analysis was assisted by SPSS version 26 software.

Results

Based on the analysis results in Table 2, the characteristics of the study participants, including age, height, weight, BMI, and the number of male and female participants, showed no significant differences between the control group (CG) and the experimental group (EG). This indicates that both groups had comparable baseline characteristics before the intervention.

The descriptive results of diving skills in Table 3 show that before the intervention, the average pretest scores of the control group (75.12) and the experimental group (75.37) were almost the same. However, after the intervention, the experimental group showed a significant increase, with an average posttest score of 94.56, compared to the control

Table 2. Characteristics of participants

Variables	CG	EG	p value
N	32	32	
Male	19	18	
Female	13	14	
Age (years)	18.55±0.09	18.45±0.09	NS
Height (m)	1.65±0.06	1.69±0.07	NS
Weight (kg)	65.04±6.43	60.58±6.69	NS
BMI (kg/m2)	16.28±	16.98±3.73	NS

Notes: CG : Control Group; EG: Experimental Group; BMI: Body Mass Index

Table 3. Descriptive Results of Diving Ability

Results	Group	N	Mean	Std. Deviation	Std. Error	Minimum	Maximum
Pretest	Control Group	32	75.1250	4.05407	0.71667	60.00	82.00
	Experimental Group	32	75.3750	3.48962	0.61688	65.00	82.00
	Total	64	75.2500	3.75436	0.46930	60.00	82.00
Posttest	Control Group	32	78.8438	3.08073	0.54460	70.00	85.00
	Experimental Group	32	94.5625	4.21164	0.74452	80.00	100.00
	Total	64	86.7031	8.72631	1.09079	70.00	100.00

group, which only reached 78.84. This indicates a greater improvement in the experimental group after the treatment.

The results of the Shapiro-Wilk normality test showed that most of the data were not normally distributed, except for the control group posttest ($p = 0.091$), which met the assumption of normality. The control group pretest ($p = 0.000$), the experimental group pretest ($p = 0.004$), and the experimental group posttest ($p = 0.000$) all showed an abnormal distribution ($p < 0.05$). Since the data were not completely normal, further analysis was conducted using non-parametric tests, namely the Wilcoxon Signed-Rank Test to measure the improvement within each group and the Mann-Whitney U Test to compare the posttest results between the control and experimental groups.

Non-parametric tests were chosen because they are more suitable for data with non-normal distributions, ensuring that the results of the analysis remain valid and accurate. The results can be seen in Table 4.

The Wilcoxon test results presented in Table 5 indicate a significant difference between pretest and posttest scores in both groups ($p = 0.000$), suggesting that participants in both the control and experimental groups experienced an improvement in their diving skills following the intervention. However, the increase in diving ability was more pronounced in the experimental group than in the control group.

In this study, the Wilcoxon Signed-Rank Test was applied to compare pretest and posttest results in both groups. In addition to analyzing the Z value and significance level (Sig.), an effect size (r) was calculated to determine the magnitude of improvement in diving skills. The effect size was computed using the formula $r = Z/\sqrt{N}$, where Z represents the Wilcoxon statistical value, and N is the total number of participants in the study. The findings revealed that the Z value was -4.977 for the control group and -4.944 for the experimental group, with each group consisting of 32 participants. Based on this formula, the calculated effect size was $r = 0.88$ for the control group and $r = 0.87$ for the experimental group.

According to standard interpretations, an effect size of $r \geq 0.5$ is considered large, indicating that both conventional and virtual reality-based training had a substantial impact on enhancing participants› diving skills. While both groups showed significant improvement, further analysis is necessary to determine whether virtual reality-based training offers additional benefits over conventional methods in specific areas, such as learning effectiveness, skill retention, and participants'confidence levels.

Furthermore, the Mann-Whitney U test in Table 6 shows that there was a significant difference between the posttest results of the two groups ($p = 0.000$), with the experimental group showing a higher improvement than the control group. The Z value of -6.756 indicates a significant difference between the two groups, with the experimental group showing greater improvement in diving skills than the control group. This analysis demonstrates that the virtual reality- and water game-based training method applied to the experimental group was significantly more effective than the traditional training method in improving novice diving skills.

Table 4. Shapiro Wilk Normality Test Results

Result	Statistic	df	Sig.
Pretest Control	0.839	32	0.000
Posttest Control	0.943	32	0.091
Experiment Pretest	0.894	32	0.004
Experiment Posttest	0.832	32	0.000

Table 5. Effect Test Results of Control Group and Experimental Group

Results	Indicator	Analysis	Z	Sig. (2- tailed)	Description
Pair 1	Control Group Pretest and Posttest	Wilcoxon	-4.977^c	0.000	Significant
Pair 2	Experimental Group Pretest and Posttest	Wilcoxon	-4.944^c	0.000	Significant

Table 6. Mann-Whitney U test results

Results	Posttest
Mann-Whitney U	10.500
Wilcoxon W	538.500
Z	-6.756
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Group

The superiority of this method can be attributed to the more realistic simulation and a more interactive learning environment, which enable participants to better understand breathing techniques, equipment usage, and underwater orientation before actually diving into the real environment.

Discussion

The results showed that the virtual reality (VR)-based training method was significantly more effective in improving basic scuba diving skills than the conventional training method. From the skill test results, the experimental group (EG) using virtual reality showed greater skill improvement than the control group (CG). The mean score of the EG's diving skill test was 94, while the CG's only reached 75 ($p < 0.05$). This finding indicates that virtual reality can provide a more effective training environment for building conceptual understanding and motor skills in novice divers.

From the results of the parametric analysis, no significant differences were found in the participants› baseline characteristics, such as age, height, weight, and body mass index (BMI), between the control and experimental groups. This suggests that the improvement in diving skills observed in the group using virtual reality was not due to individual characteristics, but rather to the effectiveness of the training method applied.

In addition to improved technical skills, most participants in the experimental group reported a more engaging and interactive learning experience. They stated that the use of virtual reality helped them feel more prepared and confident before attempting real-world dives [2,19]. In contrast, the control group that followed conventional training tended to experience boredom and increased anxiety when dealing directly with an open water environment. This aligns with previous research showing that virtual reality can reduce anxiety levels and increase learning motivation in challenging training contexts [5].

The main advantage of virtual reality in scuba diving training is its ability to create a safe, realistic, and repeatable training environment without physical risk [20]. The delivery of information in the form of interactive simulations allows participants to hone their skills unencumbered by external factors such as weather conditions or limited training facilities. Furthermore, the effectiveness of virtual reality-based training can also be attributed to the experiential nature of learning, which allows participants to learn from their mistakes in a controlled environment before transitioning to real waters [21,22].

However, there are several challenges in applying virtual reality to scuba diving training. One of these is the limitation of simulating the real physical effects of diving, such as water pressure, temperature, and motion resistance. Additionally, the absence of haptic feedback further reduces the realism of training, as participants cannot experience the tactile sensations of handling equipment underwater or the physical resistance of movement. This limitation may affect skill transfer when transitioning to real-world diving conditions.

In addition, investment in virtual reality devices and the development of appropriate software remain major obstacles to the widespread adoption of this technology [2]. High costs associated with VR hardware, software development, and maintenance make it less accessible, particularly for smaller training centers or individual learners.

Despite these limitations, strategic measures are needed to improve the accessibility and effectiveness of virtual reality for scuba diving training. Further research should explore ways to integrate haptic technology to enhance sensory engagement and improve skill acquisition. Moreover, the development of more cost-effective and scalable VR training programs is crucial to increasing adoption and making this technology more feasible for a wider range of users.

Overall, this study demonstrates that virtual reality-based training has great potential for improving basic scuba diving skills, both in terms of technical effectiveness and psychological aspects such as participants' confidence and motivation. However, a more critical analysis is required to address the current limitations of VR training and explore solutions that can enhance its realism, affordability, and effectiveness. With the continuous development of virtual reality technology, there will be more opportunities to optimize this training method, which in turn can provide innovative solutions for the scuba diving training industry in the future.

Conclusions

Based on the results of the analysis, it can be concluded that the intervention provided to the experimental group with virtual reality significantly improved diving skills compared to the control group. Although both groups improved, the higher results in the virtual reality group suggest that virtual reality-based training combined with water games is more effective for improving basic diving skills than traditional training methods. In addition, the learning experience using virtual reality was more engaging and reduced participants› anxiety. Therefore, this technology-based training can be a valuable and innovative alternative to diving instruction programs for beginners.

Further research should explore the use of virtual reality in more complex diving skills training, such as deep-sea navigation and underwater crisis management. In addition, the development of more specific and realistic virtual reality devices for scuba diving training could further increase the effectiveness of this training.

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Conflict of Interest

The authors report that there are no competing interests to declare.

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ORIGINAL ARTICLE

Exploring the role of different intensities of physical activity on fitness parameters in 9–11-year-old children: a framework for potential innovation of the physical education curriculum

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Abstract

Background and Study Aim Although physical activity (PA) is an important determinant of physical fitness (PF) in children, studies have rarely examined the associations between PA and PF in early school-age children within narrow age spans. The aim of this study was to evaluate the associations between different intensities of PA and various indices of PF in children aged 9 -11 years.

Material and Methods The participants were 121 children aged 9 - 11 years (49 girls) who were tested for PF (anthropometrics, aerobic endurance, upper body and abdominal strength, jumping power, mobility and flexibility), and the PA was directly measured via GeneActiv triaxial accelerometers. A t test was used to define differences between sexes, while Pearson's correlations between PA variables and PF indices and multiple regressions for PF criteria were used to calculate sex stratification.

Results Compared with girls, boys achieved better results in terms of jumping power capacity, upper body strength, and aerobic endurance, and they had a higher number of steps taken per day, and a higher amount of vigorous PA per day (all $p < 0.05$). The girls achieved better results in terms of flexibility and mobility. Correlations between PA-intensities and PF were weak to moderate. Multiple regression calculations revealed that vigorous PA was a significant predictor of jumping power, upper body strength, and aerobic endurance in boys (16%, 20%, and 13% of the explained variance, respectively) and jumping power in girls (18% of the explained variance). Moderate PA was a significant partial regressor of aerobic endurance in girls (13% of the explained variance).

Conclusions Tailoring physical-education curricula to gender-specific PA responses and expanding PF assessments can enhance student engagement, optimize fitness outcomes, and improve the overall effectiveness of physical education programs.

Keywords: motor performance, aerobic capacity, preadolescence, multiple regression, accelerometry

Introduction

Physical fitness (PF) can be defined as the ability to perform daily activities with vigor, alertness, and without excessive fatigue, and with ample energy to enjoy leisure-time pursuits and to meet unforeseen emergencies [1]. It encompasses a range of components, including cardiorespiratory fitness, muscular strength and endurance, flexibility, and body composition [2]. Adequate PF in children and youth includes an appropriate level of strength, cardiorespiratory fitness, and body composition and is directly associated with lower cardiovascular risk factors. Importantly, proper PF in children is associated with better bone health, psychological well-being, cognition, and school performance, and may decrease the risk of sports injury [2]. Therefore, promoting PF in children is crucial for their overall health and well-being, both in the present and future.

Physical activity (PA) is intrinsically linked to PF, and engaging in regular PA directly contributes to the development of various aspects of PF [3]. Regular PA strengthens various components of PF, including cardiovascular status, power capacity, muscular strength, and endurance. Regular PA promotes flexibility, improves bone health, helps maintain a healthy weight, and plays a crucial role in cognitive development by stimulating brain function and improving concentration, thereby influencing academic performance [4, 5]. Regular PA during childhood can establish healthy habits that continue into adulthood, reducing the risk of chronic diseases and promoting long-term health. Therefore, encouraging children to participate in a variety of PA activities is essential for their overall health and well-being, fostering not only PF but also

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mental and emotional development [6].

Measuring PA in children is crucial for several reasons. First, it helps determine the effectiveness of interventions aimed at increasing PA levels and promoting healthy lifestyles [7]. By tracking PA, healthcare professionals can identify children who are not meeting recommended activity levels and provide targeted support. Furthermore, measuring PA allows for the assessment of its impact on various PF indices. This information can be used to develop effective and targeted public health strategies and interventions to promote PA among children. Additionally, measuring PA can help raise awareness among parents, educators, and policymakers about the importance of PA for children's overall health and well-being. Collectively, by accurately assessing PA levels, valuable insights into the relationship between physical activity and various aspects of child development can be gained, leading to better strategies for promoting healthy habits and preventing chronic diseases.

Modern lifestyles have contributed to a concerning decline in PA among children [8]. Increased screen time, readily available processed foods, and a decrease in active transportation and outdoor play have created a more sedentary environment for children, and the decrease in PA is particularly evident at the beginning of elementary school education [9]. This trend has resulted in a rise in childhood obesity and a decline in overall PF. Studies indicate that children today are less fit than their counterparts from previous generations, with reduced cardiovascular health and lower levels of muscular strength and endurance [10]. This decline in PA and PF has significant implications for children's long-term health, increasing their risk of developing chronic diseases such as type 2 diabetes and cardiovascular disease. Therefore, it is not surprising that studies have attempted to evaluate the degree of association between PA and PF in children.

For example, several studies have reported an association between greater PA and better fitness performance in preschoolers [11, 12]. A Belgian study of 241 early adolescents from 30 schools reported a low-to-moderate association between directly measured PA and body fatness, somewhat stronger associations between PA and cardiovascular fitness, and low-to-moderate associations between PA and muscular fitness [13]. In a recent study, the authors reported significant correlations between indirectly measured PA and different facets of PF in Chinese children [14]. This finding is in accordance with findings among Spanish adolescents, where the authors confirmed a positive association between questionnaire-based PA and cardiorespiratory fitness (aerobic endurance) [15]. However, a recent study did not find a significant correlation between indirectly measured PA and PF indices in preadolescents from Croatia [16].

From the previous brief literature overview, it is evident that studies performed thus far have either reported total PA (and not specific PA intensities), observed specific segments of PF (i.e., cardiovascular fitness, anthropometrics), or observed children of different ages and from different environments (schools). Moreover, it is unlikely that different segments of PF are equally influenced by different PA intensities, especially considering age-, sex-, and environment-specific factors. Additionally, in studies of this type, it is important to include the direct measurement of PA, not only because of its validity but also because of its accuracy in the evaluation of different PA intensities [14, 16]. Finally, given the specifics of different sociocultural environments, the associations between PA and PF should be studied in different regions, but studies that examine this issue in southeastern Europe, including Croatia, are lacking [16].

An analysis of previous studies allows for the assumption that different intensities of PA are differentially associated with PF components in boys and girls. This assumption is based on the fact that sex-specific physiological differences may lead to distinct responses to varying PA intensities. Additionally, considering that preadolescent children from southern Croatia, specifically 3rd- and 4th-grade students, have already experienced a decline in PA since the beginning of their formal education, the potential impact of reduced PA on PF may have already emerged. Understanding these associations can provide valuable insights for refining physical education (PE) curricula, ensuring that PE is more student-oriented and designed to enhance specific PF components in this age group. Therefore, the aim of this study was to evaluate the sex-specific associations between different PA intensities and various components of PF in this population.

Materials and Methods

Participants

The participants in this study were children aged 9–11 years (n = 128; 49 girls). All participants were elementary school students from Split-Dalmatia County in southern Croatia. All children regularly attended elementary school in their community and participated in physical education classes, while some were also involved in out-of-school sports programs. The study was initially approved by the Ethical Committee of the Faculty of Kinesiology, University of Zagreb (approval number 93/2004, issued on 09 September 2024). Before the study, the authors informed school authorities about the study aims, and school principals organized meetings with the parents. During these meetings, investigators provided information about the study's objectives, protocol, risks, and benefits and asked parents to sign consent forms for their children's participation. Eighty-six percent of the parents who attended the meetings provided written consent for their children's participation in the study.

The inclusion criteria were regular participation in physical education, no illness or injury one week before the study, and no illness during the course of the study. The exclusion criteria included motor and functional impairments, health conditions preventing participation in physical education, as well as injury or illness one week prior to or during the measurement period. At baseline, 162 children were included, but due to technical issues (e.g., accelerometer measurement errors, excessive non-wear time), inconsistent data, injury, or illness, the final sample consisted of 128 children.

Research Design

In addition to age and gender (collected from school records), this study obtained data on PA and fitness variables.

For the purpose of evaluating PF, we used body mass, body height, body mass index, and tests included in the FitnessGram battery [17], with the addition of one test of power capacity. Body height was measured with stadiometer, and body mass was measured with a digital diagnostic scale (Tanita BC 418 scale; serial number 15010067, 2015), both following standardized procedures. Body mass index (BMI) was calculated by dividing body mass (in kg) by the squared body height (in meters). The 15-m Pacer test (Pacer test) was used to assess aerobic endurance (cardiovascular endurance). The test consists of 21 or more levels of seven or more intervals of running segments of 15 m. Participants run from one end to the other of a segment marked with cones and must touch the line when the buzzer sounds. At the sound of the beep, they turn and run back to the other end. The participants continue to do this until they fail to reach the line twice in a row. The goal is to cross as many levels as possible, and the result is expressed numerically in levels. The sit-up test (Sit-ups) was used to assess abdominal muscular strength and endurance. The test is performed by having the participant lift the torso as many times as possible, up to a maximum of 75 repetitions. The result is the maximum number of correctly performed sit-ups. The torso lift test (Torso-lift) was used to assess torso extensor strength and flexibility (mobility). On cue, the participant independently raises the cervical and thoracic parts of the spine in a controlled manner to their maximum, with the head in a neutral position in line with the spine. The push-up test (Push-ups) was used to assess upper body strength and endurance. The test is performed with the participant assuming a prone position on the mat with the palms under the shoulders, fingers extended, legs extended and parallel, and feet slightly apart, resting on the toes. The participant pushes off the mat with their hands until their arms are extended, keeping their legs and back straight. The participant then lowers their body using their arms until their elbows are bent at 90 degrees and their upper arms are parallel to the floor. The result is the maximum number of correctly performed push-ups. The Sit-and-Reach test was used to assess the flexibility of the lower back and hamstring muscles. The participant sits on the floor with their legs extended straight ahead, feet shoulder-width apart, and positioned against the box or measuring device. With their palms down and fingers pointing forward, the individual reaches forward along the measuring device as far as possible, holding the position for at least two seconds. Three trials are performed, and the average score is used as the final result. The standing broad jump (Broad jump) was used to assess jumping performance/power capacity. The test is performed with the participant standing behind the starting mark and jumping from a stationary position with bare feet as far as possible. A standardized measurement mat was used (ELAN, Begunje, Slovenia). The result was measured in centimeters, with the best of three attempts recorded. GeneActiv triaxial accelerometers were used for direct measurement of the PA of the participants over a seven-day period (Activinsights Ltd., Cambs, United Kingdom).

The GeneActiv is a small (43 × 40 × 13 mm), lightweight (16 g), waterproof device that collects raw acceleration data in the range of ±8 g. The device was validated for children aged 7–14 years. The devices were set to record at 30 Hz and were worn on the wrist [18]. The participants were instructed that the devices were waterproof and should be worn continuously, including while sleeping, swimming, and showering, allowing for a complete picture of their activity patterns. After the wearing period, the devices were connected to a computer, and raw acceleration data were downloaded via dedicated software. Using the same software, the data were cleaned, and non-wear time periods were removed. The PA variables observed in this study were based on accelerometer records and included the number of steps taken(steps), sedentary time, light PA, moderate PA, and vigorous PA.

Statistical Analysis

The Kolmogorov–Smirnov test was used to confirm that the data followed a normal distribution, a key assumption for many statistical tests. Means and standard deviations were calculated to provide a basic overview of the data characteristics. Independent samples t-tests were used to explore potential differences in study variables between boys and girls.

Pearson's correlation coefficients were calculated to assess the relationships between variables, and correlations were interpreted on a scale ranging from 0.00 to 0.19 (very weak), 0.20 to 0.39 (weak), 0.40 to 0.69 (moderate), 0.70 to 0.89(strong), and 0.90 to 1.00 (very strong), providing a clear indication of the strength of the associations. The correlations were calculated for the total sample and stratified by sex.

Multiple regression analyses were conducted to examine the relationships between PA variables (observed as predictors) and each PF variable (observed as a criterion). A forward stepwise approach was employed to address potential collinearity among the predictors. Since analyses of differences revealed significant differences in study variables between sexes (see the Results section for details), multiple regression calculations were stratified by sex.

Statistica (Tibco, Inc., Palo Alto, CA, USA) was used for all calculations, and a p-value of $\leqslant 0.05$ was considered statistically significant.

Results

The descriptive statistics and differences in the study variables according to sex are presented in Table 1. Compared with girls, boys achieved better results in the power capacity test (broad jump, t-test = 2.33, $p < 0.05$), upper body strength test (push-ups, t-test = 2.22, $p < 0.05$), and cardiovascular endurance test (Pacer test, t-test = 3.96, $p < 0.001$). Boys also had a higher number of steps per day (t-test = 2.54, $p < 0.01$) and engaged in more vigorous PA per day (t-test = 5.15, $p < 0.001$). Girls achieved better results in the sit-and-reach test of flexibility (t-test = 4.41, $p < 0.001$).

The linear correlations between the PA variables and PF are presented in Table 2. For the total sample, vigorous PA was negatively correlated with body height (weak correlation), body mass (weak correlation), BMI (weak correlation), and sit-and-reach test flexibility (weak correlation). Moreover, in the total sample, vigorous PA was positively correlated with broad jump performance (weak correlation), push-up test results for upper body strength (moderate correlation), and Pacer test results for aerobic endurance (moderate correlation). Additionally, when the total sample of participants was considered, the number of steps performed daily was positively correlated with broad jump performance and Pacer test results (weak correlations). When correlations were calculated specifically for girls, broad jump performance was significantly positively correlated with the number of steps performed daily (weak correlation), moderate PA (weak correlation), and vigorous PA (moderate correlation), whereas Pacer test results were positively correlated with moderate PA (weak correlation). In boys, vigorous PA was negatively correlated with body height (moderate correlation), body mass (moderate correlation), and BMI (weak correlation) and positively associated with broad jump performance (weak correlation), push-up test results (moderate correlation), and Pacer test results for aerobic endurance (weak correlation).

Multiple regression calculations (forward stepwise model) for PF variables observed as criteria and PA indices as predictors for girls are presented in Table 3. The selected predictors explained 18% of BMI ($p < 0.05$), with no significant partial regressors. When predicting broad jump performance, vigorous PA was retained as a significant partial predictor ($\beta = 0.42$, 95% CI: 0.03–0.81), explaining 18% of

Table 1. Descriptive statistics and differences between genders in study variables (t test for independent samples)

Variables	Girls		Boys		t test	
	Mean	Std.Dev.	Mean	Std.Dev.	t value	p
Body height (cm)	142.4	7.16	144.0	7.71	-1.29	0.20
Body mass (kg)	37.2	12.72	37.3	9.13	-0.08	0.94
BMI (kg/m^2)	17.6	3.53	17.8	3.29	-0.41	0.68
Broad jump (cm)	131.9	34.76	142.6	22.46	-2.33	0.02
Push-ups (reps)	9.7	9.53	13.1	9.36	-2.22	0.03
Sit-ups (reps)	17.4	13.00	15.0	12.09	1.15	0.25
Torso lift (cm)	20.6	11.05	19.3	9.82	0.75	0.45
Sit-and-reach (cm)	48.5	15.01	39.8	9.47	4.41	0.001
Pacer (levels)	6.7	2.49	8.4	2.52	-3.96	0.001
Steps (count)	12016	3507	13921	4540	-2.54	0.01
Sedentary time (min/day)	436.6	98.77	431.5	107.12	0.27	0.79
Light physical activity (min/day)	343.3	89.46	338.4	114.51	0.26	0.79
Moderate physical activity (min/day)	180.0	45.87	179.8	49.39	0.02	0.98
Vigorous physical activity (min/day)	24.8	14.55	48.1	30.37	-5.15	0.001

Table 2. Pearson's correlations between physical activity data and physical fitness variables in the total sample and separately for boys and girls

Variables		Steps	Sedentary time	Light physical activity	Moderate physical activity	Vigorous physical activity
Body height	Total	-0.03	0.08	-0.06	-0.06	-0.31*
	Girls	-0.15	0.10	-0.20	-0.02	-0.19
	Boys	0.01	0.06	0.00	-0.09	-0.43*
Body mass	Total	-0.12	0.09	-0.04	-0.11	-0.36*
	Girls	-0.14	0.09	0.04	-0.10	-0.33*
	Boys	-0.11	0.09	-0.10	-0.12	-0.49*
BMI	Total	-0.14	0.07	-0.03	-0.13	-0.32*
	Girls	-0.23	0.05	0.14	-0.18	-0.35*
	Boys	-0.10	0.09	-0.10	-0.09	-0.39*
Broad jump	Total	0.25*	0.03	-0.09	0.12	0.33*
	Girls	0.31*	-0.13	-0.07	0.29*	0.43*
	Boys	0.19	0.11	-0.09	0.04	0.29*
Push-ups	Total	0.15	-0.02	0.04	0.07	0.43*
	Girls	0.20	0.04	-0.02	0.00	0.25
	Boys	0.08	-0.05	0.08	0.12	0.45*
Sit-ups	Total	0.01	0.16	-0.05	0.06	0.02
	Girls	0.00	0.15	-0.01	-0.03	0.13
	Boys	0.04	0.18	-0.07	0.12	0.04
Torso lift	Total	-0.03	0.14	-0.01	0.00	-0.02
	Girls	0.01	0.08	0.13	-0.03	0.11
	Boys	-0.03	0.17	-0.09	0.01	-0.02
Sit-and-reach	Total	-0.04	0.03	0.01	-0.06	-0.29*
	Girls	-0.05	0.04	-0.05	0.06	0.04
	Boys	0.14	0.04	0.03	-0.17	-0.18
Pacer test	Total	0.26*	-0.01	0.00	0.17	0.42*
	Girls	0.23	0.01	0.03	0.34*	0.18
	Boys	0.20	-0.03	0.01	0.18	0.33*

Note. * - indicates a significance of $p < 0.05$

Table 3. Multiple regression results (forward stepwise model) predicting physical fitness variables by physical activity variables in girls

Regressors	Broad jump		Push-ups		Sit-ups		Pacer	
	β	b	β	b	β	b	β	b
Intercept		124.33*		8.26		0.27		4.95*
Steps			0.27	0.001				
Sedentary time					0.19	0.001		
Light physical activity								
Moderate physical activity			-0.31	0.001			0.35*	0.001*
Vigorous physical activity	0.42*	0.001*	0.24	0.001	0.18	0.001		
Multiple R	0.42*		0.34		0.23		0.35*	
Multiple R^2	0.18*		0.11		0.05		0.13*	

Note. * - indicates significance of $p < 0.05$

Table 4. Multiple regression results (forward stepwise model) predicting physical fitness variables by physical activity intensity in boys

Regressors	Broad jump		Push-ups		Sit-ups		Torso lift		Sit-and-reach		Pacer	
	β	b	β	b	β	b	β	b	β	b	β	b
Intercept		113.47*		6.59*		0.15		12.79*		42.94*		6.11*
Steps									0.20	0.00	0.15	0.00
Sedentary time					0.18	0.00	0.17	0.00				
Light physical activity												
Moderate physical activity					0.13	0.00			-0.27	0.00		
Vigorous physical activity	0.34*	0.00*	0.45*	0.00*					-0.13	0.00	0.32*	0.00*
Multiple R	0.41*		0.44*		0.21		0.17		0.25		0.36*	
Multiple R^2	0.16*		0.20*		0.04		0.02		0.06		0.13*	

Note. * - indicates significance of $p < 0.05$

the criterion variance ($p < 0.05$). Moderate PA was significantly partially associated with Pacer test results (β = 0.35, 95% CI: 0.01–0.69), explaining 13% of the variance ($p < 0.05$).

When multiple regressions were performed for boys, PA predictors were significantly correlated with three of the seven PF criteria. Specifically, vigorous PA was a significant regressor of broad jump performance (β = 0.34, 95% CI: 0.03–0.65), push-ups (β = 0.45, 95% CI: 0.10–0.75), and Pacer test results (β = 0.32, 95% CI: 0.06–0.58), explaining 15%, 16%, and 13% of the criterion variance, respectively (Table 4).

Discussion

There are several important findings related to the study aims. First, vigorous PA is significantly associated with PF in boys, whereas both moderate and vigorous PA are associated with PF in girls, influencing power and cardiovascular endurance. Therefore, our initial study hypothesis can be partially confirmed. Finally, PA appears to be a stronger determinant of PF in boys than in girls.

Vigorous physical activity and physical fitness in boys

Studies have frequently, but not consistently, confirmed that PA plays a vital role in shaping the fitness status of children and adolescents [14, 15, 16]. However, our results support the idea that different PA intensities contribute differently to fitness outcomes. It is generally accepted that light-intensity activities, such as walking or casual play, have limited effects on improving PF. These activities primarily support basic mobility and energy expenditure but do not significantly challenge the cardiovascular or musculoskeletal systems. Therefore, light PA is not expected to be significantly associated with PF [18]. On the other hand, moderate-intensity activities promote cardiovascular endurance and improve muscle strength and, therefore, could contribute to improvements in PF [19]. However, in the boys studied herein, moderate PA did not appear to be associated with better PF. The possible reasons for this are briefly discussed.

One explanation is that moderate-intensity PA does not provide the physiological stress necessary to drive substantial cardiovascular and musculoskeletal adaptations in preadolescent boys. While moderate-intensity PA is beneficial for maintaining general health, it may lack the intensity required to challenge and enhance aerobic capacity or muscular strength at this developmental stage [20]. Additionally, the energy expenditure and heart rate achieved during moderate-intensity PA might not meet the threshold needed to elicit meaningful changes in the fitness metrics used in this study, such as aerobic endurance, power, or strength, in healthy preadolescent boys [20]. Finally, it is also possible that the fitness improvements attributed to moderate-intensity PA occur over longer durations or require higher cumulative weekly volumes. Consequently, eventual associations between moderate-intensity PA and PF could become evident later in adolescence.

Moreover, our results revealed that vigorous PA was the most influential intensity for enhancing PF in boys. Indeed, high-intensity activities such as running, sprinting, jumping, or competitive sports induce substantial stress on the cardiovascular, respiratory, and musculoskeletal systems, leading to marked improvements in aerobic capacity, muscle strength, and overall endurance [20, 21]. The association between vigorous PA and fitness is especially pronounced because such activities push the body closer to its physiological limits, stimulating greater adaptations. Compared to lower-intensity activities, vigorous PA yields higher levels of metabolic stimulation, supports fat metabolism and lean muscle development, and plays a critical role in preadolescent growth, benefiting boys during this developmental stage [20].

All of these findings are supported by the fact that vigorous PA is positively correlated with strength, power, and cardiovascular endurance but not with flexibility. Specifically, vigorous PA involves repeated bursts of effort that heavily engage both the cardiovascular system and large muscle groups. These activities promote significant improvements in aerobic capacity (cardiovascular endurance), muscular strength, and explosive power due to the high levels of oxygen consumption and mechanical load placed on the muscles, tendons, and joints [22]. In contrast, flexibility is largely determined by the extensibility of muscles and connective tissues, which is not a primary focus during vigorous activities [23]. Flexibility improvements are typically achieved through activities that involve sustained stretching or movements that increase the range of motion, and vigorous PA does not inherently emphasize the slow, controlled, and prolonged movements required to improve joint and muscle flexibility. On the contrary, the fast-paced and repetitive nature of vigorous PA may actually limit opportunities for stretching or lengthening muscle fibers during exercise. This may explain the lack of a significant correlation between vigorous PA and flexibility in preadolescent boys.

Moderate physical activity and physical fitness in girls

While only vigorous PA was positively associated with PF indices in boys, both vigorous and moderate PA were positively correlated with PF in girls. These findings can be explained by a combination of physiological, hormonal, psychological, and sociocultural factors, as well as sex differences. Some of these factors will be briefly discussed below.

Two important physiological differences between boys and girls should be highlighted in relation to our findings. First, girls tend to have a greater proportion of slow-twitch muscle fibers than boys [20]. Slow-twitch fibers are optimized for low-intensity activities of prolonged duration and, therefore, respond better to lower-intensity activities. Additionally, girls typically have a higher percentage of body fat and a different fat distribution pattern than boys. Since moderate-intensity PA preferentially targets fat metabolism and aerobic capacity, these activities may be more effective at improving fitness in girls. For example, it has been empirically confirmed that women exhibit greater fat oxidation at moderate exercise intensities than men [24, 25]. Therefore, moderate-intensity exercise has been suggested to be particularly effective for targeting fat oxidation and improving fitness in women.

Hormonal specificity also plays a role in the sex-specific association between PA intensity and PF. Higher levels of testosterone in boys promote greater muscle mass and anabolic capacity, which are better developed through vigorous activities (e.g., sprinting, jumping, plyometrics, high-intensity interval training) [26]. On the other hand, higher levels of estrogen in girls directly contribute to fat metabolism and cardiovascular function, as estrogen enhances fat metabolism by facilitating free fatty acid oxidation and mitochondrial biogenesis during moderate-intensity exercise [27]. Moderate-intensity activities, such as brisk walking or cycling, align well with these hormonal profiles and are more likely to enhance cardiovascular and metabolic fitness in girls than in boys, which could at least partially explain our findings.

Some psychological and behavioral factors also deserve attention in explaining the sex-specific correlations between PAintensity and PF in our participants. First, due to social and cultural norms, boys more often than girls engage in sports and games that involve higher intensities [28]. Moreover, girls may prefer activities that are less intense but more sustained, such as dance, yoga, or walking [29]. These activities align with moderate-intensity PA and may contribute significantly to overall fitness because of the previously explained physiological and hormonal characteristics of girls. This is confirmed by our results, as boys engaged in more vigorous PA than girls, whereas differences in moderate PA were not statistically significant (see the Results section for more details). Additionally, studies have confirmed that female gender roles often lead to decreased participation in high-intensity sports, aligning women's fitness goals with moderate-intensity PA [30].

Stronger correlation between physical activity and physical fitness in boys than in girls

Our results suggest that PA is more strongly correlated with PF in boys than in girls. However, previous studies on this topic have shown inconsistent findings. While some authors reported higher correlations in boys, others observed stronger associations in girls [13, 31, 32]. Some possible explanations for our findings are discussed below.

The first explanation is contextual and relates to differences in PA habits between boys and girls. Due to social tendencies, boys typically engage in more vigorous-intensity PA, which has a stronger impact on PF metrics. On the other hand, girls often participate in moderate-intensity PA, which is beneficial (see previous discussion) but may not produce pronounced fitness outcomes. This is particularly relevant given the previously discussed hormonal differences and higher estrogen levels in girls, which promote fat deposition [20]. This factor is especially important because most PF tests are performed relative to body weight (e.g., push-ups, Pacer test, and broad jump). The results of these tests depend on body mass, where higher body fat negatively impacts PFoutcomes.

Another set of reasons is related to measurement and assessment. First, accelerometers may not capture the full spectrum of PA in girls (e.g., casual play, dance, or household chores). This could lead to an underestimation of their PA levels and weaken the correlation with PF. Additionally, the PF tests used in this study assessed strength, power, flexibility, and cardiovascular endurance. These tests are more sensitive to the effects of PA types that are more characteristic of boys (e.g., vigorous PA). On the other hand, aspects of PF that are more typical for girls and naturally associated with moderate-intensity PA (e.g., balance, coordination) were not included in the test battery used in this study. One could argue that flexibility is one of the PF components more characteristic of girls and that this fitness capacity was covered in our research. However, in the case of the correlation between PA and flexibility, the issue previously discussed is the "inadequacy of the influence." Briefly, PA intensity is not a factor that can directly influence flexibility, as PA measurement does not emphasize the types of movements required to improve joint and muscle flexibility [23].

Practical applications and pedagogical relevance in physical education settings

The previously discussed mechanisms of how different PA intensities influence PF in boys and girls could be practically applied in the physical education (PE) pedagogical process, particularly in modifying PE curricula and PF assessment. First, given the established association between vigorous PA and PF in boys, PE programs for boys should prioritize high-intensity activities, including sprinting, plyometrics, interval training, and team sports. These activities have been confirmed as highly efficient in developing cardiovascular endurance and muscular strength. Additionally, such activities align with boys' natural preference for competitive and dynamic movements and could therefore maximize PF gains during critical developmental periods [33, 34]. For girls, since both moderate and vigorous PA were found to be associated with PF, PE teachers should balance endurance-based activities (e.g., brisk walking, cycling, aerobics) with more intense exercises (e.g., circuit training, dance-based interval workouts, structured sports participation). While being more accepted among girls, these activities have been found to be effective in increasing PA levels and improving PF [35, 36]. This differentiated approach will ensure that both sexes engage in activities that best support their physiological and metabolic adaptations, ultimately enhancing overall PF outcomes in PE settings.

Beyond PE curriculum design, our findings underscore the need to rethink PF assessment as a strategic approach to encouraging sustained student engagement in PA. In the studied country and region, traditional PF assessments primarily measure strength, power, and cardiovascular endurance [16]. While these are important determinants of PF status, focusing solely on these aspects overlooks PF components that are directly influenced by moderate-intensity PA, which is particularly important for girls. To address this, PE authorities could expand PF assessment methods by incorporating balance and coordination into PF testing batteries, offering a more comprehensive evaluation of PF. Importantly, the potential benefits of such an approach extend beyond PF evaluation itself. Objective PF assessment is a fundamental prerequisite for active and motivated participation in any exercise program, including PE lessons, as it provides participants with clear benchmarks for progress and goal setting. In other words, when PF assessment accurately reflects an individual's status (e.g., strengths and areas for improvement), it fosters a sense of achievement and intrinsic motivation. This, in turn, encourages students to engage more consistently in exercise, including PE lessons [37].

It is well known that exercise programs, including PE classes, yield significantly better results when they align with the preferences and needs of the target group [38, 39]. Pedagogically speaking, the appropriateness of a training program enhances engagement and adherence and, therefore, improves overall effectiveness [40]. Regrettably, traditional PE often emphasizes generalized activity participation without considering how specific PA intensities contribute to fitness outcomes across different populations. Meanwhile, our findings clearly challenge the one-size-fits-all approach, highlighting sex-specific responses to PA and suggesting that PE curricula should be adapted to accommodate these differences. Therefore, the discussed sex-specific associations between PA intensities and PF could enable PE teachers to make more informed decisions about PE curricula and, consequently, to enhance the overall pedagogical process in this area. More specifically, by integrating our findings into PE pedagogy, teachers can develop more personalized and inclusive programs that align with students' developmental needs and long-term health goals.

Limitations and strengths

This study has certain limitations. First, the cross-sectional design limits our ability to infer causality between PA and PF. While PA could be a cause of PF, it is also possible that PA should be considered a consequence of better PF. Therefore, future prospective studies are needed to clearly evaluate these relationships. Second, the geographical specificity of our sample (a Mediterranean region with a mild climate) may limit the generalizability of our findings to other populations. Despite these limitations, this study has notable strengths. It is among the first to investigate this issue in southeastern Europe using objective measures of PA and a comprehensive battery of fitness tests. Furthermore, by having the same investigators conduct all assessments in the same region and season, we minimized potential biases and enhanced the reliability of our findings.

Conclusions

Our findings highlight the importance of vigorous PA for boys, as it contributes significantly to their strength, power, and cardiovascular endurance. In girls, both moderate and vigorous PA play crucial roles in enhancing PF. The study also revealed a stronger correlation between PA and PF in boys than in girls, suggesting that the impact of PA on fitness may be more pronounced in boys during this developmental stage.

These differences could be attributed to various factors, including hormonal profiles, PA preferences, and the sensitivity of PF tests to different types of activities. Additionally, the observed sex-specific associations between PA intensity and PF emphasize the need for tailored interventions to promote PA and enhance PF in preadolescent youth. While encouraging vigorous PA is crucial for boys, promoting both moderate and vigorous PA appears essential for girls.

Most importantly, the results emphasize the need to tailor PE to sex-specific responses to PA intensities, ensuring that boys engage in high-intensity activities while girls benefit from a balance of moderate and vigorous PA. Additionally, expanding PF assessment methods beyond traditional measures of strength and endurance to include balance and coordination can provide a more comprehensive evaluation and enhance student motivation. By integrating these insights into PE curricula, educators can create more inclusive and effective programs that promote long-term engagement and optimal PF outcomes for all students.

Investigating the influence of diverse PA types, including those more commonly preferred by girls (e.g., dance, yoga), would provide a more complete picture of the relationship between PA and PF. Moreover, exploring the role of other lifestyle factors, such as living environment, nutrition, and sleep, in conjunction with PA, will contribute to a more holistic understanding of child health and development. By addressing these research gaps, we can develop more effective strategies to promote healthy lifestyles and enhance the well-being of future generations.

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Conflict of Interest

The authors report that there are no competing interests to declare.

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ORIGINAL ARTICLE

Efficiency of high-intensity interval training on VO_2max vital capacity and body composition in male swimmers

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Abstract

Background and Study Aim — Core muscles are a key part of any swimmer's training, and using a high-intensity interval training approach can help support an athlete's performance. The aim of this study was to evaluate the effectiveness of a six-week core muscle high-intensity interval training (CM-HIIT) regimen on VO_2max, vital capacity, and body composition in male swimmers.

Material and Methods — Twenty male swimmers with similar 50-meter swimming performances participated in the study. They were randomly assigned to two groups. The experimental group (n = 10; age = 21.4 ± 0.84 years, BMI = 25.19 ± 5.00 kg/m²) performed CM-HIIT three days per week. The control group (n = 10; age = 20.4 ± 0.70 years, BMI = 24.99 ± 6.42 kg/m²) followed their usual swimming training program. VO_2max was assessed using the YMCA submaximal cycle test, vital capacity was measured with a spirometer, and body composition was evaluated using bioelectrical impedance analysis.

Results — After six weeks, VO_2max significantly increased compared to baseline ($p < 0.05$). Vital capacity also showed a significant improvement, with higher values observed after six weeks ($p < 0.05$). Body composition improved, with significant reductions in body fat percentage and fat mass, while muscle mass increased in the experimental group ($p < 0.05$). Additionally, Max HR significantly decreased after four and six weeks, whereas resting HR showed no significant changes. In the control group, body fat percentage and fat mass significantly decreased, but no significant differences were observed in body weight, BMI, or muscle mass.

Conclusions — Core muscle high-intensity interval training induces physiological adaptations, enhances cardiovascular fitness, and improves body composition in trained swimmers, all of which are critical for swimming performance. However, coaches and trainers must carefully monitor training intensity to optimize oxygen uptake while ensuring safety and performance efficiency.

Keywords: HIIT, aerobic capacity, lung function, core muscle exercise, swimming

Introduction

Currently, there are various training methods for swimmers to improve and develop their physical fitness, especially in terms of their aerobic capacity (VO_2max) and body composition, which are no less important indicators than other fitness factors that support swimmers in achieving their optimal sports performance throughout the competition [1, 2]. Swimming competitions are divided into three distances: short-distance (50–100 m), middle-distance (200–400 m), and long-distance (800–1500 m) events [3, 4]. When athletes start the competition after the starting signal, they dive into the water and swim at their maximum intensity according to their training level [5, 6].

One such training method is high-intensity interval training (HIIT), a form of training that involves intense physical exertion. It is characterized by intermittent bouts of exercise performed at a training intensity close to the maximum rate or at a level not lower than 90% of VO_2max or at 85–95% of maximum heart rate for short periods of 10–30 seconds, alternated with rest periods or training at a low-intensity level [7, 8, 9, 10, 11].

In recent years, the HIIT protocol has gained popularity and has been investigated as an alternative

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training method that can improve and develop aerobic capacity, as measured by maximum oxygen uptake (VO_2max), cardiorespiratory endurance, and body composition [12, 13, 14, 15, 16]. Many previous studies have reported that performing HIIT two to three days per week for four to eight weeks can improve aerobic performance and body composition in handball, field hockey, and football athletes more effectively than conventional training [17, 18, 19, 20]. In addition, it was found that swimmers who performed short bursts of high-intensity interval training (HIIT) at an intensity of at least 90% of VO_2max in conjunction with a regular training program three days per week experienced a 9.6% greater increase in VO_2max than a control group that followed conventional swimming training alone [4, 9, 21]. Similarly, previous studies have shown that core muscle training in male swimmers, including plank, side plank, bridging, bird dog, dead bug, leg drop, reverse arm reverse leg, reverse crunch, back bridge, and V-sitting, three times per week for six to eight weeks, can improve swimming performance and reduce swimming time more effectively than a control group that trained according to the usual program [22, 23].

From the above studies, it can be seen that VO_2max is an important factor in swimming competitions at all distances [24, 1, 25]. However, if swimmers receive appropriate muscle conditioning with an effective training method to increase VO_2max, research suggests that VO_2max is significantly related to swimming performance at various distances [5]. Therefore, efficient swimming performance is measured by the time athletes spend in competition [2, 26]. This study is expected to provide useful information for improving VO_2max and body composition, which are important factors in increasing swimming efficiency. The objective of this study was to evaluate the effectiveness of a six-week core muscle high-intensity interval training regimen on VO_2max, vital capacity, and body composition in male swimmers.

Materials and Methods

Participants

Twenty male swimmers from Roi Et Rajabhat University who trained regularly participated in this study. They were randomly divided into two groups using a randomized controlled research design. Participants were randomly assigned to either an experimental group performing core muscle high-intensity interval training (CM-HIIT) (n=10) or a control group following a normal program (n=10). The inclusion criteria for this study were that the participants had no musculoskeletal injuries that would affect their participation in the program and had at least one year of competitive experience. The exclusion criteria were that the participants sustained injuries and could not continue their participation. All participants were fully informed of the testing and data collection procedures before the intervention and gave their written consent to participate in this study. This study was approved by the Ethics Committee of Rajamangala University of Technology Isan (No. HEC-01-65-015) and followed the guidelines of the Declaration of Helsinki. The anthropometric data of swimmers at baseline are detailed in Table 1.

Table 1. Baseline Anthropometric Data of Swimmers

Variable	Experimental group (n = 10)	Control group (n = 10)
Age (yrs)	21.1 ± 0.84	20.4 ± 0.70
Weight (kg)	76.67 ± 15.47	73.00 ± 18.49
Height (m)	1.71 ± 0.05	1.74 ± 0.05
Body Composition (kg/m^2)	25.19 ± 5.00	24.99 ± 6.42

Procedures

Participants in the high-intensity interval training group were asked to complete 18 sessions, training three days per week for six weeks, with each session lasting 50 minutes (10-minute warm-up, 30-minute main training, and 10-minute cool-down). Both the experimental and control groups underwent the YMCA submaximal cycle test to assess VO_2max, vital capacity assessment using a spirometer [27], and body composition analysis using a bioelectrical impedance analyzer (InBalance 300).

Training Protocol

The experimental group in this study received a CM-HIIT intervention consisting of six core exercises (flutter kicks, single-leg V-ups, trunk extension, alternating-arm Russian twist, plank-to-push-up, and bird dog) [28, 29, 22], performed at maximum speed. The training protocol was conducted for 18 sessions over six weeks (three times per week, 50 minutes per session), as shown in Table 2.

Measurements

All participants in this study underwent three assessments of body composition, lung function, and VO_2max: before, after week four, and after week six. All tests were performed sequentially and under the supervision of the investigators throughout the testing.

Body composition assessment

Body composition assessment in this study was performed using a bioelectrical impedance analyzer (InBalance 300). Participants removed their shoes and stood still in the designated foot positions on the device for approximately 20 seconds. Body weight (kg), body mass index (BMI), body fat percentage (%), fat mass (kg), and muscle mass (kg) were recorded.

Table 2. Core muscle-high intensity interval training

Week	Exercises: 1. Flutter kicks 2. Single leg V-ups 3. Trunk extension 4. Alternating arm Russian twist 5. Plank to push up 6. Bird dog	
1 - 2 ↓ 15*6*15*30	1. 	4. 
3 - 4 ↓ 20*6*10*45	2. 	5. 
5 - 6 ↓ 30*6*15*30	3. 	6. 

Note. Repetition (second)*Sets*Rest/set (second)*Rest/exercises (second)

Lung function

In this experiment, a spirometer was used to test lung function efficiency [27], consisting of three parameters:

1. The maximum volume of air that can be inhaled and exhaled rapidly and forcefully (forced vital capacity, FVC);
2. The volume of air expelled in the first second of rapid and forceful expiration (forced expiratory volume in one second, FEV_1);
3. The volume of air from full inhalation and exhalation in one minute (maximum voluntary ventilation, MVV).

The subjects were asked to take two to three normal breaths, then take a full breath and blow out forcefully and quickly until all the air was exhaled. For MVV, the subjects were asked to take deep and fast breaths in and out as much as possible within 15 to 20 seconds.

Maximum oxygen consumption

This study used the YMCA submaximal cycle test (VO_2max) to assess aerobic capacity and predict maximal oxygen uptake [30]. The YMCA cycle ergometer test estimates VO_2max by monitoring heart rate for two to three minutes at a submaximal workload and calculating the maximum heart rate (Max HR) (220 – age) to determine the work rate. The test was conducted by cycling for two to four periods with increasing resistance. Each period lasted three minutes, and heart rate was recorded in the last 30 seconds of each period. The test was considered complete when the heart rate was between 110 and 150 bpm (85% Max HR) in at least two workload periods, with each period increasing in intensity based on the heart rate after the first period.

Statistical Analysis

Data analysis of all outcomes in this study was performed using IBM SPSS Statistics version 22.0 for Windows (SPSS Inc., 2010, IBM Corp., Armonk, NY). All data are presented as mean ± standard deviation. After the Shapiro-Wilk test to determine the normal distribution of the sample data, differences in maximal oxygen uptake, lung function, and body composition were tested using a two-way ANOVA with repeated-measures analysis of variance (2 groups × 3 time points: before, after week four, and after week six) with a significance level of 0.05.

Results

Maximal Oxygen Consumption

The results for Max HR and VO_2max are presented in Tables 3 and 4. There was a group × time interaction. In the experimental group, Max HR significantly decreased after four and six weeks compared to baseline (Table 3). VO_2max significantly increased after four and six weeks, with a greater improvement observed at six weeks compared to four weeks (Table 3).

In the control group, Max HR also significantly decreased over time, although the reduction was less pronounced compared to the experimental group (Table 4). However, VO_2max significantly decreased after six weeks compared to baseline in both groups (Table 4). Resting HR did not show significant differences between time points.

Lung Function

Vital capacity significantly increased in both groups over time (Tables 3 and 4). In the experimental group, it showed a steady improvement after four and six weeks, with a greater increase observed at six weeks (Table 3). In the control group, vital capacity also increased significantly, though the improvement was less pronounced (Table 4). When compared between groups, vital capacity was significantly different after six weeks ($p < 0.05$).

Body Composition

Body composition data are presented in Tables 3 and 4. Significant group × time interactions were observed in body weight, body mass index, body fat percentage, fat mass, and muscle mass (Tables 3 and 4). In the experimental group, body weight, body fat percentage, and fat mass significantly decreased after six weeks, while muscle mass increased (Table 3). In contrast, in the control group, body fat percentage and fat mass significantly decreased, but no significant changes were observed in body weight, BMI, or muscle mass (Table 4).

Discussion

This study was conducted to investigate the effectiveness of a six-week core muscle high-intensity interval training regimen on VO_2max, vital capacity, and body composition. In this study, male swimmers showed significant increases in VO_2max, lung function, and muscle mass, as well as significant decreases in body mass index, body fat percentage, and fat mass after six weeks of core muscle high-intensity interval training.

VO_2max and Lung Function

From the results of CM-HIIT, it can be seen that the experimental and control groups had significantly different decreases in Max HR and VO_2max after six weeks in both groups, but no significant difference in resting HR was found after

Table 3. The variable of the experimental groups

Variables	Experimental group (n = 10)		
	Before	**4 Weeks**	**6 Weeks**
Maximal Oxygen Consumption			
Resting HR (beats/min)	79.40 ± 10.89	79.80 ± 8.28	77.10 ± 8.29
Max HR (beats/min)	165.70 ± 17.71	156.80 ± 12.14*,†	153.80 ± 11.01*,†
Vo2max (ml/kg/min)	29.75 ± 10.99	33.84 ± 9.80*	38.77 ± 10.84*,**
Vital Capacity			
Vital capacity (cc/kg)	59.05 ± 13.42	65.69 ± 10.56*	67.93 ± 11.57*,**,†
Body Composition			
Body Weight (kg)	76.67 ± 15.47	75.89 ± 14.18	75.05 ± 14.50*,**
Body Mass Index (kg/m^2)	25.19 ± 5.00	24.93 ± 4.53	24.66 ± 4.66*,**
Body fat percentage (%)	23.79 ± 8.28	22.43 ± 9.18*	21.64 ± 9.17*,**
Fat mass (kg)	19.09 ± 10.24	18.09 ± 10.19*	17.56 ± 10.12*,**
Muscle mass (kg)	53.25 ± 5.37	53.92 ± 5.00	54.72 ± 4.85*

Note. Significant difference from before, *$p < 0.05$; week 4, **$p < 0.05$; between groups, †$p < 0.05$

Table 4. The variable of the control groups

Variables	Control group (n = 10)		
	Before	**4 Weeks**	**6 Weeks**
Maximal Oxygen Consumption			
Resting HR (beats/min)	79.90 ± 13.16	78.10 ± 11.69	75.50 ± 11.11
Max HR (beats/min)	175.2 ± 16.16	167.90 ± 12.41*	163.20 ± 10.77*
Vo2max (ml/kg/min)	31.45 ± 6.70	30.47 ± 11.32	34.81 ± 7.02*
Vital Capacity			
Vital capacity (cc/kg)	55.56 ± 11.64	59.28 ± 13.31*	58.98 ± 10.29*
Body Composition			
Body Weight (kg)	73.00 ± 18.49	71.80 ± 18.58	72.34±17.29
Body Mass Index (kg/m^2)	24.99 ± 6.42	24.58 ± 6.51	24.77 ± 6.10
Body fat percentage (%)	21.92 ± 10.58	19.67 ± 10.16*	21.80 ± 9.91**
Fat mass (kg)	17.58 ± 12.75	15.74 ± 12.47*	17.11 ± 11.90**
Muscle mass (kg)	51.58 ± 6.95	50.23 ± 10.69	51.44 ± 6.53

Note. Significant difference from before, *$p < 0.05$; week 4, **$p < 0.05$; between groups, †$p < 0.05$

four weeks and six weeks. When compared between the groups, it can be seen that in the experimental group that received HIIT, after four and six weeks, Max HR decreased significantly more than in the control group ($p < 0.05$). However, when comparing the VO_2max values in the experimental group, it was found that VO_2max increased by ~4.09–9.02 ml/kg/min, with an increase of ~4.09 ml/kg/min after four weeks and ~9.02 ml/kg/min after six weeks compared to baseline. Additionally, after six weeks, VO_2max increased by ~4.93 ml/kg/min compared to four weeks. In the control group, VO_2max increased after six weeks by ~3.64 ml/kg/min compared to baseline, indicating that the group that received three days per week of high-intensity core training combined with a conventional swimming program for six weeks had better VO_2max than the control group that followed a conventional swimming program alone.

Previous studies have shown that a group that received short bursts of rapid muscle training three days per week can stimulate the work level to at least 90% of VO_2max, resulting in a 9.6% increase in VO_2max efficiency, which is higher than in the control group that trained only in swimming [9, 21, 4]. At the same time, the increase in VO_2max in both groups, as presented in this study, shows a significant improvement in lung function, as indicated by the vital capacity test results after four and six weeks ($p < 0.05$). Previous studies have consistently shown that CM-HIIT improves VO_2max, lung function, and cardiovascular endurance significantly [27, 31, 32]. The efficiency of these improvements depends on the coordination of the cardiovascular and respiratory systems, which is influenced by the processes of anaerobic and aerobic respiration during HIIT, leading to enhanced fitness levels [33, 34] (referring to [35]). Meanwhile, VO_2max is considered a physiological variable that reflects cardiovascular system efficiency [34] (referring to [36, 37]). When athletes are trained at an appropriate intensity, leading to the activation of the nervous system, the strength of the respiratory muscles improves, VO_2max increases, and lung function efficiency significantly improves [38, 39, 37, 40]. The data from this study demonstrate that high-intensity interval training performed at an appropriate intensity and targeting core muscles involved in swimmer movements can improve maximal oxygen consumption in a shorter period compared to previous studies.

Body Composition

After receiving 18 sessions of CM-HIIT, it was found that the experimental group had significantly decreased body fat percentage and fat mass after four and six weeks compared to baseline ($p < 0.05$). In the control group, which did not receive HIIT training, body fat percentage and fat mass also significantly decreased after four weeks compared to baseline and after six weeks compared to four weeks ($p < 0.05$). This is consistent with previous studies reporting similar results after four weeks of training in football players [18], female ice hockey players [41], and healthy male individuals [15], as well as after eight weeks in field hockey players[20] and handball athletes [42, 19], showing that the HIIT training pattern resulted in a significant decrease in body fat percentage and fat mass ($p < 0.05$).

The continuous training pattern that athletes normally follow may result in higher-intensity muscle work, which can help stimulate the metabolic rate during training and reduce body fat percentage and fat mass. Murawska-Ciałowicz et al.[43] stated that the reduction in body fat due to intensive training allows muscles to work continuously at an appropriate level, increasing the basal metabolic rate. Similarly, Mohammad et al. [42] and Tahir & Muhammed [18] pointed out that an appropriate HIIT training pattern improves physical fitness and allows athletes to lose weight and BMI, helping to reduce body fat.

Regarding the body composition results showing statistically significant changes only in the experimental group, it was reported that muscle mass significantly increased after six weeks compared to baseline. This may be due to the appropriate high-intensity interval training pattern used in this study, which was intense enough to stimulate muscular adaptation at a high level. Such high-intensity endurance training improves neuromuscular function, leading to enhanced muscle strength and function [44]. However, it has been shown that HIIT at appropriate levels can increase muscle mass in athletes [42, 18].

This increase in muscle mass can be explained by the stimulation of concentric and eccentric muscle contractions induced by high-intensity training, which enhances muscle protein synthesis and leads to muscle fiber hypertrophy[45]. Although both regular swimming and high-intensity interval training can stimulate metabolic rate and decrease body fat percentage and fat mass in swimmers, the present data show that after **six weeks,** swimmers who received high-intensity interval training had increased muscle mass, resulting in more efficient muscle function than those who followed only a conventional swimming program.

The findings of this study suggest that a six-week core muscle high-intensity interval training (CM-HIIT) program effectively enhances VO_2max, lung function, and body composition in male swimmers. The observed improvements in cardiorespiratory fitness and body composition highlight the potential of HIIT-based core training as a valuable supplement to conventional swimming programs. Future research should consider a larger sample size, a longer intervention period, and controlled dietary factors to enhance the robustness of findings and further explore the long-term physiological adaptations associated with HIIT-based core training in swimmers.

Limitations of the Study

This study has some limitations. First, the sample size was relatively small, consisting of only twenty male swimmers, which may limit the generalizability of the findings to broader athletic populations. Second, the study duration was six weeks, which may not fully capture the long-term effects of CM-HIIT on VO_2max, lung function, and body composition. Third, the study did not control for dietary intake, which could influence body composition changes. Finally, the participants' individual training loads outside of the study protocol were not monitored, which may have affected the results. Future research should consider a larger sample size, a longer intervention period, and controlled dietary factors to enhance the robustness of findings.

Conclusions

Maximum oxygen consumption, lung function, and body composition in swimmers improved after six weeks of core muscle high-intensity interval training (CM-HIIT). These adaptations resulted in physiological changes, enhanced cardiovascular fitness, and improved body composition in trained swimmers, all of which are important for swimming performance. However, coaches and trainers must carefully consider training intensity and program design to optimize maximal oxygen uptake while ensuring athlete safety and performance efficiency.

Conflict of Interest

The authors report that there are no competing interests to declare.

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ORIGINAL ARTICLE

Gamification in physical education: improving rhythmic gymnastics skills and student engagement through coaching games

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

Abstract

Background and Study Aim Rhythmic gymnastics is a sport that combines athleticism, artistry, and musicality, offering numerous physical and cognitive benefits for children. However, traditional training methods often emphasize repetitive drills, which may reduce student engagement and hinder skill acquisition. This study aims to analyze the effects of Coaching Games (COG) on students' jumping skills and interest compared to traditional training methods.

Material and Methods The study employed a quasi-experimental pretest-posttest design. A total of 72 participants (mean age: 10.97 ± 0.80 years) were equally assigned to COG and CON groups. The training lasted for two months and included 18 sessions. The COG group practiced game-based activities, while the CON group followed traditional exercises. Student performance was assessed using multiple methods. Jumping ability was measured with the Stretched Jump instrument (validity: 0.995). Interest and engagement were evaluated using a validated 31-item Likert-scale questionnaire (Cronbach's α: 0.986).

Results Students in the COG group showed a significant increase in engagement (Δ=9.50±7.45, p<0.001, d=1.022). Their results were higher than those of the CON group (Δ=1.89±7.44, p=0.186). Both groups improved their jumping skills (COG: 6.33 ± 10.65, p=0.001; CON: 4.83 ± 7.78, p=0.010). However, the difference between them was not statistically significant (p=0.689, d=0.161).

Conclusions The COG model enhances student engagement in rhythmic gymnastics by reducing monotony. It provides a more enjoyable alternative to conventional training without compromising skill development.

Keywords: coaching games, conventional training, physical education, stretched jump, interest

Introduction

Physical education (PE) contributes to the development of physical fitness, motor skills, and overall well-being in children. One of its components is rhythmic gymnastics, which involves strength, flexibility, coordination, and musicality. Traditional training methods often focus on repetitive drills, which may lead to lower student engagement and slower skill acquisition. Examining alternative approaches can provide insights into more effective ways of teaching rhythmic gymnastics.

In this context, PE not only fosters physical health but also supports cognitive, social, and emotional development [1]. Among various physical education programs, rhythmic gymnastics combines creative expression with physical activity. It requires a high level of technical ability, coordination, and engagement. However, despite these characteristics, teaching rhythmic gymnastics to students, particularly those in upper elementary school (ages 10–12), is challenging [2]. Conventional training methods often fail to maintain students' attention and interest, which can lead to lower engagement and slower skill development [3]. For this reason, researchers highlight the importance of creative approaches that can enhance both technical skills and student engagement [4].

Recent research has explored the use of game-based learning methods in physical education, particularly in increasing student involvement and motivation [5, 6]. One commonly applied approach is Coaching Games (COG), which incorporates gamification elements into training sessions [7]. Obstacle games, hopscotch, and agility ladder drills in the COG model create a more engaging learning environment and provide cognitively stimulating challenges that align with children's developmental needs [3, 8]. This approach supports students' sense of autonomy, competence, and relatedness, which are key factors in intrinsic motivation as described in Self-Determination Theory (SDT) [6].

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Leaps are a key element in rhythmic gymnastics, contributing to both aesthetics and performance, particularly among primary school children. This sport integrates dance, acrobatic movements, and prop mastery to develop coordination and artistic expression [9, 10]. However, traditional teaching methods are sometimes associated with low student engagement due to their repetitive nature [11]. A game-based approach has been shown to enhance student motivation by creating an enjoyable learning environment, supporting motor skill development, and increasing self-confidence [5, 6]. A study conducted in Yogyakarta City reported low enthusiasm for rhythmic gymnastics among students, as well as limited participation in competitions. Public perception often regards the sport as technically complex, and there is little effort to promote it. Additionally, the study identified a lack of structured training models that incorporate games to improve gymnastics skills. As a result, rhythmic gymnasts have not fully developed their motivation and active participation, which may contribute to a decline in performance.

Although research on game-based learning in physical education is expanding, studies on the effects of the COG model in rhythmic gymnastics, particularly among upper elementary school children, remain limited. Most existing studies focus on general physical activities or sports rather than the specific requirements of rhythmic gymnastics, such as jumps, balance, and rhythmic movements [11, 12]. Additionally, while some studies have examined the impact of game-based methods on motivation, few have explored their effects on technical skill development in rhythmic gymnastics, particularly in leaps, which are fundamental to the sport [13, 14].

Recent findings on motor skill learning suggest that using diverse and mentally challenging training methods can help children acquire new skills more quickly [15, 16]. Comparing COG with conventional training (CON) provides empirical evidence of its effectiveness in enhancing student motivation and performance [17].

An analysis of previous studies has shown that researchers have primarily focused on addressing issues related to student engagement and motivation in rhythmic gymnastics. Many studies have explored game-based learning in physical education, but few have examined its impact on the technical aspects of rhythmic gymnastics, particularly in skill development. Despite numerous investigations, there is still a need for a more detailed examination of this issue and the search for more effective training approaches.

This study aims to analyze the effects of COG on students' jumping skills and interest compared to traditional training methods.

Materials and Methods

Participants

This study involved 72 students selected through purposive sampling. Inclusion criteria required participants to be 10–12 years old in 2024, have graduated from elementary school in Yogyakarta City, have a normal BMI, have no injuries in the past six months, and be willing to participate in 18 sessions over two months. The students were equally assigned to two groups: 36 students in the COG group, who received coaching games training, and 36 in the CON group, who underwent conventional training. Group assignment was randomized using a lottery method.

Ethical Standards

This study complied with applicable ethical standards, particularly regarding the involvement of children as participants. Before the study began, parents or guardians received a detailed explanation of its purpose, procedures, benefits, and potential risks. An informed consent form was provided, requiring a signature from parents or guardians as official approval for their child's participation. This document stated that participation was voluntary and that participants had the right to withdraw at any time without consequences. Additionally, special permission was required for the use of participant photos in scientific publications. Parents or guardians were given the option to approve or decline the use of their child's photos through a separate written consent form. Any published photos depicted educational research activities without revealing personal identities. All personal data were kept confidential and used solely for research purposes in accordance with good clinical practice (GCP) principles and applicable ethical regulations.

Research Design

This study employed a quantitative experimental approach using a one-group pretest-posttest design. The experiment compared a game-based coaching model (Coaching Games, COG) with a conventional training model (CON) to determine which method more effectively improves jump techniques and maintains engagement among children aged 10 to 12 in rhythmic gymnastics.

Data collection took place over two months and included 18 training sessions, each lasting approximately 45 minutes. Both the experimental (COG) and control (CON) groups participated in rhythmic gymnastics sessions. The experimental group followed a gamified training model, while the control group adhered to conventional training techniques (Table 1).

In the control group (CON), a rhythmic gymnastics training program was conducted three times a week for two months. Each session lasted approximately 45 minutes and included warm-up, core training, and cool-down phases. The session began with a 10-minute warm-up, during which students performed static and dynamic stretching exercises targeting muscles involved in jumping, such as those in the legs, hips, and shoulders.

The core training phase followed and was divided into three sections, each lasting 10 minutes and focusing on conventional rhythmic gymnastics exercises. The first section (sessions 1–6) covered basic jumps, including jumping with both feet without equipment and variations in speed and height (Figure 1). The second section (sessions 7–12) emphasized graduated jump techniques, such as jumping over low obstacles (wooden boxes) and performing forward and sideways jumps using cones while ensuring soft landings. The third section (sessions 13–18) integrated multiple jumps with rhythmic movements using equipment such as mats and agility ladders. These exercises were performed to music to create a more engaging training environment. Finally, the session concluded with a 5-minute cool-down, during which students performed stretching exercises and slow movements to reduce muscle tension.

The coaching games training program consisted of multiple sessions, each using a different game-based method. Each session began with 10 minutes of static and dynamic stretching to prepare the muscles and body. This was followed by the core training phase.

In sessions 1–6, obstacle games were used. Children jumped over five wooden boxes and then over three cones placed 30 cm apart (Figure 2). Each training session ended with a ready position after passing the cones. Sessions 7–12 incorporated

Table 1. Implementation of Exercises in Both Training Models

Training Model	Procedure
COG Training Model	Sessions began with a 10-minute dynamic warm-up. The core activities included obstacle games (sessions 1–6), hopscotch drills (sessions 7–12), and agility ladder exercises (sessions 13–18). Each session concluded with a 5-minute cool-down.
CON Training Model	Followed a traditional format: 10-minute warm-up, 30-minute structured skill drills, and 5-minute cool-down. Training phases progressed from basic jumps (sessions 1–6) to graduated jumps over obstacles (sessions 7–12) and rhythmic movement integration (sessions 13–18).

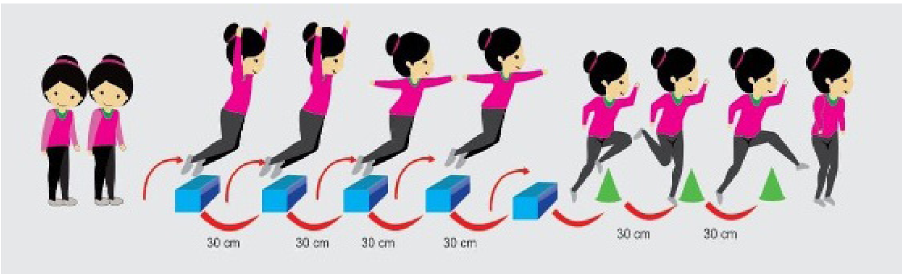

Figure 1. Basic jump exercise [14]

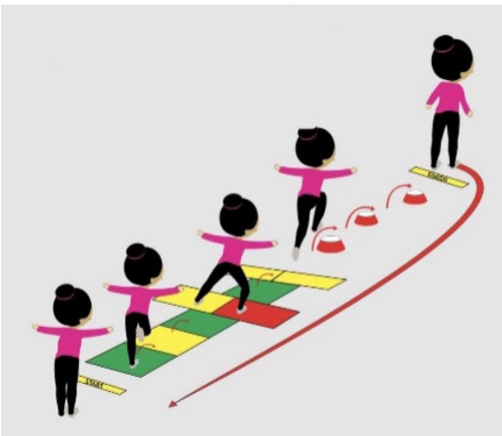

Figure 2. Obstacle game [14]

hopscotch games using a designated mat (Figure 3). Students played hopscotch with their arms outstretched, then jumped over three cones arranged 30 cm apart, finishing in an upright position. Sessions 13–18 introduced the agility ladder method (Figure 4). In these sessions, students stepped on the ladder with alternating foot positions, jumped on one leg, performed alternating sideways jumps, and jumped in and out of the agility ladder.

Each core training session lasted 30 minutes, with a three-minute break between sets. The program concluded with a five-minute cool-down to aid recovery. The equipment used included wooden boxes, cones, hopscotch mats, and agility ladders.

In these sessions, students stepped on the ladder with alternating foot positions, jumped on one leg, performed alternating sideways jumps, and jumped in and out of the agility ladder. Each core training session lasted 30 minutes, with a three-minute break between sets. The program concluded with a five-minute cool-down to support recovery. The equipment used included wooden boxes, cones, hopscotch mats, and agility ladders.

After completing the training sessions, data were collected from both groups. Two research instruments were used: the Stretched Jump test, which had a validity score of 0.995, and a closed-ended questionnaire based on a study by Armande [18]. The Stretched Jump test was selected to assess students' technical ability due to its high validity and relevance to rhythmic gymnastics. It evaluated technical proficiency based on form, execution, and landing. While alternative jump tests exist, this measure was considered the most suitable for the study.

The test consisted of three main components: the starting position, execution, and final position (Figure 5). Each component included specific indicators as assessment criteria. In the starting position, proper body posture was emphasized. For example, both legs had to be straight, arms positioned downward with fingers together, the body upright with a forward gaze, and the abdominal muscles engaged to maintain stability. During execution, participants were required to begin with bent legs. While in the air, the toes had to be pointed, and the gaze directed forward. Additionally, both hands were raised for balance, and the knees were bent upon landing to absorb impact.

In the final position, students were assessed based on whether their gaze remained straight ahead, their knees were bent upon landing, their hands were raised, and their feet were together, returning to the starting position. This skill assessment used a rating scale to reflect the level of movement accuracy. A score of 85–100 was given if the dominant movements were correct with less than 10% errors. A score of 61–85indicated correct execution with minor errors (less than 25%). If the performance contained multiple incorrect movements with errors below 50%, the score ranged from 30–60. The lowest score of 1–30 was assigned if only one indicator was met and errors exceeded 50%. This instrument served as a comprehensive guide for evaluating participants' technical execution of the Stretched Jump in a structured manner.

After collecting data on technical ability, the study used a closed-ended questionnaire to assess students' interest (Table 2). The questionnaire consisted of 31 items rated on a four-point Likert scale (1 = Strongly Disagree, 2 = Disagree, 3 = Agree, 4 = Strongly Agree). Its validity was tested using the product-moment correlation formula, and its reliability was assessed with Cronbach's alpha, yielding a value of 0.986. This result indicates that the questionnaire was both valid and reliable. Eight main indicators were measured: fighting spirit (6 items), discipline (4 items), independence (3 items), personality (4 items), honesty (3 items), sportsmanship (3 items), self-confidence (4 items), and expectations of rewards (4 items).

Some questions were constructed using the reverse-scoring method to minimize response bias, such as questions 18 and 24 [18]. This approach accounted for potential biases in participants' answers. The questionnaire aimed to assess students'

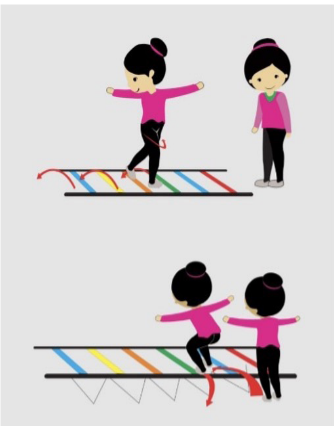

Figure 3. Hopscotch game [14]

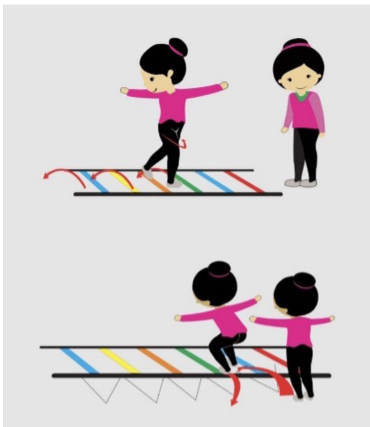

Figure 4. Agility ladder drill game [14]

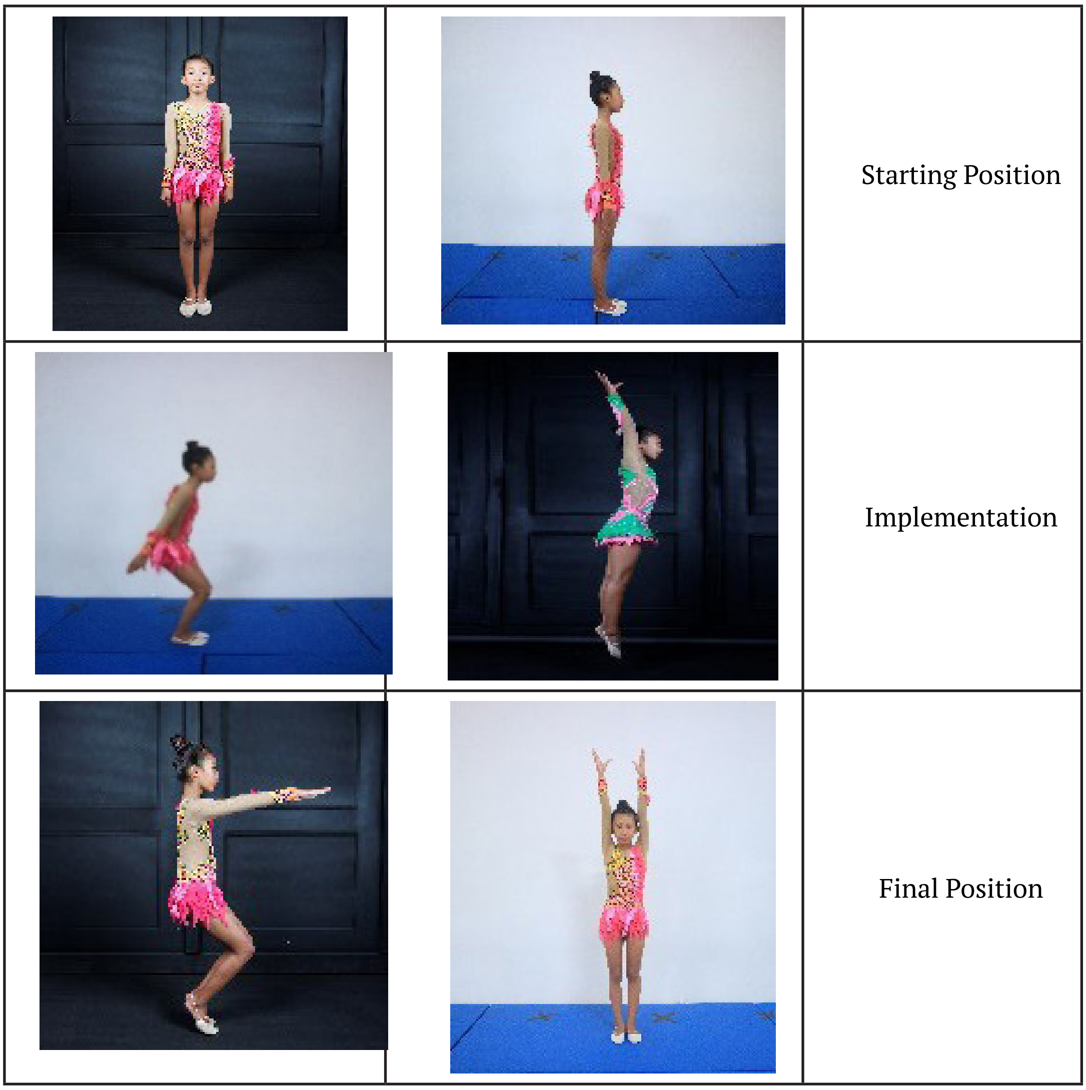

Figure 5. Stretched Jump skill assessment (personal documentation)

interest in rhythmic gymnastics by considering both internal factors, such as motivation, enthusiasm, and self-confidence, and external factors, such as support from friends, family, and school. Participants completed the questionnaire under the supervision of a gymnastics instructor, with assistance from a physical education teacher. The survey was administered in a classroom setting with a maximum of 15 participants per session to ensure a quiet and comfortable environment while minimizing distractions.

Statistical Analysis

The analysis documented the mean, standard deviation, minimum, and maximum values for each variable. Paired t-tests were used for normally distributed data to assess within-group differences, while the Wilcoxon signed-rank test was applied for non-parametric data. The significance threshold was set at $p < 0.05$. The Mann-Whitney U test was performed to evaluate the efficacy of the COG and CON training models. Effect sizes were calculated using Cohen's d to assess the practical significance of differences between groups. An effect size greater than 0.8 was considered substantial, values between 0.5 and 0.8 were classified as moderate, and values below 0.5 were regarded as small. Data analysis was conducted using Microsoft Excel and SPSS version 23 software.

Results

The study included 72 students (63.9% male, 36.1% female) with a mean age of 10.97 ± 0.80 years. The average anthropometric characteristics were as follows: height, 136.21 ± 4.49 cm; weight, 36.69 ± 2.99 kg; and BMI, 1.79 ± 1.54 kg/m^2. Table 3 presents detailed characteristics of students in both groups.

Table 3 also presents the results of the Stretched Jump test and the questionnaire on students' interest and engagement. In the CON group, the mean Stretched Jump score increased significantly from 68.11 ± 6.96 to 72.94 ± 6.47 (Δ = 4.83 ± 7.78, p = 0.010). Although interest in this group also increased from 88.22 ± 5.13 to 90.11 ± 4.53 (Δ = 1.89 ± 7.44, p = 0.186), the change was not statistically significant.

Table 2. Table of specifications for the study's questionnaire

No	Items	Indicators
1	I feel enthusiastic every time I join rhythmic gymnastics training.	
2	I consistently arrive punctually for all rhythmic gymnastics' activities.	
3	I can do rhythmic gymnastics movements without help from friends or teachers.	
4	I am pleased when I succeed in doing rhythmic gymnastics movements correctly.	
5	I correct movement errors after getting feedback from the teacher.	
6	Praise from the teacher increases my motivation to participate in rhythmic gymnastics.	
7	In my opinion, rhythmic gymnastics is essential for maintaining physical fitness.	
8	I practice rhythmic gymnastics movements at home outside of school hours.	
9	I am confident when performing rhythmic gymnastics movements in front of others.	
10	I am motivated if there is a prize for those good at rhythmic gymnastics.	
11	Rhythmic gymnastics movements are easy for me to learn and practice.	
12	I follow the movement instructions carefully during practice.	
13	The facilities and infrastructure at school are adequate for rhythmic gymnastics activities.	
14	Friends' support makes me more enthusiastic about participating in rhythmic gymnastics.	
15	The rhythmic gymnastics training program at school is well organized.	
16	My parents support my participation in rhythmic gymnastics activities.	
17	The principal pays special attention to rhythmic gymnastics activities.	
18	I feel bored when participating in rhythmic gymnastics.*	
19	I engage in rhythmic gymnastics voluntarily, not under duress.	
20	Rhythmic gymnastics movements make my body feel healthier and fitter.	
21	I would be embarrassed if I could not follow rhythmic gymnastics movements well.	
22	I memorize the sequence of rhythmic gymnastics movements outside of practice hours.	
23	My friends' enthusiasm influences my enthusiasm for rhythmic gymnastics.	
24	I prefer other activities to rhythmic gymnastics.*	
25	The accompanying music for rhythmic gymnastics makes the exercise more enjoyable.	
26	The rhythmic gymnastics cool-down movements help reduce my fatigue.	
27	I was proud when I successfully completed the entire rhythmic gymnastics series.	
28	In my opinion, rhythmic gymnastics is a useful activity.	
29	The rhythmic gymnastics warm-up movements effectively prepare the body for exercise.	
30	I want rhythmic gymnastics to become a routine activity at school.	
31	I would recommend rhythmic gymnastics to my friends or juniors.	

Table 3. Description of subjects' characteristics

Group	Variable		Mean±SD	Min	Max	One-Sample Kolmogorove-Smirnov test	Paired test
CON	Stretched Jump	Pre	68.11±6.96	55	82	0.124#	0.010*
		Post	72.94±6.47	58	85	0.004	
		Δpre-post	4.83±7.78	-13	18		
	Interest	Pre	88.22±5.13	81	96	0.012	0.186
		Post	90.11±4.53	82	98	0.173#	
		Δpre-post	1.89±7.44	-10	16		
COG	Stretched Jump	Pre	69.89±8.25	53	81	0.200#	0.001†*
		Post	76.22±5.50	67	87	0.200#	
		Δpre-post	6.33±10.65	-12	31		
	Interest	Pre	87.61±5.06	79	85	0.200#	0.000†*
		Post	97.11±6.62	96	111	0.107#	
		Δpre-post	9.50±7.45	-4	24		

Note. Δ is the difference; # - normally distributed with p>0.05; * - significantly different with p<0.05; † - Using the paired t-test; without (†) using the Wilcoxon test.†

Table 4. The influence of the Coaching Games training method on jumps technique and students' interest

Variable	Group (Mean±SD)		P (sig.)	Effect size (d_{Cohen})
	CON	COG		
Stretched Jump	4.83±7.78	6.33±10.65	0.689	0.161
Interest	1.89±7.44	9.50±7.45	0.000*	1.022

* - significant difference at p<0.05

In the COG group, a significant increase was observed in the Stretched Jump score, rising from 69.89 ± 8.25 to 76.22 ± 5.50 (Δ = 6.33 ± 10.65, p = 0.001). Similarly, interest showed a significant improvement from 87.61 ± 5.06 to 97.11 ± 6.62 (Δ = 9.50 ± 7.45, $p < 0.001$).

Since not all data were normally distributed, a Mann-Whitney U test was conducted to compare differences between groups. The results are presented in Table 4.

Table 4 shows that the Coaching Games (COG) training method was more effective in increasing students' interest in rhythmic gymnastics than the conventional training method (CON). The average increase in interest in the COG group was 9.50 ± 7.45, which was substantially higher than in the CON group, where the increase was only 1.89 ± 7.44. Statistical tests confirmed a significant difference between the two groups ($p < 0.001$) with an effect size of 1.022, indicating a large effect. These findings demonstrate that the Coaching Games method effectively enhances students' interest in rhythmic gymnastics.

For jump technique, measured using the Stretched Jump test, the COG group showed a greater improvement than the CON group, with an average increase of 6.33 ± 10.65 compared to 4.83 ± 7.78. However, despite this difference, statistical tests did not indicate a significant difference between the two groups (p = 0.689) with an effect size of 0.161, which is considered small. These results suggest that while the Coaching Games method yields better outcomes, it does not lead to a statistically significant improvement in jump techniques compared to the conventional method.

Discussion

This study demonstrates that the Coaching Games (COG) model had a significant effect size (d = 1.022) in increasing interest in rhythmic gymnastics among upper elementary school students compared to the conventional (CON) method. This finding aligns with previous research, including Self-Determination Theory, which suggests that game-based learning environments foster intrinsic motivation by promoting autonomy, competence, and relatedness [6]. Game-based methodologies can enhance student engagement and motivation in sports by introducing engaging variations and challenges tailored to their developmental stage [19].

One of the factors contributing to the effectiveness of COG is its structured yet dynamic nature. Integrating obstacle courses, hopscotch, and agility ladder drills in COG appears to have enhanced student participation by making training sessions more engaging and enjoyable. These strategies align with research suggesting that game-based interventions increase student engagement and involvement in physical education (PE) [3]. Additionally, the use of music and varied challenges in COG may have stimulated emotions and fostered social connections, both of which are essential for sustaining interest [11].

Beyond engagement, emotional arousal plays a key role in maintaining attention. In COG, the combination of music and dynamic visuals, such as colored mats and cones, strengthens students' connection with the activities. The rhythmic cues provided by music synchronize movement and improve mood, thereby reducing perceived effort and increasing commitment to physical exercise [20]. This aligns with the study results, where 84% of COG participants stated that "music made training more enjoyable" (Q25), directly correlating with higher post-test interest levels.

Furthermore, COG employs a reward-based approach, such as verbal praise for completing workouts or peer recognition for skill mastery. This method integrates external motivators while fostering intrinsic satisfaction. Maintaining student motivation requires a balance between extrinsic and intrinsic incentives. External rewards, such as badges and leaderboards, initially encourage participation, while intrinsic enjoyment ensures long-term commitment [5]. In this study, reverse-scored questions (e.g., Q18: "I feel bored during rhythmic gymnastics") further highlight COG's effectiveness in reducing monotony, a common issue in traditional PE methods.

COG incorporates a variety of games across sessions, including obstacle games, hopscotch, and ladder drills. These activities help sustain student interest and prevent habituation caused by repetitive tasks, which can lead to disengagement [21]. Neurocognitive studies suggest that such activity variation introduces novel stimuli, activating dopamine pathways and enhancing memory recall and motivation [22]. Agility ladder drills, for example, not only refine coordination but also provide cognitive challenges by integrating physical and mental tasks—an approach that increases student engagement [23, 24, 25].

While the increase in student interest in rhythmic gymnastics highlights the role of educational innovation in PE [26], different training methods serve distinct purposes. Conventional training methods remain effective for skill development, although they may not sustain student engagement over time. In contrast, the interactive, reward-based COG method fosters intrinsic satisfaction through peer recognition and clear goals, though it still incorporates extrinsic motivators [6, 27]. The finding that gamification enhances both immediate engagement and long-term commitment to physical activity aligns with this dual motivational framework [5].

However, several factors must be considered when implementing the Coaching Games approach, including the need for diverse training tools and the availability of coaches qualified to design game-based exercises aligned with training objectives [28]. To achieve optimal results in improving rhythmic gymnastics skills, future research should focus on long-term observations and explore the integration of the Coaching Games method with more intensive technical training.

Besides interest and skill development, this study also compared the Jumping Technique variable between the COG and CON groups. While both groups showed significant improvements after training, the COG group demonstrated slightly better jumping technique gains ($\Delta = 6.33$ vs. 4.83 for CON). However, the difference was not statistically significant. The effectiveness of the COG method is likely influenced by the use of training aids, such as agility ladders and cones, which enhance students' coordination and balance. Zhang et al. [16] demonstrated that incorporating training aids accelerates motor learning and improves children's physical performance.

This suggests that both approaches effectively teach basic jump skills, possibly due to their shared emphasis on skill development. The study's short duration (eight weeks) may explain the lack of significance, as motor skill learning often requires more time to produce measurable changes [1]. Additionally, while the Stretched Jump test is a relevant assessment tool, it may lack the sensitivity to capture subtle technical improvements. Jump technique involves a biomechanical component that necessitates structured and intensive training, regardless of the training method used. Morrow et al. [29] similarly emphasized the importance of consistent technique-based training in developing specific motor skills in children. Future research could employ biomechanical analysis methods, such as motion capture or force plates, to detect more nuanced differences in jump mechanics [30].

Although the Coaching Games method enhances motivation and engagement, the technical aspects of jumping in rhythmic gymnastics still require more structured, technique-based training. Game-based learning models are generally more effective in improving psychological factors such as motivation and engagement but may be less effective in developing technical skills over a short period [11]. Motor skill development, particularly in jumping techniques that involve complex biomechanical components, requires a longer training duration to produce significant improvements [29]. This study lasted only eight weeks with 18 training sessions, which may have been insufficient to observe substantial changes in the biomechanical aspects of jumping [11].

Individual differences in basic motor skills, influenced by prior experience, physical condition, and motor coordination, also play a role in training outcomes. Participants with advanced jumping skills at the start of the study may have experienced a ceiling effect, where performance improvements were minimal despite additional training interventions [12]. While coaching games introduce variety and increase student engagement, not all participants adapt immediately to different training methods. Some children may require more time to develop neuromuscular responses to game-based training compared to traditional approaches [31].

Although the Stretched Jump test has high validity (0.995), it may lack sensitivity in detecting gradual improvements in jumping technique. A more detailed biomechanical analysis, such as motion capture or force plate assessments, may be necessary to identify subtle changes in performance that standard measurement tools might overlook [16].

Limitations of the study

While this study provides valuable insights, several limitations should be acknowledged. The sample was drawn exclusively from elementary schools in Yogyakarta, Indonesia, which limits the generalizability of the findings to broader populations. Additionally, the eight-week intervention period may have been too short to capture long-term changes in jump technique or sustained interest.

Self-reported interest measures were susceptible to social desirability bias, and a longer follow-up period would help determine whether the observed improvements persist over time. Although the Likert-scale questionnaire demonstrated high reliability, self-reported data remain inherently vulnerable to response biases. The Stretched Jump evaluation assessed overall technical performance but may not have been sensitive enough to detect subtle biomechanical improvements.

Uncontrolled external factors, such as parental support or participation in extracurricular physical activities, were not accounted for, potentially influencing the outcomes. Variability in instrumentation and implementation could have affected the intervention's impact, particularly on skill-based measures like jumping technique. Lastly, the study primarily relied on quantitative methods, leaving qualitative insights unexplored, and the practical significance of the effect sizes remains uncertain.

Conclusions

The Coaching Games (COG) model significantly enhances upper elementary students' interest in rhythmic gymnastics compared to conventional training (CON). The COG approach, which incorporates obstacle courses, hopscotch, agility ladder drills, and music, aligns with Self-Determination Theory by reducing monotony and increasing emotional engagement. However, the difference in jump performance between the COG and CON groups was not statistically significant, suggesting that short-term interventions may be insufficient to address the biomechanical complexity of jumps. These findings indicate that game-based methodologies in physical education can enhance student motivation and promote long-term participation in rhythmic gymnastics.

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Conflict of Interest

The authors report that there are no competing interests to declare.

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ORIGINAL ARTICLE

A study on the key predictors of 100m sprint performance: identification and ranking

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

Abstract

Background and Study Aim The sprint is one of the most prestigious events in athletics, requiring a combination of explosive power and acceleration. However, talent identification remains a challenge, as early sprint performance does not always predict long-term success. The aim of this study is to identify and rank the most relevant predictors of 100m sprint performance among young athletes.

Material and Methods This study involved 11 subjects (6 boys and 5 girls) born in 2008, who were in their first year of the U18 category in 2024. They participated in the 100m event both in 2023 and 2024. Speed, strength, coordination, and mobility were assessed using tests, including 30m sprint from a standing start, 60m sprint from a standing start, 30m sprint with a flying start, bounding strides over 30m, standing long jump, triple jump, countermovement jump, medicine ball throw, and Sit and Reach test. Specific agility was evaluated using the Witty SEM system. Balance parameters and lower limb strength were assessed with the SensaBalance platform and the OptoJump system, respectively. Statistical analysis was conducted using Pearson's correlation, Spearman's rank correlation, and Bootstrapped Pearson's correlation to identify the most relevant predictors. The bootstrapping technique was applied to enhance the reliability of the correlation estimates. Statistical significance was set at $p < 0.05$.

Results The analysis revealed that not all of the 12 assessed tests had significant predictive value for sprint performance. Parameters such as specific agility, static and dynamic balance, squat jump, and Sit and Reach mobility test did not show strong correlations with 100m sprint outcomes. These findings support the use of selected physical and anthropometric variables in a secondary selection model for young sprinters.

Conclusions This study confirms that specific physical, psychomotor, and anthropometric variables significantly influence 100m sprint performance among young athletes. It also proposes a secondary selection model that incorporates the most relevant predictors to support talent identification and training optimization.

Keywords: sprint performance, selection model, predictive factors, young athletes, anthropometric characteristics

Introduction

The 100m sprint serves as the fundamental benchmark for assessing human speed and is the standard for identifying the fastest athlete in the world at any given time. Its widespread popularity and media exposure make sprinting highly appealing to young athletes. However, not all young athletes possess the psychomotor abilities required for high-performance sprinting. Therefore, coaches must evaluate whether an athlete's physical and psychological profile aligns with the specific demands of sprinting at an elite level. This evaluation requires careful consideration of the biomechanical, physiological, psychological, and anthropometric determinants of sprint performance.

The 100m sprint can be divided into three distinct phases: block start with acceleration, maximum velocity, and deceleration [1]. Each phase presents unique biomechanical and physiological challenges, and performance in these phases is influenced by various factors described in scientific literature. While many studies have analyzed the kinematic parameters of elite sprinters during competitions, experimental research directly involving elite athletes remains limited. Most existing studies rely on competition data to develop mathematical models, including biomechanical simulations, force-velocity profiles, and sprint performance predictors [2].

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Some authors argue that neurological and mechanical factors are more critical to sprint performance than purely physiological ones, particularly emphasizing the ability to generate high ground reaction forces (GRF) relative to body weight (BW) and to apply these forces in minimal contact time [3]. Furthermore, during sprint acceleration, the orientation of the resultant ground reaction force vector, rather than its absolute magnitude, has been shown to have a stronger correlation with sprint performance [2].

Among physiological factors, two are consistently associated with sprint performance: muscle fiber composition, particularly a higher proportion of fast-twitch fibers [4, 5], and the capacity to utilize high-energy phosphate compounds efficiently [6]. In addition to these functional parameters, several anthropometric characteristics have been identified as advantageous for sprinting success, such as a high body mass index (BMI) due to greater muscle mass [7, 8], and longer lower limb length, which contributes to stride length and mechanical efficiency [9].

Analysis of previous studies has shown that sprint performance is influenced by a complex interaction of physiological, biomechanical, and anthropometric factors. Various authors highlight the importance of identifying specific physical and structural characteristics that contribute to sprinting success, particularly in young athletes. Despite numerous investigations into sprint mechanics and performance determinants, there remains a need for more in-depth research aimed at establishing objective, comprehensive selection models. Such models should integrate multiple performance indicators to better support talent identification and optimize training strategies in youth sprinting.

Analysis of existing research provides a foundation for formulating specific hypotheses regarding the predictors of sprint performance and for defining the aim of the present study.

Working Hypotheses: H1. There is a statistically significant relationship between specific physical, psychomotor, and anthropometric variables and 100m sprint performance in young athletes. H2. A selection model incorporating key physical, psychomotor, and anthropometric predictors can effectively differentiate young athletes with higher sprint potential from their peers.

The aim of this study is to identify and rank the most relevant predictors of 100m sprint performance among young athletes.

Materials and Methods

Participants

This research is part of a broader project involving 16-year-old athletes specializing in sprint, hurdles, and jumping events. From this group, 11 athletes who competed in sprint events were selected as participants for the present study (5 girls and 6 boys). They were in their first year of the U18 junior category (born in 2008) and took part in the 100m event in both 2023 and 2024.

Written informed consent was obtained from the parents of all minor participants, in accordance with the Declaration of Helsinki. The protocol for anthropometric measurements, as well as the procedures for field and laboratory testing, was explained in detail to both the athletes and their parents. Participants were also informed of their right to withdraw from the study at any time. The study was approved by the respective sports clubs through the coaches of the participating athletes.

Research Design

The study was structured as an in-depth case analysis for each athlete, enabling a comprehensive assessment of the alignment between individual psychomotor predispositions and the specific demands of the 100m sprint. This design prioritized qualitative depth over sample size, allowing for a detailed and individualized evaluation of factors influencing sprint performance. Multiple testing sessions were conducted to monitor trends, adaptations, and fluctuations in performance, providing a more accurate understanding of how these variables affect sprint success in a longitudinal context.

Testing Procedure and Measurements

The subjects were tested in three distinct stages: T1, T2, and T3. Anthropometric measurements were performed only during T1 and T3, as the interval between T1 and T2 was too short for significant anthropometric changes to occur. The period between T1 and T3 was approximately nine months. The initial testing (T1) took place during the preparation period in the fall of 2023, while the intermediate (T2) and final tests (T3) were conducted in 2024, following the national indoor and outdoor championships, respectively.

To assess speed, strength, coordination, and mobility, the following tests were conducted:

- 30m sprint from a standing start (30m s.s.);
- 60m sprint from a standing start (60m s.s.);
- 30m sprint with a flying start (30m f.s.);
- Execution time of bounding strides over 30m (BS 30m);
- Standing long jump (SLJ);
- Two-foot take-off triple jump (STJ);
- Countermovement jump (CMJ);
- 3 kg medicine ball throw from a supine position (MBT);
- Sit and Reach mobility test (SR).

Additional assessments included:

- Specific agility (Ag.) measured using the Witty SEM light system;
- Static bipedal balance (SBiB), lateral dynamic bipedal balance (LDBiB), and vertical dynamic

bipedal balance (VDBiB) assessed with the Sensamove SensaBalance platform;
- Explosive lower limb strength measured using CMJ and squat jump (SQJ), both performed with the OptoJump system.

Anthropometric indices measured included: height (H), torso length (T), body mass (BM), lower limb length (LLL), left and right foot length (LFL, RFL), left and right thigh circumference (LTC, RTC), left and right calf circumference (LCC, RCC), left and right ankle circumference (LAC, RAC), biacromial diameter (BiaD), and bitrochanteric diameter (TrohD).

All testing equipment used in this study belongs to the Human Performance Research Center of the Doctoral School of Sports Science and Physical Education in Pitești, affiliated with the National University of Science and Technology Politehnica Bucharest.

Based on these evaluations, the dynamics of the subjects' physical and psychomotor development were analyzed. However, statistical analysis in this study was performed exclusively using the data recorded during the final testing stage (T3). The evolution of the investigated parameters across the three stages was interpreted within the framework of individual case studies.

Statistical Analysis

The best performance achieved by each athlete in official 100m competitions [10] was used as the dependent variable. This was correlated with independent variables from the physical and psychomotor domains. To account for the small sample size and assess the robustness of the results, Pearson's correlation was complemented by Spearman's rank correlation. Additionally, bootstrap resampling techniques were applied, generating multiple resampled datasets to estimate confidence intervals and to minimize the risk of Type I and Type II errors.

Results

Given the small sample size ($n = 11$), Pearson's correlation (to assess linear relationships), Spearman's rank correlation (to assess monotonic relationships), and bootstrapping (for stability assessment) were applied to enhance the robustness of the analysis. The statistical correlations between 100m sprint performance and the variables assessed using specialized equipment are presented in Table 1.

The strength and direction of the observed correlations, as well as their statistical significance, were interpreted according to established thresholds. Correlation coefficients (r) with absolute values greater than 0.7 were considered strong, those between 0.3 and 0.7 as moderate, and values below 0.3 as weak or negligible. Positive correlation coefficients ($r > 0$) indicated that higher values of the independent variable were associated with better sprint performance, while negative values ($r < 0$) suggested the opposite relationship [11]. Statistical significance was determined using a threshold of $p < 0.05$; p-values exceeding this level were regarded as non-significant and potentially attributable to random variation [12].

As shown in Table 1, countermovement jump (CMJ) demonstrated the strongest and most consistent negative correlation with 100m sprint performance across all statistical methods. This indicates that higher CMJ values are associated with faster sprint times, and the association is both statistically significant and stable. In contrast, squat jump (SQJ) exhibited a moderate negative correlation, but the lack of statistical significance and the inclusion of zero within the confidence interval suggest that this relationship is not reliable.

Agility and balance-related variables showed weak correlations, with correlation coefficients close to zero and p-values far exceeding the significance threshold. Additionally, their confidence intervals included zero, confirming the instability and low predictive value of these parameters in relation to sprint performance.

These results indicate that only CMJ can be considered a valid predictor of sprint performance among the tested parameters, while agility and

Table 1. Statistical correlation between 100m performance and the variables assessed using specialized equipment

Tests	Pearson (r)	p-value	Spearman (r)	p-value	Bootstrapped Pearson (r)	95% CI Lower	95% CI Upper
CMJ (cm)	-0.857	0.0007	-0.882	0.0003	-0.844	-0.975	-0.562
SQJ (cm)	-0.551	0.0791	-0.555	0.0767	-0.537	-0.840	0.047
Ag. (s)	-0.104	0.7614	-0.191	0.5739	-0.105	-0.693	0.488
LDBiB (%)	0.214	0.5267	0.091	0.7894	0.196	-0.664	0.837
VDBiB (%)	0.209	0.5369	0.282	0.4011	0.210	-0.355	0.674
SBiB (%)	-0.183	0.5896	-0.257	0.4446	-0.180	-0.755	0.423

Note: CMJ - Countermovement Jump; SQJ - Squat Jump; Ag. - Agility; LDBiB - Lateral Dynamic Bipedal Balance; VDBiB - Vertical Dynamic Bipedal Balance; SBiB - Static Bipedal Balance; CI - Confidence Interval.

balance measures do not offer meaningful insight in this context.

In addition to the variables assessed using specialized equipment, statistical correlations were calculated for the independent variables derived from physical performance tests conducted under field conditions. The results of these analyses are summarized in Table 2.

The interpretation of correlation coefficients in this analysis followed established statistical conventions. Correlations with absolute r-values greater than 0.7 were considered strong, those between 0.3 and 0.7 were classified as moderate, and correlations below 0.3 were regarded as weak or negligible. Positive r-values indicated that higher values of the independent variable were associated with slower sprint performance (i.e., longer time), whereas negative r-values suggested that higher values of the independent variable corresponded to faster sprint performance (i.e., shorter time) [11]. Statistical significance was determined at a threshold of $p < 0.05$; p-values equal to or greater than this level was interpreted as non-significant, implying that the observed relationships might have occurred by chance [12].

As shown in Table 2, among the parameters evaluated through tests, anterior spinal mobility—as assessed by the Sit and Reach test—was the only variable that exhibited a weak and statistically non-significant relationship with 100m sprint performance. All other tested variables demonstrated strong and significant correlations, confirming their relevance as predictors.

Due to the close alignment between Pearson's and Spearman's correlation coefficients across variables, the ranking of predictors was determined based on the width of the confidence intervals derived from bootstrapped correlation estimates. Narrower intervals reflect greater statistical stability, thereby indicating higher reliability of the associated predictor.

Standing long jump (SLJ) emerged as the most robust predictor of sprint performance, showing the strongest absolute correlation and the narrowest confidence interval. The 60m sprint from a standing start also demonstrated a very strong relationship with 100m performance, although its statistical stability was slightly lower than that of SLJ. Bounding strides over 30m ranked closely behind, confirming its importance in assessing sprinting ability.

Standing triple jump (STJ) and countermovement jump (CMJ) also proved to be strong negative predictors, indicating that greater explosive strength is associated with better sprint performance. The Medicine Ball Throw (MBT) further reinforced this trend by demonstrating a consistent and significant correlation. Additionally, sprint times over 30m from both standing and flying starts provided meaningful predictive value, with the flying start variation being more indicative of sprint potential.

Overall, the data suggest that power-based tests, particularly those evaluating lower limb explosive strength and sprinting efficiency over short distances, are the most reliable indicators of 100m performance in young athletes.

In addition to psychomotor and performance-related tests, anthropometric measurements were analyzed to determine their association with 100m sprint performance. The results of these statistical correlations are presented in Table 3.

The correlation coefficients obtained for anthropometric variables were interpreted according to conventional statistical thresholds. Absolute r-values exceeding 0.7 were considered indicative of strong correlations, values between 0.3 and 0.7 reflected moderate associations, and those below 0.3 were regarded as weak or negligible. Positive r-values signified that greater values of

Table 2. Statistical correlations between performance in 100m and independent variables assessed through tests

Tests	Pearson (r)	p-value	Spearman (r)	p-value	Bootstrapped Pearson (r)	95% CI Lower	95% CI Upper
30m s.s. (s)	0.783	0.0044	0.815	0.0022	0.805	0.607	0.952
30m f.s. (s)	0.865	0.0006	0.820	0.0020	0.874	0.716	0.973
60m s.s. (s)	0.893	0.0002	0.945	0.0000	0.899	0.749	0.979
BS 30m (s)	0.886	0.0003	0.851	0.0009	0.873	0.686	0.980
BS 30m (no.)	0.786	0.0041	0.751	0.0078	0.783	0.539	0.962
SLJ (m)	-0.913	0.0001	-0.870	0.0005	-0.916	-0.980	-0.806
STJ (m)	-0.880	0.0004	-0.918	0.0001	-0.899	-0.989	-0.773
CMJ (cm)	-0.857	0.0007	-0.882	0.0003	-0.840	-0.964	-0.592
MBT (m)	-0.819	0.0020	-0.847	0.0010	-0.835	-0.945	-0.670
SR (cm)	-0.270	0.4227	-0.278	0.4080	-0.298	-0.747	0.194

Note: s.s. - Standing start; f.s. - Flying start; BS - Bounding strides; SLJ - Standing Long Jump; STJ - Standing Triple Jump; MBT - Medicine Ball Throw; SR - Sit and Reach; CI - Confidence Interv

Table 3. Statistical correlations between performance in 100m and independent variables assessed through anthropometric measurements

Anthropometric Indices	Pearson (r)	p-value	Spearman (r)	p-value	Bootstrapped Pearson (r)	95% CI Lower	95% CI Upper
H (cm)	-0.555	0.0766	-0.469	0.1454	-0.563	-0.853	-0.068
T (cm)	-0.604	0.0489	-0.552	0.0785	-0.578	-0.858	-0.122
BM (kg)	-0.752	0.0076	-0.655	0.0289	-0.743	-0.948	-0.395
LLL (cm)	-0.314	0.3463	-0.384	0.2442	-0.343	-0.827	0.337
LFL (cm)	-0.657	0.0281	-0.648	0.0310	-0.653	-0.873	-0.330
RFL (cm)	-0.657	0.0281	-0.648	0.0310	-0.653	-0.873	-0.330
LTC (cm)	-0.515	0.1053	-0.381	0.2480	-0.472	-0.930	0.298
RTC (cm)	-0.499	0.1180	-0.318	0.3406	-0.446	-0.919	0.474
LCC (cm)	-0.642	0.0334	-0.469	0.1456	-0.578	-0.925	0.097
RCC (cm)	-0.642	0.0334	-0.469	0.1456	-0.578	-0.925	0.097
LAC (cm)	-0.780	0.0046	-0.687	0.0195	-0.752	-0.938	-0.251
RAC (cm)	-0.780	0.0046	-0.687	0.0195	-0.752	-0.938	-0.251
BiaD (cm)	-0.752	0.0075	-0.790	0.0038	-0.759	-0.960	-0.463
TrohD (cm)	-0.801	0.0030	-0.732	0.0105	-0.771	-0.965	-0.321

Note: H - Height; T - Torso Length; BM - Body Mass; LLL - Lower Limb Length; L/RFL - Left/Right Foot Length; L/RTC - Left/Right Thigh Circumference; L/R CC - Left/Right Calf Circumference; L/R AC - Left/Right Ankle Circumference; BiaD - Biacromial Diameter; TrohD - Bitrochanteric Diameter; CI - Confidence Interval.

the anthropometric measurement corresponded to longer sprint times (i.e., slower performance), while negative r-values indicated that higher values of the variable were associated with shorter sprint times (i.e., better performance) [11]. Statistical significance was determined at the $p < 0.05$ level; p-values equal to or greater than this threshold was interpreted as non-significant, implying a potential influence of random variation [12].

As shown in Table 3, all anthropometric variables exhibited negative correlations with 100m sprint performance, indicating that greater values of these measurements tend to be associated with faster sprint times. Overall, the strength of these relationships was moderate, rather than strong, for most indices.

Among the measured parameters, bitrochanteric diameter (TrohD) emerged as the most reliable predictor, demonstrating the strongest negative association with sprint performance and the greatest statistical stability. Ankle circumference (LAC/RAC) ranked closely behind, showing consistent significance and a similarly stable correlation pattern. Body mass and biacromial diameter (BiaD) also presented moderate negative relationships with performance, with BiaD showing slightly higher stability based on rank correlation and confidence interval analysis.

Foot length (LFL/RFL) demonstrated a moderate and statistically significant correlation, although wider confidence intervals suggest reduced reliability. In contrast, torso length (T) and calf circumference (LCC/RCC) displayed statistically significant linear correlations; however, the strength of their monotonic (rank-based) relationships was weaker or inconsistent, limiting their predictive value.

Other measurements, including height (H), thigh circumference (LTC/RTC), and lower limb length (LLL), did not show statistically significant correlations with sprint performance, and their confidence intervals indicated a lack of stability. These findings suggest that only select anthropometric characteristics are meaningfully associated with sprint success, while others have limited or no predictive utility in this context.

Based on the key predictors identified in this study, and supported by findings from previous research, a secondary selection model for the 100m sprint event was developed. This model includes the following performance tests and anthropometric measurements: 60m sprint from a standing start (60m s.s.), bounding strides over 30m (BS 30m), standing long jump (SLJ), standing triple jump (STJ), countermovement jump (CMJ), bitrochanteric diameter (TrohD), body mass (BM), and foot length (FL). Using this model, each subject's compatibility with the specific demands of the 100m sprint was evaluated (Table 4).

As shown in Table 4, compatibility was determined by comparing each subject's performance and anthropometric measurements against thresholds derived from the key predictors. A portion of the subjects demonstrated a high level of alignment

Table 4. Subject compatibility with the 100m sprint event

Subjects	STJ (m)	SLJ (m)	CMJ (cm)	60m s.s. (s)	BS 30m (s)	TrohD (cm)	BM (kg)	FL (cm)	Compatibility with 100m event
Boys									
B.A.	9.20	2.85	45.20	6.50	3.88	35.0	73	27.0	Compatible
B.D.	8.60	2.80	43.80	7.00	4.09	35.0	68	26.0	Compatible
B.L.	7.48	2.52	32.30	7.60	4.30	35.0	74	27.5	Not Compatible
M.M.	7.45	2.50	32.50	7.80	4.20	30.0	52	25.0	Not Compatible
T.R.	7.50	2.48	30.00	7.70	4.10	31.0	62	26.5	Not Compatible
T.A.	7.90	2.45	40.40	7.15	4.20	34.0	60	26.0	Compatible
Girls									
C.D.	7.11	2.50	31.90	7.90	4.20	33.0	52.5	24.0	Compatible
C.A.	6.08	2.12	28.60	8.10	4.85	30.0	57	25.5	Not Compatible
C.S.	6.60	2.20	30.90	8.02	4.93	30.0	50	24.0	Compatible
I.R.	6.50	2.10	24.30	8.35	5.15	28.0	47	24.0	Not Compatible
M.S.	6.75	2.25	36.40	7.82	4.85	32.0	53.5	24.0	Compatible

Note: Secondary selection model based on key predictors. STJ - Standing Triple Jump; SLJ - Standing Long Jump; CMJ - Countermovement Jump; 60m s.s. - 60m sprint from a standing start; BS 30m - Bounding Strides over 30m; TrohD - Bitrochanteric Diameter; BM - Body Mass; FL - Foot Length.

with the specific demands of the 100m sprint event, indicating potential for successful specialization. These findings support the practical applicability of the proposed secondary selection model and suggest that integrating performance-based and anthropometric assessments can enhance talent identification and training efficiency in young sprinters.

Discussion

The findings of this study confirm that specific physical, psychomotor, and anthropometric variables significantly influence 100m sprint performance in young athletes, thereby supporting the first working hypothesis (H1). Additionally, the results indicate that a scientifically grounded secondary selection model, based on key performance predictors, may improve the identification of athletes with high sprint potential. Although these findings provide partial support for the second hypothesis (H2), further validation of the model with a larger sample is necessary to ensure its applicability.

Among the variables assessed using specialized equipment, countermovement jump (CMJ) emerged as the most significant predictor of sprint performance. This result highlights the importance of explosive lower limb strength, particularly the athlete's ability to rapidly generate force through the stretch-shortening cycle, as a critical determinant of sprint success.

Regarding the tests, standing long jump (SLJ), 60m sprint from a standing start (60m s.s.), bounding strides over 30m (BS 30m), and standing triple jump (STJ) emerged as the strongest predictors of 100m sprint performance. These results confirm that sprinting ability is supported by horizontal explosive power, stride efficiency, effective force application, and dynamic strength. The countermovement jump (CMJ), when conducted in field conditions, also demonstrated a strong correlation with sprint performance, consistent with the results obtained through the OptoJump system. This reinforces the significance of vertical explosive power in sprinting; however, horizontal power indicators such as SLJ and STJ appear to be even more relevant in predicting sprint success. Numerous specialized studies have sought to identify biomechanical indicators associated with successful 100m sprint performance. These investigations consistently conclude that the primary objective in sprinting is the development of maximum horizontal velocity of the entire body, achieved through force production and optimal running technique [13, 14, 15].

Additionally, the 30m sprint with a flying start (30m f.s.) proved to be a more relevant predictor of 100m performance than the 30m sprint from a standing start (30m s.s.). This suggests that an athlete's ability to accelerate efficiently and sustain high velocity over short distances plays a critical role in overall sprint performance.

The relationships between the investigated anthropometric indices and 100m sprint performance appeared moderate rather than strong. This finding suggests that no single anthropometric measurement can be regarded as a dominant predictor of sprint performance, reinforcing the notion that sprint ability results from a complex interplay of biomechanical, neuromuscular, and technique-related factors, rather than body dimensions alone.

The most relevant anthropometric predictors identified in this study were bitrochanteric diameter (TrohD), ankle circumference (AC), body mass (BM), biacromial diameter (BiaD), and foot length (FL). Although their correlations with performance were moderate, these variables likely influence sprint ability indirectly by affecting stride length, ground reaction forces, stability, and energy transfer during the acceleration and maximum speed phases. For example, bitrochanteric diameter may impact stride mechanics and lateral stability; smaller ankle circumference could reduce inertial resistance, allowing for more efficient propulsion; optimal body mass is essential to balance acceleration and power output; biacromial diameter may contribute to upper body control during sprinting; and larger feet might enhance push-off efficiency, although this relationship remains debated. These parameters must be considered alongside dynamic performance measures such as explosive strength, acceleration ability, and sprinting technique for a comprehensive evaluation of sprint potential.

Numerous studies have emphasized the role of muscular power in sprint performance, focusing on key kinematic variables. These include spatiotemporal factors (stride length, stride frequency, ground contact time, flight time), lower limb configuration at ground contact and take-off, and segmental velocities before and during ground contact [16]. These determinants are, in turn, influenced by a combination of anthropometric, psychological, and genetic characteristics specific to each athlete, as well as biomechanical factors specific to sprinting and related events [17, 18]. Additionally, research on the musculoskeletal structure of elite sprinters has highlighted the significance of foot morphology in sprint speed development. Specifically, longer toes have been associated with prolonged ground contact time, which may enhance propulsive force and acceleration capacity [19].

The small number of subjects may affect the statistical robustness of the findings and limit the generalizability of the results. However, all participants were 16-year-old competitive sprinters, which reduced variability related to age, training background, or event specialization. While these findings may not be applicable to athletes of different age groups or performance levels, they offer relevant insights for individuals in the same stage of athletic development. Moreover, previous research in sports biomechanics and sprint performance has frequently employed small sample sizes due to the limited availability of highly trained sprinters. Notably, studies by Morin et al. [2] and Weyand et al. [3] have derived meaningful conclusions about sprint mechanics from similarly small or even smaller cohorts.

Within the broader research framework, the present study adopted an individual case study approach, allowing for a detailed analysis of each athlete's anthropometric, physical, and psychomotor profile in relation to sprint performance. This individualized analysis enabled a more nuanced understanding of the relationships between measured variables and sprint ability, potentially contributing to the refinement of secondary selection models for young sprinters.

Based on the findings of this study, as well as evidence from previous research, the most relevant predictors of 100m sprint performance include anthropometric indices, results from field-based and laboratory-based tests, and specialized evaluation techniques. The complementarity of these factors is essential for the accurate and effective orientation of young athletes toward sprint events.

The individualized analysis of each subject's physical and psychomotor profile, in correlation with their competition performance in the 100m event during the experimental year (2024), enabled an assessment of the alignment between psychomotor predispositions and the specific demands of sprinting. Ensuring this alignment is critical for optimizing training efficiency and achieving competitive success in future athletic development.

This study contributes to sports science by identifying and ranking the most relevant physical, psychomotor, and anthropometric predictors of 100m sprint performance in young athletes. The use of correlation-based analysis, including Pearson's, Spearman's, and bootstrapped correlations, enabled statistically robust interpretation without reliance on complex predictive modeling. These findings offer a practical basis for developing standardized selection procedures and targeted training strategies for sprint performance.

Furthermore, the results may serve as a foundation for future research employing predictive modeling techniques, such as regression analysis or machine learning, to further enhance talent identification frameworks. Additional biomechanical investigations, particularly those examining ankle structure, force application, and neuromuscular coordination, could also contribute to refining evidence-based sprint training methodologies.

Limitations of the Study

This study was conducted as a case-by-case analysis, focusing on detailed athlete profiling rather than population-level generalization. This approach is particularly relevant in talent identification, where individualized performance trajectories provide more actionable insights than group averages. Repeated measurements across three testing stages (T1, T2, and T3) enhanced the reliability of the observations.

A recognized limitation of this research is the small sample size, which is a common challenge in sports science, especially in studies involving competitive or specialized athlete populations. Limited access to high-performance athletes, along with declining participation in track and field among youth in Romania, restricted the available talent pool and precluded large-scale data collection. Further validation with a larger and more diverse cohort is necessary to confirm the reliability and generalizability of the proposed selection model.

This research was approved by the Ethics Committee of the Doctoral School of Sports Science and Physical Education, Pitești University Center, Romania.

Conclusions

The results of this study support the first hypothesis (H1), demonstrating that specific physical, psychomotor, and anthropometric variables significantly influence 100m sprint performance among young athletes. The second hypothesis (H2) is partially supported, as the proposed secondary selection model shows potential for practical application but requires further validation.

Key predictors of sprint performance were identified and applied to assess each athlete's compatibility with the 100m event, revealing that some individuals exhibit a stronger natural predisposition for sprinting. From a practical perspective, these findings can be incorporated into athlete selection and training programs by including performance indicators such as explosive strength (CMJ), acceleration ability (e.g., 30m sprint with a flying start), and biomechanical efficiency (e.g., BS 30m, AC) in standardized evaluation protocols. The use of these variables within secondary selection models may help coaches and talent scouts objectively identify young athletes with sprint potential and design training interventions that enhance acceleration, stride efficiency, and force application.

Conflict of Interest

The authors report that there are no competing interests to declare.

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