

ISSN 2664-9837

PEDAGOGY

of Physical Culture
and Sports

№04/2025



Key title: Pedagogy of Physical Culture and Sports (Abbreviated key-title: Pedagogy phys. cult. sports; ISSN 2664-9837).

Publisher: IP Iermakov S.S.

Certificate to registration:

R40-05596, 04.10.2024, No 2951.

Previous title «Pedagogics, psychology, medical-biological problems of physical training and sports» (e-ISSN 2308-7269; p-ISSN 1818-9172; ISSN-L 2308-7269).

Frequency – 6 numbers in a year.

e-mail: sportart@gmail.com

<https://www.sportpedagogy.org.ua>

INDEXING

Web of Science Core Collection - [Emerging Sources Citation Index (ESCI)] - http://mjl.clarivate.com/cgi-bin/jrnlst/jlresults.cgi?PC=MASTER&ISSN=*2664-9837

Scopus - <https://www.scopus.com/sourceid/21101040604>

DOAJ (Directory of Open Access Journals) - <https://doaj.org/toc/2664-9837>

ERIH PLUS (The European Reference Index for the Humanities and the Social Sciences) - <https://dbh.nsd.uib.no/publiseringskanaler/erihplus/periodical/info?id=497967>

WorldCat (WorldCat is the world's largest network of library content and services) - <http://www.worldcat.org>

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Dimensions - https://app.dimensions.ai/discover/publication?search_text=10.15561%2F26649837.&search_type=kws&search_field=doi

Crossref - <https://search.crossref.org/?q=2664-9837>

Open Ukrainian Citation Index (OUCI) - <https://ouci.dntb.gov.ua/en/editions/E1DygdjZ/>

MIAR - <http://miar.ub.edu/issn/2664-9837>

ResearchGate - https://www.researchgate.net/journal/2664-9837_Pedagogy_of_Physical_Culture_and_Sports

Hinari Access to Research for Health - http://extranet.who.int/hinari/en/journal_keyword_search.php?query=Pedagogy+of+Physical+Culture+and+Sports

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Learning of gross motor skills based on fun games: a study of coordination development in 5–6-year-old children

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Abstract

Background and Study Aim Coordination skills in early childhood are essential for overall physical, cognitive, and social development. However, conventional approaches to teaching basic motor movements often fail to produce optimal outcomes. The research aims to formalize learning basic movements based on fun games to develop the coordination of movements in children aged 5–6 years.

Material and Methods Forty-five children from several schools in Padang City, West Sumatra Province, Indonesia, comprised the experimental group, who participated in fun game-based movement learning. The control group did not engage in such learning. The experimental design for this study adopted the pre-test and post-test measurement and comparison method between the groups. The data collected were analyzed using covariance analysis with SPSS version 26.

Results The experimental group showed a significant difference in children's movement coordination development compared to the control group. They also showed significant differences in the development of the ability to perform balance beam, eye-hand coordination, jumping sideways, moving sideways, and shuttle throw among the sub-factors of the test items conducted for movement coordination, compared to the control group.

Conclusions The research results also indicated the importance of a fun game-based form of basic movement learning as an implication for Early Childhood Education programs. The movement-based learning model using fun games effectively teaches movement patterns while enhancing children's coordination, motivation, responsibility, and social skills. Its engaging nature makes it suitable for early childhood education, helping improve learning quality for children aged 5–6 across Indonesia.

Keywords: motor learning, fun game based, movement coordination, programs

Introduction

Motor coordination serves as a foundation for effective participation in physical activities and daily life during childhood. The development of coordination and the identification of effective learning approaches represent an important element in the system of educational practices in early childhood.

Early childhood is a critical period that shapes physical, cognitive, and socio-emotional development [1]. At this stage, posture and basic motor skills begin to form and require appropriate stimulation for healthy growth. Among various developmental domains, motor skills are fundamental for learning and adaptation [2]. Motor skills enable children to perform both gross (e.g., running, jumping) and fine (e.g., writing) movements, and their development depends on factors such as parenting and nutrition [3, 4]. Coordination, a key element of motor development, integrates multiple body systems to produce controlled and efficient movement [5]. It supports everyday actions

and adaptive behavior in diverse situations [6, 7]. Insufficient stimulation can hinder motor progress, reduce confidence, and limit social interaction [8]. Coordination involves the integration of sensory and motor functions and is affected by age, fitness level, environment, and access to play [9, 10, 11]. Assessing posture transitions and dynamic movements helps identify coordination levels, which are linked to future motor potential [12, 13, 14, 15].

Children who are active in free and structured play tend to have better coordination than those with less motor stimulation. However, coordination does not develop automatically but requires appropriate learning strategies, even when physical activity is adequate [16]. Unfortunately, many teachers, parents, and coaches still lack an understanding of how to teach coordination systematically and engagingly, resulting in some children struggling to master basic movements. This emphasizes the need for transformative learning approaches that not only teach motor skills but also the context in which they are applied in various situations [17, 18]. Research indicates that physical activity and games effectively enhance coordination at all educational levels [19]. Different approaches, such as conventional methods, outdoor activities, and

fun games, can improve overall motor skills.

In physical education and early childhood development, fun games can improve children's motivation and learning outcomes. Through fun and interactive games, children can practice basic motor skills such as running, jumping, and playing with a ball [20]. These games encourage physical activity, reduce sedentary behavior, and support social development through activities like sharing, cooperation, and following rules [21]. One of the key strengths of fun games is their ability to stimulate movement coordination indirectly. These games simultaneously enhance children's physical, cognitive, social, and emotional skills [22]. During play, children engage in pressure-free learning that improves balance, distance estimation, limb coordination, and responsiveness to stimuli.

In addition to fun games, outdoor physical activities also play an essential role in children's motor development. Nature-based activities offer multisensory and social learning experiences through organized sports, free play, and exploration [23]. Compared to indoor activities, outdoor play provides greater sensory stimulation, encourages cooperation and communication, and benefits children's physical and mental health [24]. It strengthens muscles, improves overall endurance and fitness [25], and supports cognitive functions such as memory and focus [26]. Physical movement is crucial for motor development, both in sports and in daily tasks [27], with natural engagement in play requiring complex coordination between the brain and muscles [28]. Gross motor skills, such as running and jumping, improve a child's balance, strength, and overall physical health [29].

Children with good gross motor skills tend to be more confident and socially active [30], indicating that motor development also affects cognitive, social, and emotional domains. They are also more agile and efficient in completing daily tasks [31]. Given children's limited attention span, interesting and varied learning strategies are needed [32]. Engaging in fun physical activities can enhance concentration by improving blood flow to the brain, stimulating the release of endorphins, and supporting cognitive function. Outdoor play can also improve mood and mental alertness, contributing to overall development [33].

An analysis of previous research has shown that various learning approaches, including fun games and outdoor activities, contribute positively to the development of motor coordination in early childhood. Researchers have identified key components such as motivation, engagement, and multisensory experiences as important elements of effective movement-based learning. Despite extensive research on motor skill development, there is still a need to explore structured and engaging methods that are tailored to the

developmental needs of young children. This study aims to identify and evaluate structured, engaging, and developmentally appropriate coordination learning strategies.

Materials and Methods

Participants

Participants were selected using purposive sampling techniques, resulting in a total of 45 children. They were divided into three groups: Experimental Group A (Fun Games), Experimental Group B (Outdoor Physical Activities), and the Control Group. Each group consisted of 15 children. To ensure comparable baseline abilities across groups, a blocked random assignment technique was applied based on pre-test scores. Participants were ranked from highest to lowest and grouped into 15 blocks, each containing three children with similar scores. Within each block, participants were randomly assigned to one of the three groups, resulting in balanced distribution in terms of initial motor coordination. The intervention was delivered to the experimental groups 16 times, with a frequency of three sessions per week.

The study was conducted in accordance with ethical standards for research involving human participants. Written informed consent was obtained from the parents or legal guardians of all participants prior to data collection. The research protocol was reviewed and approved by the institutional ethics committee of Padang State University.

Research Design

This study employed a quasi-experimental design with pre-test and post-test measurements across groups [34]. It aimed to examine the effectiveness of a fun game-based learning model formulated to improve motion coordination in kindergarten students at the Padang State University Development School. The game-based program was structured in two levels: Level 1 included simple coordination activities, while Level 2 involved more advanced coordination tasks.

The study began with the collection of pre-test data from children in both control and experimental groups. These data were used to ensure an equal distribution of initial abilities across the groups. The division aimed to maintain comparable coordination levels between the experimental and control groups before the intervention.

To assess coordination, the following motion coordination tests were used [35]:

- (1) Balance Beam,
- (2) Eye-Hand Coordination,
- (3) Jumping Sideways,
- (4) Moving Sideways, and
- (5) Shuttle Throw.

The level of locomotor skills was measured using the Test of Gross Motor Development-2 (TGMD-

2), a standardized and internationally validated instrument for assessing children’s gross motor development [36, 37, 38]. Its established reliability and validity support its use in evaluating the effectiveness of fun game-based motor learning interventions in children.

Procedure

The fun game-based movement coordination training model is illustrated in Figure 1

Based on Figure 1, the activities are designed to improve children’s coordination, particularly eye-hand and eye-foot coordination. They also aim to develop fundamental motor skills such as running, jumping, throwing, catching, and balancing. The games are progressively structured and delivered in an engaging manner to promote active participation during learning. Conducted in groups, these activities foster cooperation, communication, and turn-taking. Additionally, children are encouraged to develop strategies collaboratively, select group leaders, and call each other’s names when taking turns, thereby promoting positive social interaction.

The fun games intervention used in this study was designed as an alternative approach to incorporating structured play-based activities into motor coordination programs. The model was reviewed by five specialists in early childhood education and motor development, receiving an average score of 0.87 in terms of material content, objectives, and activity relevance, indicating alignment with expert-defined criteria. The model was organized into sequential stages with the aim of ensuring consistent implementation.

Game Rules

1. All teams are required to complete each task in

order.

2. Each task must be completed before moving on to the next one.
3. Group discussion is required to determine the best strategy to complete the task.
4. A leader is appointed to make the final decision at each step of the game.
5. Group members call each other by name when giving turns, reinforcing interaction and communication.
6. Children are instructed to quickly and orderly move the plastic ball into the basket.

In addition, the children also ran and climbed on the blocks while remaining focused on the game. The game forms are described in Table 1.

Other Group

The Outdoor Physical Activity group engaged in activities aimed at developing children’s gross motor skills through direct interaction with natural environments. These included light hiking, walking, jogging in open areas, and games such as jumping rope and cricket [39]. The activities were designed to stimulate coordination, balance, muscle strength, and social interaction through free exploration and teamwork. The outdoor setting offered diverse movement experiences and multisensory stimulation that contributed to children’s overall development. All sessions were conducted within a single lesson hour and combined exploratory play with structured teacher guidance.

In contrast, the Conventional Motor Learning group participated in school curriculum-based activities such as light gymnastics, marching, and ball-throwing and catching exercises. These activities were carried out indoors, with a focus on repetitive

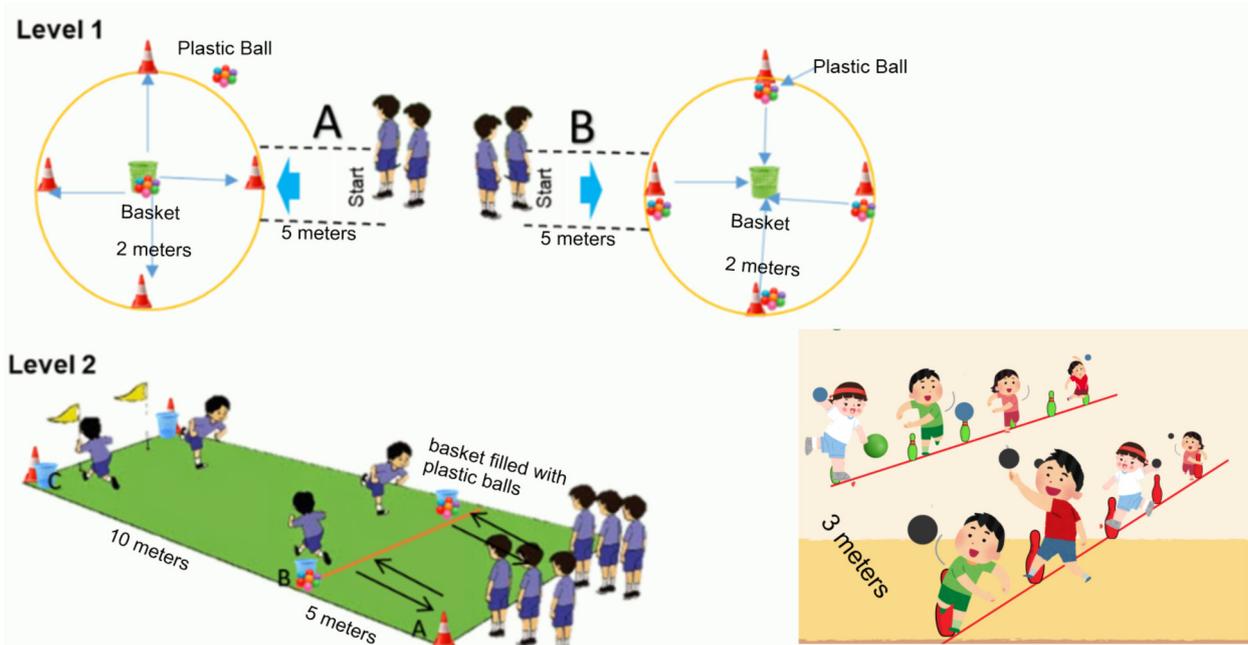


Figure 1. Motion Learning Activities (Author’s own work)

movement patterns and direct teacher instruction. This method emphasized discipline and order but offered limited environmental variety and reduced opportunities for active child participation. The duration of these sessions was also one lesson hour.

Statistical Analysis

Before data analysis, preliminary tests were conducted to assess the distribution and suitability of the data. The Kolmogorov–Smirnov (KS) test was used to assess the normality of each variable, and the equality of the covariance matrix was examined. Statistical analysis was performed using the ANCOVA method, and all data were processed with the SPSS version 26 software package.

Results

Homogeneity

One of the key assumptions in ANCOVA is the homogeneity of regression slopes, meaning that the relationship between the covariate (pre-test scores) and the dependent variable (post-test scores) should be consistent across all groups (Experimental Group A, Experimental Group B, and Control Group). This assumption ensures that the covariate’s influence on the outcome does not vary by group. To test this, an interaction analysis was conducted between the covariate (pre-test) and group factors on the dependent variable (post-test). The results of this analysis are presented in Table 2. As shown in the

table, all p-values were above 0.05, indicating that there were no statistically significant interactions between pre-test scores and group membership for any coordination variable. Therefore, the assumption of homogeneity of regression slopes was satisfied.

Normality

Before conducting the ANCOVA analysis, the assumption of normal distribution was tested using the Kolmogorov–Smirnov test on the pre-test, post-test, and residual score data for each group and coordination aspect. According to the criteria, if $p > 0.05$, the data are considered normally distributed, and the assumption is satisfied. The results of this test are presented in Table 3. As shown in the table, all p-values were greater than 0.05, indicating that the data for each coordination aspect in all three groups were normally distributed.

ANCOVA

This study aimed to evaluate the effectiveness of the intervention in improving physical coordination in several sub-groups: Experimental Group A, Experimental Group B, and the Control Group. Measurements were taken across five coordination skill components—Balance Beam, Jumping Sideways, Moving Sideways, Eye-Hand Coordination, and Shuttle Throw—as well as the Coordination Total Score, which represents the combined score across all components. The results of this analysis are presented in Table 4. Overall, the Coordination Total Score in Experimental Group A and Experimental

Table 1. Game Forms

Level	Description	Skills Practised
Level 1	<ul style="list-style-type: none"> – Students are divided into two groups (A and B). – Each group stands at the starting point, 5 meters from the playing area. 	Develops basic movement coordination, combining running speed and throwing accuracy.
	<ul style="list-style-type: none"> – In the center of the area is a basket (2 meters in diameter) with four colored cones and a plastic ball inside. – Taking turns, students run towards the basket and place the plastic ball inside. 	
Level 2	<ul style="list-style-type: none"> – Increased difficulty: the track is extended to 10 meters with designated points A, B, and C. – The plastic ball is placed at point A and moved in a zigzag path toward the main basket at point B. – The route includes obstacles, requiring students to jump and maintain balance while running along a defined path. 	Enhances speed, accuracy, obstacle navigation, and overall body balance.

Table 2. Homogeneity Test Results

Coordination Aspect	Group Interaction	Description
Balance Beam	p = 0.45	Homogeneous
Jumping Sideways	p = 0.62	
Moving Sideways	p = 0.51	
Eye-Hand Coordination	p = 0.39	
Shuttle Throw	p = 0.48	
Coordination Total Score	p = 0.53	

Table 3. Normality Test Results

Coordination Aspect	Group	Pre-test (p)	Post-test (p)	Description
Balance Beam	Experiment A	0,200	0,157	Normal
	Experiment B	0,156	0,182	
	Control	0,179	0,168	
Jumping Sideways	Experiment A	0,162	0,143	
	Experiment B	0,194	0,134	
	Control	0,182	0,170	
Moving Sideways	Experiment A	0,184	0,173	
	Experiment B	0,152	0,198	
	Control	0,172	0,185	
Eye-Hand Coordination	Experiment A	0,148	0,162	
	Experiment B	0,169	0,144	
	Control	0,160	0,150	
Shuttle Throw	Experiment A	0,174	0,160	
	Experiment B	0,158	0,166	
	Control	0,176	0,182	
Coordination Total Score	Experiment A	0,196	0,151	
	Experiment B	0,141	0,173	
	Control	0,188	0,177	

Table 4. Mean and Standard Deviation, Pre-Test, and Post-Test Corrected by Movement Coordination Data Group for 5-6 Year Old Children

Sub-Group	Group	Pre Test		Post Test		Corrected post-test		p-value
		M	SD	M	SD	M	SD	
Balance Beam	Experimental group A	2.31	0.32	4.46	3.57	4.54	1.93	0.000**
	Experimental group B	2.41	0.34	3.84	4.26	3.80	1.12	0.000**
	Control group	2.31	0.32	2.55	2.70	3.51	0.87	0.130**
Jumping Sideways	Experimental group A	3.21	0.54	4.07	2.32	4.09	0.32	0.000**
	Experimental group B	2.62	0.45	3.76	3.43	3.75	1.23	0.000**
	Control group	2.41	0.34	2.40	2.18	3.39	1.43	0.121**
Moving Sideways	Experimental group A	3.12	0.77	4.01	4.29	4.06	0.78	0.000**
	Experimental group B	2.31	0.32	2.83	3.76	3.82	0.89	0.000**
	Control group	2.32	0.32	3.10	3.32	3.06	0.35	0.087**
Eye-Hand Coordination	Experimental group A	3.31	0.87	4.50	4.44	4.44	1.13	0.000**
	Experimental group B	2.32	0.32	4.27	4.09	4.29	0.45	0.000**
	Control group	2.23	0.23	2.20	3.09	3.24	0.84	0.170**
Suttle Throw	Experimental group A	2.11	0.21	4.15	4.24	4.17	1.22	0.000**
	Experimental group B	2.22	0.23	3.69	4.99	3.68	1.18	0.000**
	Control group	2.31	0.32	2.14	4.92	3.12	1.02	0.173**
Coordination Total Score	Experimental group A	14.12	4.56	21.85	4.23	20.65	4.23	0.000**
	Experimental group B	14.35	3.45	19.53	4.86	20.48	4.37	0.000**
	Control group	14.23	3.23	17.36	3.74	17.89	3.54	0.084**

Table 5. Post Hoc

Sub-Component	A vs Control	B vs Control	A vs B
Balance Beam	p < 0.01 (4.54 vs. 3.51)	p < 0.01 (3.80 vs. 3.51)	p < 0.05 (4.54 vs. 3.80, A > B)
Jumping Sideways	p < 0.01 (4.09 vs. 3.39)	p < 0.01 (3.75 vs. 3.39)	p > 0.05 (4.09 vs. 3.75)
Moving Sideways	p < 0.01 (4.06 vs. 3.06)	p < 0.01 (3.82 vs. 3.06)	p > 0.05 (4.06 vs. 3.82)
Eye-Hand Coordination	p < 0.01 (4.44 vs. 3.24)	p < 0.01 (4.29 vs. 3.24)	p > 0.05 (4.44 vs. 4.29)
Shuttle Throw	p < 0.01 (4.17 vs. 3.12)	p < 0.01 (3.68 vs. 3.12)	p > 0.05 (4.17 vs. 3.68)
Coordination Total Score	p < 0.01 (20.65 vs. 17.89)	p < 0.01 (20.48 vs. 17.89)	p < 0.05 (20.65 vs. 20.48, A > B)

Group B increased significantly from 14.12 to 21.85 (corrected 20.65) and from 14.35 to 19.53 (corrected 20.48), respectively, with a *p*-value of 0.000. Meanwhile, the Control Group showed only a slight increase from 14.23 to 17.36 (corrected 17.89), which was not statistically significant (*p* = 0.084). In the table, all statistically significant *p*-values are marked with (**), indicating a high level of significance (*p* < 0.01). This suggests that the interventions applied in Experimental Groups A and B had a measurable effect on coordination test outcomes, whereas the changes observed in the Control Group were likely due to chance rather than the intervention.

Table 5 presents the results of the post hoc analysis. Both experimental groups (A and B) showed statistically significant improvements in all coordination sub-components compared to the control group (*p* < 0.01). Group A demonstrated higher performance than Group B in the Balance Beam task and the Total Coordination Score (*p* < 0.05), while no statistically significant differences were observed between the two experimental groups in the remaining sub-components. These findings suggest that the intervention implemented in Group A may have been more effective in enhancing certain aspects of coordination than the approach used in Group B.

Discussion

This study aimed to identify and assess coordination learning strategies that are structured, engaging, and developmentally appropriate. The analysis indicated improvements in multiple aspects of coordination skills among children in the experimental groups (A and B) compared to the control group. The Fun Games approach, integrating elements of play into motor learning, appears to support children’s engagement and motivation. Engaging in enjoyable activities during learning may contribute to increased participation and attentiveness among young learners [40].

The effectiveness of such strategies is closely linked to the teacher’s ability to plan and deliver varied forms of instruction [41]. Considering that children differ in learning styles, interests, and developmental levels [42], the application of diverse teaching methods is important for supporting

their cognitive, affective, and motor development [43]. Through methodical variation, educators can create learning environments that foster deeper understanding and sustain children’s interest in physical activities [44].

Basic movement coordination in children may be developed through appropriately designed game-based activities. The Fun Games method integrates elements of play with structured physical exercises aimed at enhancing key coordination skills in an engaging and developmentally appropriate manner [45]. For instance, Balance Beam tasks are used to support postural control, Jumping Sideways contributes to foot coordination and agility, Moving Sideways develops lateral movement patterns, while eye-hand coordination games aim to improve targeting and precision. Shuttle Throw activities additionally engage throwing mechanics and coordination.

These structured activities, refined through a systematic development process and supported by existing research, may serve as a pedagogical tool for improving movement coordination. Moreover, the implementation of such methods in outdoor settings could support not only motor development, but also motivation, cooperative behavior, and social interaction in early childhood contexts [46]. Previous studies suggest that the integration of play-based strategies in physical education contributes to increased engagement and alignment with children’s developmental needs [47, 48, 49, 50].

The present play-based learning model builds upon earlier findings by demonstrating its potential to enhance motor skills while supporting meaningful and engaging learning experiences for children [51]. Active participation in diverse movement-based contexts, including assessment procedures, has been associated with increased levels of engagement among young learners [52]. At the same time, several methodological considerations should be addressed to strengthen the validity of the findings. These include the possibility of group disparities, measurement bias, and individual differences in responsiveness to the intervention. Moreover, the long-term impact of the Fun Games approach remains to be fully examined, as motor coordination trajectories may vary over extended periods or within different educational

and cultural settings [53]. Previous research has indicated that games may provide developmentally appropriate opportunities for learning, particularly in children aged 5–6 years who show high interest in play-based activities [54, 55, 56]. While play can foster creativity and external motivation, further investigation is needed to understand how internal motivation during movement-based learning can be effectively supported and sustained over time [57].

The discussion highlights that structured game-based learning approaches can positively contribute to the development of coordination skills in early childhood. By integrating elements of fun, cooperation, and physical challenge, such methods offer an engaging alternative to conventional physical education formats. The findings reinforce the importance of selecting pedagogical strategies that align with children's developmental needs and emphasize active, varied, and meaningful participation.

Limitations and Future Directions

This study presents several limitations that should be acknowledged. The intervention was conducted over a relatively short duration, which restricts conclusions regarding the long-term effectiveness and retention of coordination improvements. Furthermore, the sample was limited to a single kindergarten affiliated with Universitas Negeri Padang, which reduces the generalizability of

the findings. The modest sample size and potential measurement biases may also influence the validity of the results. Future research should employ longitudinal study designs involving participants from diverse educational and cultural contexts. It is also recommended to use more objective measurement instruments and to compare multiple game-based and conventional movement learning models to determine the most effective strategies for enhancing children's coordination and broader developmental outcomes.

Conclusions

This study highlights the potential of structured, game-based physical activities as a developmentally appropriate approach in early childhood motor coordination programs. Integrating playful elements into movement-based learning may offer pedagogical value by promoting engagement, social interaction, and active participation among children. Such models can be considered in the planning and implementation of physical education curricula in early childhood settings, with attention to age-specific needs and educational objectives.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the research, authorship, or publication of this article.

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Cite this article as:

Masrun, Okilanda A, Khairuddin, Utama J, Putra AR. Learning of gross motor skills based on fun games: a study of coordination development in 5–6-year-old children. *Pedagogy of Physical Culture and Sports*, 2025;29(4):233–242.
<https://doi.org/10.15561/26649837.2025.0401>

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Received: 09.06.2025

Accepted: 14.07.2025; Published: 30.08.2025

Non-pharmacological approach based on physical exercise in the campus environment as a strategy to prevent sedentary lifestyle among university students

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Abstract

Background and Study Aim

Sedentary behavior among university students has become a pressing public health issue that requires innovative and context-specific interventions within the campus setting. One strategic approach to addressing this issue is the implementation of structured, non-pharmacological, exercise-based programs. Therefore, this study aimed to design and evaluate a campus-based, non-pharmacological exercise intervention to prevent sedentary lifestyles among university students.

Material and Methods

A total of 58 university students (26 females and 32 males), aged 18–20 years, participated in this study. All participants completed a 4-week intervention combining aerobic exercise (jogging and power walking) with bodyweight resistance training. Four key indicators, namely physical activity level (PA level), sedentary duration (sitting or lying time), cardiorespiratory fitness (VO₂max), and resting heart rate (resting HR), were measured at baseline (pretest) and after the 4-week intervention (posttest) in both male and female groups. Statistical analysis was conducted using a paired-sample t-test with a significance level of 5%.

Results

Physical activity levels significantly increased between the pretest and posttest by 2,022.75 METs (114.17%) in males and 1,769.08 METs (114.65%) in females. Sedentary duration significantly decreased by 109.22 minutes (–22.65%) in males and 131.58 minutes (–17.73%) in females. VO₂max showed a significant improvement, increasing by 10.09 mL/kg/min (27.43%) in males and 7.81 mL/kg/min (27.50%) in females. Resting heart rate also decreased significantly by 7.32 bpm (–11.32%) in males and 7.26 bpm (–10.29%) in females.

Conclusions

This study demonstrates that a 4-week, non-pharmacological, exercise-based intervention is effective in reducing sedentary behavior and improving key health indicators among university students.

Keywords:

healthy campus environment, healthy lifestyle, physical exercise, university students

Introduction

The global prevalence of sedentary lifestyles, along with associated health risks such as cardiovascular, metabolic, and mental health disorders, has emerged as a major public health concern, particularly among university students [1]. According to data from the World Health Organization [2], 31 percent of adults and 80 percent of adolescents fail to meet the recommended levels of physical activity. Sedentary behavior is defined as any waking activity involving energy expenditure

of 1.5 metabolic equivalents (METs) or less, such as sleeping, sitting, lying down, watching television, or engaging in other screen-based entertainment [3, 4]. Most university students do not meet the WHO physical activity guidelines, with fewer than 10 percent considered active and approximately 40.5 percent classified as highly inactive [5]. As a population undergoing the transition to adulthood [6], students are particularly vulnerable to adopting inactive lifestyles, often driven by academic stress [7, 8], lifestyle changes, and the ease of access to technologies that encourage prolonged sitting [9]. The college years represent a critical period for shaping long-term behavioral patterns that significantly influence the risk of developing chronic diseases later in life [10, 11, 12, 13]. Therefore,

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doi:10.15561/26649837.2025.0402

sedentary behavior among university students should be treated as a serious health issue requiring innovative and context-specific approaches within the campus environment.

Recently, physical inactivity has been widely recognized as a leading risk factor for premature mortality and chronic conditions such as type 2 diabetes, metabolic syndrome, and cardiovascular disease. Additionally, growing evidence suggests that high levels of sedentary behavior negatively impact mental health, increasing the risk of anxiety and depression [14, 15, 16, 17, 18, 19]. Although various studies have confirmed the harmful effects of sedentary behavior [10], most existing preventive interventions remain generalized, lack specificity for student populations, and rarely adopt structured, exercise-based approaches within campus settings [11]. Furthermore, many existing programs focus heavily on pharmacological treatment or theoretical education, without integrating practical physical activities into students' daily routines [12]. These gaps highlight the need for innovative preventive strategies that are physically engaging, contextually relevant, and tailored to meet the specific needs of students, while promoting long-term behavioral change toward an active lifestyle [13].

One strategic approach to addressing sedentary behavior among university students is the implementation of non-pharmacological, exercise-based interventions within the campus environment [20]. Such interventions emphasize the promotion of daily physical activity through simple yet consistent exercise programs that can be seamlessly integrated into academic life [21]. The primary goal of these interventions is to reduce prolonged sitting time, enhance cardiorespiratory capacity, improve body composition, and support mental health through beneficial neurobiological activation [22, 23]. Additionally, the social engagement that emerges from group-based exercise programs has the potential to boost students' intrinsic motivation to maintain an active lifestyle [24]. Several studies have shown that exercise-based interventions are effective in increasing physical activity levels, reducing sedentary time, and producing positive psychosocial outcomes among university students [25, 26, 27].

Analysis of the reviewed studies has shown that structured, non-pharmacological interventions based on physical activity can effectively reduce sedentary behavior and improve key health indicators among university students. The authors emphasize that such interventions are most effective when they are context-specific, seamlessly integrated into academic routines, and promote both individual engagement and social interaction. At the same time, there remains a clear need for further research to explore the long-term sustainability, adaptability, and psychological impact of these

interventions in diverse student populations and educational settings.

Therefore, this study aimed to design and evaluate a campus-based, non-pharmacological exercise intervention to prevent sedentary lifestyles among university students.

Materials and Methods

Participants

This study employed a two-group pre-experimental design using pretest and posttest assessments. A total of 58 participants (32 males and 26 females) were recruited from the Department of Sport Coaching Education, Faculty of Sport and Health Science, Universitas Negeri Surabaya (Indonesia). All participants were recruited using consecutive sampling. All eligible individuals who met the inclusion criteria and volunteered during the data collection period were enrolled in the study. Inclusion criteria included age between 18 and 20 years, body mass index (BMI) between 18.5 and 24.9 kg/m², and absence of any cardiovascular or metabolic diseases. Participants also had no history of smoking or alcohol consumption in the past five years and had not taken any medication in the last three months. All procedures complied with the principles of the Declaration of Helsinki.

Study Design

Both male and female participants underwent a 4-week combined exercise intervention involving aerobic exercise (jogging and power walking) and bodyweight resistance training. Four outcome variables were observed: resting heart rate (resting HR), cardiorespiratory fitness (VO₂max), physical activity level, and sedentary time (sitting or lying duration).

Exercise programs for male and female

The exercise intervention was conducted under the supervision of certified coaches from the Department of Sports Coaching Education to ensure the correct and safe performance of each movement. Participants followed a structured combined exercise program, consisting of aerobic exercise (jogging and power walking) and bodyweight resistance training, four times per week for four consecutive weeks. Sessions were conducted from 06:00 to 07:30 AM at the Universitas Negeri Surabaya Athletic Field. To ensure progressive physiological adaptation, the training program was designed based on the principle of progressive overload. In this approach, the intensity and duration of both aerobic and resistance components were gradually increased each week. This method is widely supported in exercise science as it allows the body to continuously adapt to increasing physical demands. As a result, it enhances cardiorespiratory fitness, muscular strength, and endurance. The

incremental adjustments, which were reflected in training time, repetition schemes, and target heart rates, were structured to avoid plateau and to optimize performance gains throughout the intervention period. Details of the intervention are presented in Table 1.

Data collection methods

Resting heart rate (resting HR) was assessed using the Polar H10 heart rate sensor (Polar Electric, Inc., Bethpage, NY, USA) [28]. Cardiorespiratory fitness (VO₂max) was measured using the 20-meter Multi-Stage Shuttle Run Test [29]. Physical activity

Table 1. Details of the exercise program

Group	Frequency	Intensity	Time	Type	Warm-up	Cooldown
Male and Female	Week 1	85% HRmax	3 sets (15 seconds training and 15 seconds rest) for each movement	Strength training (jumping jacks, plank jacks, burpees, jumping squats, mountain climb)	Dynamic stretching for 5 min	Static stretching for 5 min
		Jogging: 75% HRmax	30 min	Aerobic exercise (5 minutes jogging and 5 minutes power walking) 3 repetitions		
	Week 2	90% HRmax			3 sets (20 seconds training and 20 seconds rest) for each movement	Strength training (jumping jacks, plank jacks, burpees, jumping squats, mountain climbs)
		Jogging: 75% HRmax	40 min	Aerobic exercise (5 minutes jogging and 5 minutes power walking) 4 repetitions		
	Week 3	90% HRmax			3 sets (25 seconds training and 25 seconds rest) for each movement	Strength training (jumping jacks, plank jacks, burpees, jumping squats, mountain climbs)
		Jogging: 75% HRmax	50 min	Aerobic exercise (5 minutes jogging and 5 minutes power walking) 5 repetitions		
	Week 4	95% HRmax			3 sets (30 seconds training and 30 seconds rest) for each movement	Strength training (jumping jacks, plank jacks, burpees, jumping squats, mountain climb)
		Jogging: 75% HRmax	60 min	Aerobic exercise (5 minutes jogging and 5 minutes power walking) 6 repetitions		
	Power walking: 60% HRmax					

level and sedentary behavior (sitting or lying time) were assessed using the Global Physical Activity Questionnaire (GPAQ) from the World Health Organization [30]. All variables were measured at baseline (pretest) and after the intervention period of four weeks in both male and female participants.

Statistical analysis

Descriptive statistics were used to calculate means, standard deviations, and the distribution of the data. The Kolmogorov–Smirnov test was used to assess normality, and Levene’s test was used to assess homogeneity of variance. For normally distributed data, paired sample t-tests were used to evaluate changes between pretest and posttest values. Effect sizes were calculated using Cohen’s d, with values interpreted as small ($d = 0.2$), medium ($d = 0.5$), and large ($d \geq 0.8$). All statistical analyses were conducted using SPSS version 21 (SPSS Inc., Chicago, IL, USA), and the significance level was set at $p < 0.05$. Sample size calculations were performed using G*Power software (Düsseldorf, Germany).

Results

A total of 26 female and 32 male participants voluntarily provided written informed consent and completed the four-week intervention program. The demographic characteristics of the participants

are presented in Table 2. The observed changes in resting heart rate (resting HR), cardiorespiratory fitness (VO_2max), physical activity level, and sedentary time (sitting or lying duration) between pretest and posttest for both sexes are illustrated in Figure 1.

Table 2. Demographic characteristics of study participants

Characteristics	Female (n = 26)	Male (n = 32)
Age (years)	19.00 ± 0.40	19.03 ± 0.31
Height (m)	1.59 ± 0.05	1.70 ± 0.05
Weight (kg)	55.91 ± 6.71	65.34 ± 7.14
Body Mass Index (kg/m ²)	22.02 ± 2.06	22.58 ± 2.08

Note. Data are presented as mean ± standard deviation (SD).

Based on the results of the normality test (Kolmogorov–Smirnov) and homogeneity test (Levene’s), the data showed a normal distribution and homogeneous variance. Therefore, the parametric test could be applied.

As shown in Figure 1, the results of the paired sample t-test indicated a significant reduction in resting heart rate (resting HR) between pretest and posttest in both males (64.63 ± 5.35 vs. 59.75 ± 3.96

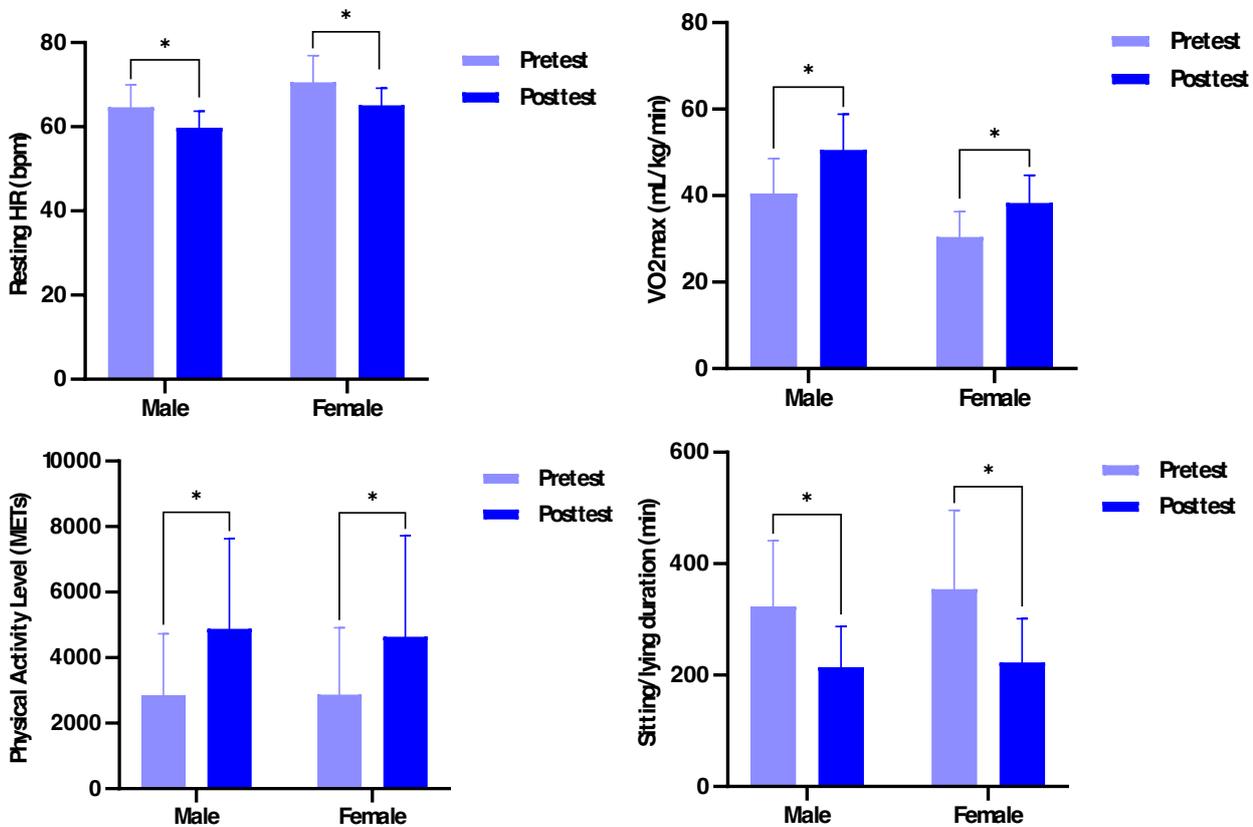


Figure 1. Assessment of Resting HR, VO_2max , Physical Activity Level, and Sitting/Lying Duration Between Pretest and Posttest in Both Sexes. *Significantly different from pretest ($p < 0.001$). p-values were obtained using paired sample t-tests. Data presented as mean ± standard deviation. Effect size calculated using Cohen’s d.

bpm; $p = 0.001$; effect size [ES] = 1.037; 95% CI: 3.64, 6.12) and females (70.54 ± 6.34 vs. 65.12 ± 4.03 bpm; $p = 0.001$; ES = 1.022; 95% CI: 3.43, 7.42). This corresponds to a decrease of 7.32 bpm (a reduction of 11.32 percent) in males and 7.26 bpm (a reduction of 10.29 percent) in females.

Cardiorespiratory fitness, as measured by $VO_2\max$, showed a statistically significant improvement between pretest and posttest for both males (40.49 ± 8.09 vs. 50.58 ± 8.23 mL/kg/min; $p = 0.001$; ES = 1.237; 95% CI: 7.43, 12.75) and females (30.46 ± 5.84 vs. 38.27 ± 6.42 mL/kg/min; $p = 0.001$; ES = 1.272; 95% CI: 5.67, 9.95). $VO_2\max$ increased by 10.09 mL/kg/min (an increase of 27.43 percent) in males and 7.81 mL/kg/min (an increase of 27.50 percent) in females.

Significant increases in physical activity levels were also recorded. Male participants showed an increase from 2855.75 ± 1870.84 to 4878.50 ± 2753.76 METs ($p = 0.001$; ES = 0.859; 95% CI: 1394.92, 2650.58). Female participants increased from 2870.46 ± 2040.55 to 4639.54 ± 3081.11 METs ($p = 0.001$; ES = 0.677; 95% CI: 1038.14, 2500.01). This corresponds to an increase of 2022.75 METs (an increase of 114.17 percent) in males and 1769.08 METs (an increase of 114.65 percent) in females.

Additionally, sedentary time (measured as sitting or lying duration) significantly decreased in both groups. Males reduced from 323.44 ± 117.93 to 214.21 ± 72.92 minutes ($p = 0.001$; ES = 1.114; 95% CI: 64.27, 154.17). Females reduced from 354.08 ± 141.5 to 222.50 ± 78.71 minutes ($p = 0.001$; ES = 1.149; 95% CI: 63.19, 199.96). This represents a reduction of 109.22 minutes (a decrease of 22.65 percent) in males and 131.58 minutes (a decrease of 17.73 percent) in females.

Discussion

This study aimed to design and evaluate a campus-based, non-pharmacological exercise intervention to prevent sedentary lifestyles among university students. The findings demonstrate that a combination of aerobic exercise (jogging and power walking) and bodyweight-based resistance training has a significant impact. It improves cardiorespiratory fitness ($VO_2\max$), lowers resting heart rate, increases daily physical activity, and reduces sedentary time among university students. These results support the effectiveness of non-pharmacological, physical activity-based interventions in the context of a healthy, non-clinical population. This study addresses gaps in the literature, which has predominantly examined aerobic and resistance training separately. In addition, most existing research has focused on clinical populations or individuals with high metabolic risk [31, 32, 33, 34, 35, 36]. By integrating both training modalities into a single protocol and applying it to a student population, this study offers

a more comprehensive experimental approach. It is tailored to the preventive active lifestyle needs of university students. Although combined aerobic and resistance training is not a novel concept, this study distinguishes itself by applying a minimal-equipment protocol within an open-campus setting. It targets healthy students in a real-world university environment.

The significant increase in $VO_2\max$, particularly in the aerobic group, indicates physiological adaptations such as increased stroke volume, muscle perfusion, and oxygenation efficiency [37, 38]. $VO_2\max$ is a key parameter in assessing cardiorespiratory capacity and has been linked to long-term cardiovascular risk and mortality [39]. Interestingly, the resistance training group also exhibited $VO_2\max$ improvements, although to a lesser degree. This finding is consistent with earlier studies suggesting that bodyweight-based resistance exercises can induce sufficient metabolic and neuromuscular stimuli to enhance aerobic capacity, particularly in untrained individuals [40, 41, 42]. The reduction in resting heart rate further reflects increased cardiac efficiency. This is likely due to improved parasympathetic tone, indicating autonomic adaptation to the training program [43, 44].

In addition to physiological responses, the increase in METs scores indicates positive behavioral changes among participants in enhancing daily physical activity. The exercise program designed in this study combines moderate to high intensity with a practical structure. This enables students to engage in activity beyond formal training sessions. Aerobic exercise provides a rhythmic and familiar format that is easy to adopt. Resistance training involves simple but intense movements that target functional strength and muscle capacity [45, 46]. The significant reduction in sedentary time also reflects a shift toward a more active lifestyle among students. This finding supports the meta-analysis by Ekelund et al. [47], which showed that moderate to vigorous physical activity, even in short bouts, can reduce mortality risk associated with prolonged sitting behavior.

The improvements in physical activity levels and reductions in sedentary time observed in this study may be partially interpreted through established behavioral frameworks, although no psychological constructs were directly measured. Self-determination theory (SDT) suggests that when individuals experience autonomy, competence, and relatedness, they are more likely to develop intrinsic motivation for sustained physical activity [48]. The format of the intervention, which was simple, required no equipment, and was conducted in open campus settings, may have supported these needs. It may have done so by fostering a sense of choice, perceived capability, and social engagement.

Similar findings by Li et al. [49] highlight how such motivational contexts can enhance adherence and even cardiorespiratory fitness among college students, although our study did not assess these mediators directly.

In addition, the Theory of Planned Behavior (TPB) provides a complementary perspective. TPB posits that attitudes, perceived norms, and behavioral control predict intentions and subsequent behaviors [50]. While we did not collect data on these specific constructs, the structure of the intervention, with its regular scheduling and group participation, may have influenced students' perceived feasibility and social acceptability of engaging in physical activity. Wang and Kang [51] also emphasize the role of behavioral triggers, such as routine scheduling and peer support, which were embedded in our intervention and may have contributed to beneficial behavioral changes.

The university campus provides a distinct and practical setting for implementing physical activity interventions, particularly for young adults navigating academic and lifestyle transitions. As emphasized by García-Álvarez and Faubel [52], interventions that incorporate social engagement and participatory elements are more likely to encourage sustainable health habits among students. This study followed similar approaches by offering open-space sessions on campus that reduced structural and financial barriers.

Yin et al. [53] also noted the importance of contextual relevance and perceived enjoyment in university HIIT programs. These factors were present in the current intervention through its informal, flexible, and socially supportive design.

In line with broader trends in digital health promotion, the present study, although not incorporating technology directly, reflected essential principles of digital-social models. As demonstrated by Bi et al. [54], interventions that include peer interaction and behavioral cues through digital platforms improve student engagement and physical outcomes. Group-based outdoor sessions in this study may have reproduced some of these motivational effects through visible participation and shared routines.

Social reinforcement and perceived relatedness, as described in both SDT and TPB frameworks, likely contributed to adherence. In addition to behavioral improvements, emerging research highlights the mental and cognitive benefits of combining exercise modalities. Dhahbi et al. [55] reported that aerobic and resistance training support cognitive resilience. Wang et al. [56] found that regular combined training in supportive environments may help reduce depressive symptoms.

Taken together, these insights support the potential of integrated and socially embedded physical activity interventions to promote multiple

benefits for young adult populations in non-clinical academic settings. Such program characteristics may be especially relevant in the post-pandemic academic environment, where promoting physical activity must address increased screen exposure, digital fatigue, and limited social interaction.

From a practical standpoint, the design of this intervention offers flexibility and broad applicability. Activities such as jogging, power walking, and bodyweight resistance training can be performed with minimal infrastructure. This makes the program particularly suitable for institutions with limited resources. The ACSM's position statement affirms that moderate-intensity aerobic and resistance training are sufficient to improve cardiorespiratory, neuromuscular, and functional health in healthy adults [45]. Steele et al. [46] also support the integration of effort-based resistance models in public health programming. These recommendations align with the structure of our intervention and support its relevance, even in resource-limited educational settings. From a methodological perspective, the use of a pre-post experimental design allowed for direct observation of behavioral and physiological change. Furthermore, targeting a healthy young adult population adds a distinct contribution, as most combination training studies have focused on clinical or at-risk groups. This focus provides useful insight into preventive strategies for wider, non-clinical populations within higher education.

Study Limitations

Despite its promising findings, this study has several limitations that should be acknowledged. The absence of a control group limits the ability to attribute the observed changes solely to the intervention, as other external influences may have contributed to the outcomes. Furthermore, the relatively small and demographically homogeneous sample (in terms of age, baseline activity level, and health status) reduces the generalizability of the findings to broader student populations. The short intervention duration of four weeks may also be insufficient to capture long-term physiological adaptations. This is especially relevant for parameters such as VO_2 max and resting heart rate, which usually require extended exposure to demonstrate sustained improvement. In addition, uncontrolled external variables such as diet, sleep patterns, academic stress, and individual motivation could have introduced variability in participant responses. Another limitation lies in the use of self-reported instruments, including the Global Physical Activity Questionnaire (GPAQ), to assess physical activity and sedentary time. Although GPAQ is a widely validated tool, it remains subject to potential recall bias and social desirability effects, which may have led participants to overreport or underreport their actual behaviors.

Future studies would benefit from incorporating objective measures such as accelerometers to improve data accuracy and reliability. To address current limitations, future research should consider including randomized control groups, extending intervention durations, and recruiting more diverse populations across different institutions and activity backgrounds. Further research is also needed to evaluate the long-term sustainability of such interventions and their adaptability across varied demographic and institutional contexts. This should involve the use of randomized controlled designs and extended follow-up periods. In addition, future applications may include integrating structured exercise programs into student health services, academic curricula, or campus wellness policies. Applying mixed-methods approaches may enhance understanding of psychosocial determinants of physical activity. These include habit formation, fatigue perception, and environmental barriers, particularly among university students [57, 58]. Such approaches may help explore the dynamics of student motivation in maintaining participation after the formal intervention period.

Conclusions

This study demonstrates that a short-term,

structured physical activity intervention can lead to measurable improvements in cardiorespiratory fitness and reductions in sedentary behavior among healthy university students aged 18 to 20. While these findings are specific to a relatively homogeneous, non-clinical student population, they suggest that simple and low-cost exercise strategies, when implemented within the campus environment, can be both feasible and effective. Instead of aiming for broad generalization, these results support the development of targeted interventions within educational institutions, particularly in contexts with limited access to fitness infrastructure.

Conflict of Interest

The authors declare that they have no conflicts of interest.

AI Tools Usage

During the preparation of this manuscript, the authors utilized the AI-based tool ChatGPT (OpenAI) to assist in language editing and initial phrasing of certain background sections. The content was subsequently reviewed and revised by the authors to ensure accuracy and originality. No data analysis or interpretation was performed using AI tools. The authors take full responsibility for all content.

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Cite this article as:

Pranoto A, Hidayat T, Witjaksono AD, Muhammad, Subagio I, Kusnanik NW, Siantoro G, Pramono BA, Andriana LM, Orhan BE. Non-pharmacological approach based on physical exercise in the campus environment as a strategy to prevent sedentary lifestyle among university students. *Pedagogy of Physical Culture and Sports*, 2025;29(4):243–252. <https://doi.org/10.15561/26649837.2025.0402>

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Received: 02.06.2025

Accepted: 14.07.2025; Published: 30.08.2025

Evaluating the effect of a 6-week progressive running interval training program on endurance and body mass index in overweight college students

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Abstract

Background and Study Aim The increasing prevalence of overweight and obesity among university students has emerged as a notable public health concern. This trend is exacerbated by sedentary academic settings and a lack of time-efficient fitness programs. Thus, this study aimed to evaluate the effectiveness of a 6-week progressive running interval training (PRIT) program on endurance and body mass index (BMI) among overweight college students.

Material and Methods A total of 30 students (BMI \geq 25), aged 18–21 years, were randomly assigned to either an experimental group (n = 15), which engaged in thrice-weekly PRIT sessions supplemented with strength-endurance circuits, or a control group (n = 15), which did not participate in any organized physical training. Statistical analyses included paired and independent samples t-tests. The significance threshold was established at $p < .05$.

Results Post-test results demonstrated a significant increase in the training group across all assessed variables. Improvements in upper body, lower body, and core endurance were all statistically significant ($p < .001$). Moreover, a significant decrease in BMI was observed ($p < .001$). The control group showed minimal changes. These findings confirm the effectiveness of PRIT in improving endurance and reducing BMI within a brief intervention period.

Conclusions The results confirm the efficacy of the progressive running interval training (PRIT) program in enhancing endurance and reducing BMI over a short intervention period. This supports the integration of scalable, evidence-based interval training into campus wellness programs to improve student health, physical performance, and academic outcomes.

Keywords: endurance, body mass index, running interval training, overweight, college students

Introduction

The growing prevalence of overweight and obesity among university students has become a significant public health concern. This is especially true in academic environments where sedentary behaviors, poor dietary habits, and physical inactivity are increasingly normalized. Excess body weight compromises physical health and adversely influences academic achievement [1, 2], self-esteem [3, 4], and social engagement [5, 6, 7]. Despite widespread awareness of these consequences, many higher education institutions still lack structured, accessible, and time-efficient fitness programs specifically designed for overweight students [8, 9,

10]. Current health interventions often fail to meet the complex needs of this population. This may be due to inadequate intensity, limited progression, or poor integration with broader wellness initiatives [11, 12]. These issues highlight a critical gap in preventive strategies that are both feasible and sustainable within the academic environment.

One promising approach is progressive running interval training (PRIT), a scalable and structured training method that builds upon the core principles of high-intensity interval training (HIIT) [13, 14, 15]. Both PRIT and HIIT aim to improve aerobic and muscular endurance through intermittent bursts of effort followed by active recovery [16, 17, 18]. These modalities have consistently shown benefits across populations, including improvements in VO_2 max, cardiorespiratory fitness, and metabolic health [13, 14, 15, 16]. For overweight individuals, HIIT

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doi:10.15561/26649837.2025.0403

protocols have demonstrated reductions in body fat percentage and BMI over short durations, typically between six and eight weeks [19, 20, 21]. PRIT specifically has been recognized for its adaptability and progressive intensity. This makes it suitable for individuals with low baseline fitness. However, current literature predominantly examines these outcomes in general adult populations or athletes. Often, studies do not isolate the effects of such interventions in overweight university students, a group with unique psychological, academic, and behavioral demands [22, 23, 24].

Moreover, the potential advantages of progressive training programs, particularly those focused on running, in improving cardiovascular health, physical performance, and long-term fitness development are becoming more widely acknowledged [25, 26, 27]. Running activities, particularly those employing interval formats, have demonstrated significant enhancements in VO_2 max, lactate threshold, and overall movement economy. These elements are essential for both athletic and functional performance [28, 29]. Particularly, research by Michaelides et al. [30] indicated that college soccer players who participated in an eight-week interval running program greatly improved their aerobic capacity and ability to sprint repeatedly. This helped them sustain performance longer during games. Likewise, team sports players have shown improvements in explosive power and agility after engaging in progressive sprint interval training. This affirms its contribution to enhanced court performance [31, 32, 33]. In volleyball, structured running combined with plyometric training has demonstrated the ability to enhance jump height and reduce lower limb injury risks [34, 35]. In addition to competitive athletics, interval running has proven effective in improving BMI, muscular endurance, and metabolic indicators in sedentary or overweight college students [14, 36].

Furthermore, existing studies frequently overlook the integration of strength-endurance components with running-based interventions. These components may enhance training outcomes and adherence [37, 38]. While some evidence supports the use of school-based HIIT or interval programs to boost cardiovascular fitness and muscular endurance [38, 39, 40], limited research has focused on combining progressive running intervals with supplementary bodyweight strength circuits in an academic context. Moreover, few studies employ rigorous experimental designs to examine the short-term effects of such interventions, particularly over six weeks, on both endurance and BMI outcomes in overweight college students.

Thus, this study aimed to evaluate the effectiveness of a 6-week progressive running interval training (PRIT) program on endurance and body mass index (BMI) among overweight college students.

Materials and Methods

Participants

A priori power analysis was conducted using G*Power (version 3.1.9.7) for a two-tailed independent samples t-test. The analysis specified an alpha level of 0.05, power of 0.80, and a medium to large effect size ($d = 0.65$). It indicated that a minimum total sample size of 30 participants (15 per group) would be sufficient to detect statistically significant differences between groups. The study involved 30 overweight college students ($BMI \geq 25$), aged 18 to 21 years ($M = 19.33$, $SD = 0.72$), enrolled during the academic year 2024 to 2025. A purposive sampling approach was initially used to identify eligible participants based on predetermined inclusion criteria. These included: (1) classified as overweight according to World Health Organization (WHO) BMI standards, (2) enrolled as full-time college students, (3) medically cleared for moderate to vigorous physical activity, and (4) provided written informed consent. Following this, eligible participants were assigned to either the training group ($n = 15$) or the control group ($n = 15$) using a computer-generated randomization process to ensure unbiased group allocation.

Each participant completed a brief health and fitness assessment questionnaire before group assignment. The questionnaire included demographics, physical activity level, and history of illness or sports injuries. For safety and ethical compliance, the study excluded participants with chronic medical illnesses, metabolic or cardiovascular disease, or orthopedic injuries that could worsen with moderate to strenuous physical activity. Only cleared participants who provided written informed consent were admitted to the study. Individuals who met the inclusion criteria were randomly assigned to either the training group ($n = 15$), which engaged in the six-week running interval program, or the control group ($n = 15$), which did not undergo any structured exercise intervention. The following characteristics of the participants are shown in Table 1.

This study adhered strictly to ethical research standards prior to the start of the experiment. Participants were thoroughly informed of the research objective, and formal informed consent was obtained from every participant. The researchers outlined the prospective advantages of the study for the institution, the wider community, and the progression of scientific understanding. Participants were guaranteed that the data gathered would not be used in any subsequent study activities. They were also informed that their decision to withdraw from the study at any time would not affect their relationship with the researchers or the affiliated institutions. It would also not influence their access to current or future services. To maintain confidentiality and

anonymity, all identifying information was omitted during the processes of data collection, analysis, and distribution of findings. Participants were given the option to request a debriefing session or to withdraw at any time.

Study Design

This study employed a quasi-experimental pretest-posttest control group design over a six-week duration. After obtaining ethical approval and informed consent, participants were screened using a health and fitness questionnaire. The screening assessed eligibility based on BMI classification, age, and medical history. Participants who satisfied the inclusion criteria and received medical clearance for physical activity were randomly assigned to either the training group (experimental) or the control group.

The training group participated in a six-week progressive running interval program, held three times weekly. Each session lasted about 30 to 45 minutes and included a standardized warm-up and cool-down phase. The training structure and progression followed the protocol specified in Table 2. This table outlines the running intervals, set durations, intensity levels, and targeted endurance components for each two-week phase. The program aimed to incrementally challenge participants' cardiovascular and muscular endurance, prioritizing safety and gradual adaptation. In addition, the group performed complementary strength-endurance circuits twice a week. These circuits included dynamic bodyweight exercises, as shown in Table 3.

The control group did not undergo any structured fitness intervention. They were instructed to maintain their regular daily routines while avoiding the initiation of any new physical training programs during the six-week intervention period. To ensure compliance, participants were required to submit weekly physical activity logs. These logs recorded the duration and type of daily activities, including walking, commuting, screen time, and any form of recreational exercise. For three non-consecutive days per week, including one weekend day, participants used basic step-tracking devices such as pedometers, smartphone fitness apps like Google Fit and Apple Health, or digital wristbands with step-counting features. These tools objectively monitored their activity levels. Step count estimates were recorded and reported to the researchers weekly to ensure low to moderate activity during the intervention.

After six weeks, all participants completed post-test assessments that matched the pretests to evaluate changes in endurance and BMI. All testing procedures were standardized. Data collection was conducted under consistent environmental conditions to reduce external influences. Facilitators with training oversight monitored each session to ensure participant safety, adherence to the training protocol, and consistency in the execution of the intervention.

Statistical Analysis

All statistical analyses were performed using SPSS version 20. Descriptive statistics, including means, standard deviations, and frequencies, were

Table 1. Demographics of the participants

Demographic Variable	Training Group (n=15)	Control Group (n=15)
Male	5	6
Female	10	9
Age	19.33 ± .723	19.07 ± 1.03
Height (cm)	160.27 ± 4.46	162.33 ± 4.72
Weight (kg) before training	67.73 ± 2.86	68.80 ± 4.23
BMI (kg/m ²) before training	26.38 ± .941	26.11 ± 1.23

Table 2. Progressive Running Interval Training Program

Phase	Description	Interval Structure	Targeted Structure	Intensity and Rest
Weeks 1-2	Foundation Phase (build aerobic base)	3-4 sets of: 2 min light jog + 1 min walk	Core endurance (posture, rhythm, breathing)	60-65% HRmax Rest: 2 min between sets
Weeks 3-4	Development Phase (increase volume and tempo)	4-5 sets of: 3 min moderate run + 30 sec walk	Lower and upper body endurance (stride control, arm drive)	70-75% HRmax Rest: 90 sec between sets
Weeks 4-6	Performance Phase (add speed bursts and recovery)	5-6 sets of: 1.5 min fast run + 30 sec jog + 1 min walk	Full-body endurance (speed, posture, recovery capacity)	80-85% HRmax Rest: 1-2 min between sets

Table 3. Complementary Strength endurance circuits

Test Variables	Specific Exercise	How to Execute	Sets x Reps / Time	Target Benefit
Upper Body Endurance	Shadow Boxing with Footwork	Stand in a guard position and throw punches (jab, cross) while moving from side to side. Stay light on your feet and move quickly.	3 x 30 seconds	Cardio, arms, shoulders, and coordination
	Bear Crawls (Forward and Back)	Get on all fours, with your knees hovering. Then, crawl forward with your right hand and left foot, and then backward.	3 x 20 seconds	Endurance in the shoulders and arms, stability in the trunk
Lower Body Endurance	Squat Jumps / Bodyweight Squats	Stand up, kneel down, and then jump up. Land carefully back into the squat. Take out the jump for less effect.	3 x 10–12 reps	Leg strength, explosive endurance
	High Knees (Jog or March in Place)	Quickly pull your knees to your chest while pumping your arms on each side. For a low-impact version, march in place.	3 x 30 seconds	Endurance in the heart and lungs, flexibility in the hips
Core Endurance	Mountain Climbers	While in plank position, switch driving knees toward the chest. Keep the beat constant. If you need to, slow down.	3 x 20–30 seconds	Core engagement, shoulder support, and cardio
	Standing Oblique Knee Drives	Put your hands behind your head and twist your torso to bring one knee up to the same-side elbow. Switch sides.	3 x 20 reps (10/side)	Obliques, balance, and trunk control

calculated to summarize participant demographics and test outcomes. To evaluate within-group changes from pretest to posttest, paired samples t-tests were used. Between-group differences were analyzed using independent samples t-tests. For each t-test, effect sizes were computed using Cohen’s d, and 95% confidence intervals (CIs) were reported to provide estimates of the precision and magnitude of observed effects. Before conducting parametric tests, the assumptions of normality and homogeneity of variance were assessed. Normality of the data was examined using the Shapiro–Wilk test, and homogeneity of variance was tested using Levene’s test. All variables met the assumptions for t-test procedures, justifying the use of parametric analyses. A significance level of $p < .05$ was used for all inferential tests. Wherever applicable, exact p-values are reported. Values below .001 are denoted as $p < .001$ only when software output does not provide greater precision.

Results

Independent samples t-tests confirmed that there were no significant baseline differences between the training and control groups across all variables, indicating group equivalence prior to the intervention (Table 4). For example, upper body endurance scores were comparable ($t = 0.425, p = .674$), as were values for lower body endurance, core endurance, and BMI. All showed non-significant differences with small effect sizes. These findings support the initial homogeneity of the groups and justify the validity of subsequent comparisons.

Post-test independent samples t-tests revealed significant differences between the training and control groups across all measured outcomes, with the training group demonstrating substantially greater improvements (Table 5). Specifically, participants in the intervention group outperformed their counterparts in upper body, lower body, and core endurance, as well as in BMI reduction. All comparisons yielded $p < .001$. For example, the largest mean difference was observed in lower body endurance ($t = 16.362$), followed by core endurance ($t = 14.871$), upper body endurance ($t = 12.096$), and BMI ($t = 5.337$). These results provide strong evidence of the effectiveness of the progressive running interval training program in enhancing muscular endurance and improving body composition among overweight college students.

Table 6 summarizes the within-group comparisons using paired samples t-tests. The training group exhibited significant improvements across all measured variables after the six-week PRIT program. These improvements were accompanied by large effect sizes and narrow confidence intervals, supporting the robustness of the findings. Notable gains were observed in upper, lower, and core endurance (all $p < .001$), alongside a significant reduction in BMI ($t = -10.554, p < .001, 95\% \text{ CI } [-3.004, -1.989]$). In contrast, the control group showed only marginal pre-to-post improvements, with small effect sizes and relatively minor changes in endurance and BMI. Although some changes reached statistical significance (e.g., $p = .028$ to $.006$), their magnitude was considerably lower than

Table 4. Pre-test scores for both training and control groups

Test Variables	TRg M ± SD	CTg M ± SD	t-value	p-value	Mean Difference	95% CI
Upper Body Endurance	5.73 ± .88	5.867 ± .83	.425	.674	.133	-.509 - .776
Lower Body Endurance	4.80 ± .68	5.13 ± .64	1.387	.176	.333	-.159 - .826
Core Endurance	4.87 ± .74	4.60 ± .632	-1.058	.299	-.267	-.783 - .249
Body Mass Index	26.38 ± .94	26.11 ± 1.23	-.685	.499	-.274	-1.095 - .546

Note: TRg- training group; CTg- control group; M- mean; SD- standard deviation

Table 5. Post-test Scores for both training and control groups

Test Variables	TRg M ± SD	CTg M ± SD	t-value	p-value	Mean Difference	95% CI
Upper Body Endurance	8.67 ± .49	6.27 ± .59	12.096	<.001	2.400	2.806 – 1.994
Lower Body Endurance	9.40 ± .63	5.67 ± .62	16.362	<.001	3.267	4.201 – 3.266
Core Endurance	8.47 ± .52	5.20 ± .68	14.871	<.001	3.733	3.717 – 2.817
Body Mass Index	23.89 ± 1.77	25.98 ± 1.28	5.337	<.001	1.645	1.013 – 2.276

Note: TRg- training group; CTg- control group; M- mean; SD- standard deviation

Table 6. Paired Sample T-test for both training and control groups of college students

Parameters	Pretest M ± SD	Posttest M ± SD	t-value	p-value	95% CI
Upper-Body Endurance					
Control Group	5.867 ± .83	6.27 ± .59	2.449	.028	.050 - .75
Training Group	5.73 ± .88	8.67 ± .49	10.330	<.001	2.324 - 3.542
Lower-Body Endurance					
Control Group	5.13 ± .64	5.67 ± .62	3.228	.006	.179 - .87
Training Group	4.80 ± .68	9.40 ± .63	19.572	<.001	4.096 - 5.104
Core Endurance					
Control Group	4.60 ± .632	5.20 ± .676	3.154	.007	.192 - 1.008
Training Group	4.87 ± .74	8.47 ± .52	16.837	<.001	3.141 - 4.059
Body Mass Index					
Control Group	26.11 ± 1.23	25.98 ± 1.28	-2.642	.019	-.231 - -.024
Training Group	26.38 ± .942	23.89 ± .765	-10.554	<.001	-1.989 – -3.004

that of the training group. These results reinforce the conclusion that the observed improvements were primarily driven by the structured intervention rather than natural variability or incidental activity.

Discussion

This study examined the effects of a six-week progressive running interval training (PRIT) program on endurance and BMI among overweight college students. The findings demonstrated that participants in the training group experienced significant improvements in upper body, lower body, and core endurance, along with a notable reduction in BMI. These results provide empirical support for the utility of structured, time-efficient interventions in improving fitness and body composition among students who are typically underserved by traditional university wellness programs.

The observed improvements in endurance align

with previous studies highlighting the efficacy of interval training in enhancing aerobic and muscular performance [14, 41]. However, unlike many existing interventions that focus on either continuous training or athletic populations, this study applied a structured PRIT protocol tailored specifically to overweight college students. Notably, while most literature reports HIIT's effectiveness in general or athletic populations [42], fewer studies have explored such interventions in overweight student cohorts using strength-endurance complements. This targeted approach contributes to a growing yet still limited body of research focused on scalable fitness solutions within academic environments. One point of contrast arises from studies suggesting that short-term interventions may produce inconsistent or unsustainable results, particularly when factors such as participant adherence, training intensity, or motivational support are not adequately addressed.

For example, Bellicha et al. [20] concluded in their meta-analysis that while exercise training can result in weight loss and improved fitness in individuals with obesity, the outcomes tend to vary widely across short-term programs, especially when supervision is limited or sessions are not progressively structured. Similarly, Baillot et al. [10] found that individuals with overweight or obesity often experience low adherence to physical activity programs due to early fatigue, perceived difficulty, or lack of motivational reinforcement. This was echoed by Oppert et al. [21], who emphasized the importance of behavioral support mechanisms in sustaining physical activity engagement in weight management contexts.

In contrast, other studies have found outcomes similar to the present research. For instance, Sonchan et al. [14] and Hu et al. [9] reported significant improvements in cardiovascular fitness and BMI following short-duration interval training among university students. These findings highlight the potential of time-efficient interventions when combined with adequate progression and participant supervision. Ramos-Campo et al. [43] also reported that structured resistance circuit-based interventions can significantly improve both aerobic capacity and body composition over brief periods, particularly when integrated into participants' daily routines.

The current study's high compliance rate and notable improvements may be attributed to its gradual progression in intensity, incorporation of bodyweight strength circuits, and alignment with student schedules. These features may have enhanced both feasibility and engagement. This contrasts with interventions that apply fixed high-intensity protocols without accounting for participant fitness levels or preferences, which often lead to early dropout or minimal gains [5, 44]. Moreover, the blend of aerobic and functional exercises in this study likely improved exercise variety and reduced monotony, which is known to support adherence [45]. These findings underscore the importance of tailoring interventions not only to physiological capacity but also to the psychosocial context of the target population.

The results of this study have substantial implications for educational practice and health promotion, particularly in the context of increasing obesity rates and physical inactivity among college students. The six-week progressive running interval training (PRIT) program was effective in improving endurance and lowering body mass index (BMI). These findings suggest that structured, time-efficient, and accessible fitness programs can help overweight individuals improve their overall health and physical performance. For educational institutions, this implies that PRIT can be integrated into physical education classes or campus wellness programs to help students maintain lifelong fitness,

counteract sedentary behavior, and enhance both physical and mental well-being, which may positively affect academic performance. Additionally, the program offers student-athletes a beneficial off-season or supplementary training method that improves cardiovascular endurance, core strength, and body composition – key elements in injury prevention and athletic readiness. Furthermore, the implementation of evidence-based interventions aligns with global health priorities, particularly those outlined by the World Health Organization (WHO), which emphasize physical activity as a strategy to prevent non-communicable diseases.

In light of these findings, it is recommended that colleges and universities institutionalize structured exercise programs, such as PRIT, within general health curricula or extracurricular offerings. Health educators and fitness professionals may also consider adapting similar progressive training methods for diverse populations, including students with varying fitness levels or health-related risks. Future studies could examine long-term compliance, psychological outcomes (e.g., motivation, self-efficacy), and the effects of integrating PRIT with nutritional interventions to optimize health outcomes. Expanding this research to include various demographic groups and testing its applicability in mixed or remote learning environments may yield valuable insights for broader implementation.

Study Limitations and Directions for Future Research

The current study provides significant insights into the advantages of a six-week progressive running interval training (PRIT) program; however, it has certain limitations. First, the study involved a relatively small sample size of 30 participants, potentially limiting the generalizability of the findings to larger populations. The participants were overweight college students from a single institution, further restricting the applicability of the results to broader age groups, activity levels, or individuals with varied health conditions. The study utilized BMI as the primary measure of body composition, which, although commonly employed, does not differentiate between fat mass and lean mass. More precise metrics, such as body fat percentage or waist-to-hip ratio, could offer a more comprehensive understanding of the physical changes resulting from the intervention. Second, the intervention lasted only six weeks. While this duration was sufficient to observe notable improvements in endurance and BMI, it remains uncertain whether these benefits are sustainable over the long term without continued training. Moreover, the study did not assess psychological characteristics such as motivation, enjoyment, or adherence, which may influence the long-term efficacy and feasibility of the intervention in real-world settings. Future

research should include longitudinal designs with larger and more diverse populations to improve the generalizability of findings. Incorporating detailed body composition assessments and physiological indicators (e.g., VO_2 max, lactate threshold) would enhance understanding of the mechanisms driving observed changes. Subsequent studies may also explore the integration of nutritional monitoring, behavioral coaching, or digital tools (e.g., fitness applications, wearable trackers) to promote adherence and optimize outcomes. Ultimately, examining the psychological and academic impacts of structured exercise programs may provide a more holistic understanding of the role of physical fitness in student success and well-being.

Conclusions

This study provides concrete evidence that a six-week progressive running interval training (PRIT) program, combined with functional strength-endurance exercises, can significantly improve upper, lower, and core muscular endurance while reducing BMI in overweight college students. Unlike many existing interventions, this program was specifically designed to align with the physical capabilities and time constraints of university students with excess body weight, demonstrating

both effectiveness and feasibility in a campus setting. The study's key contribution lies in its integration of progressive aerobic and bodyweight circuits into a time-efficient format that produced measurable physiological benefits within a short duration. These findings highlight the value of customized, low-cost training strategies for addressing sedentary lifestyles in higher education institutions, particularly where access to formal fitness resources may be limited. In addition to confirming health improvements, the study emphasizes the importance of structured, scalable programs that account for the motivational and logistical barriers commonly faced by overweight students. Institutions may consider adopting similar interventions as part of campus wellness programs, physical education curricula, or extracurricular health initiatives to promote long-term student well-being and academic performance. Future research should examine the sustainability of these gains, their psychological impacts, and potential adaptations for diverse student populations.

Conflict of interests

The authors declare that there is no conflict of interests.

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Cite this article as:

Longakit J, Fajardo RA, Coming L, Toring-Aque L, Aque FJ, Villaganas EJ, Bagayas JC, Cuya M, Cordova AJ. Evaluating the effect of a 6-week progressive running interval training program on endurance and body mass index in overweight college students. *Pedagogy of Physical Culture and Sports*, 2025;29(4):253–262. <https://doi.org/10.15561/26649837.2025.0403>

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Received: 08.06.2025

Accepted: 12.07.2025; Published: 30.08.2025

Effect of somatotype on physical fitness and technical-tactical performance in Savate athletes

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Abstract

Background and Study Aim Individualized training programs based on morphological characteristics are increasingly applied in combat sports. However, the influence of somatotype-specific training on physical and technical-tactical performance in French boxing Savate has not yet been analyzed in detail. The purpose of this study was to assess the influence of athletes' somatotype on physical fitness and technical-tactical effectiveness.

Material and Methods Twenty-four male athletes aged 15–17 were divided into three somatotype groups: ectomorphs, mesomorphs, and endomorphs (n = 8 per group). Over a 12-week period, each group followed a training program adapted to their somatotype. Performance was assessed using the Punch Power Test, Footwork Test, and expert ratings of punch accuracy, combination rate, and tactical literacy.

Results The ectomorph group showed a 21% increase in punch power. The mesomorph group improved in punch accuracy (+13%) and punch power (+18%). The endomorph group demonstrated the greatest gains in endurance (Footwork Test: +16%), tactical effectiveness (+12%), and combination execution (+23%). Statistically significant differences were observed between the groups ($p < 0.05$).

Conclusions Somatotype has a measurable impact on the development of physical and technical-tactical performance. Individualized training programs based on somatotype enhance training outcomes and are recommended for implementation in sports schools and boxing academies.

Keywords: training process, physical fitness, technical- tactical effectiveness, somatotype, combat sports, individualization

Introduction

Individualization of training has become a central paradigm in optimizing performance across various combat sports. While generalized programs may be sufficient for beginners, advanced athletes benefit more from training models adapted to their unique physiological and morphological characteristics. Among these characteristics, somatotype is a classification of body build based on structural composition. It is often used as a practical tool for performance profiling and training design. In this context, technical-tactical effectiveness refers to the athlete's ability to select and execute appropriate actions during combat, based on timing, accuracy, decision-making, and the efficient use of offensive and defensive maneuvers.

Although previous studies in boxing and MMA have linked somatotype to performance outcomes such as strength and endurance [1, 2, 3, 4], they offer limited insight into sport-specific adaptations. These disciplines differ substantially from Savate in

terms of technical complexity, movement structure, and tactical rhythm. Furthermore, the role of morphological traits in shaping training responses beyond general conditioning has not been examined in detail, particularly in relation to technical-tactical performance. For example, athletes with ectomorphic characteristics tend to perform well in agility-based tasks, mesomorphic athletes often excel in explosive movements, and endomorphic athletes typically demonstrate advantages in sustained effort and endurance [3, 4, 6]. Despite the distinct physical and technical demands of Savate, the use of somatotype-based training approaches in this sport has not yet been systematically addressed. Existing studies have focused primarily on general conditioning or technical development [7, 8], with little attention to morphological profiling as a foundation for individualized training strategies. While somatotype-based recommendations have been proposed in other combat sports, their applicability to French boxing Savate remains uncertain. It can be assumed that this study represents one of the few existing attempts to evaluate the effects of somatotype-specific training

on both physical and technical-tactical performance in adolescent Savate athletes.

Analysis of previous studies indicates that somatotype-based approaches have shown potential in improving specific aspects of physical performance in combat sports. Several authors have emphasized the relevance of individual morphological characteristics when designing training programs, particularly in disciplines such as boxing, taekwondo, and MMA. These studies have demonstrated that tailoring training to somatotype can enhance outcomes related to strength, agility, and endurance. However, there remains a clear need for further research to examine whether these benefits extend to sports with different technical and tactical demands, such as French boxing Savate.

Despite encouraging results in related disciplines, somatotype-based training has not yet been investigated within the specific context of French boxing Savate. Existing studies have largely focused on general conditioning and physical profiling, without examining how morphological differences influence technical-tactical development. Furthermore, most available research lacks sport-specific intervention models or fails to account for the distinct biomechanics and pacing structure of Savate. This gap limits the current understanding of how individualized programming based on body type could be optimized in this discipline.

To address this gap, it was hypothesized that adolescent Savate athletes with different somatotypes would exhibit distinct adaptations in physical and technical-tactical performance when exposed to individualized training. To test this hypothesis, the present study assessed the influence of athletes' somatotype on physical fitness and technical-tactical effectiveness.

Materials and Methods

Participants

Twenty-four male adolescents (age: 16.1 ± 0.7 years; height: 172.8 ± 6.2 cm; body mass: 61.3 ± 5.8 kg) voluntarily participated in this study. All participants had been training regularly in French boxing Savate for at least 12 months and were members of regional youth teams in western Ukraine. Their average training experience was 2.3 ± 0.6 years. Participants were categorized into three equal groups using the Heath-Carter anthropometric method [9]. Classification into ectomorph, mesomorph, or endomorph categories was determined by the dominant somatotype component, defined as a difference of at least 1.0 point compared to the other two components, based on standardized calculation formulas. Each group consisted of eight athletes:

- Group 1 (Ectomorphs), $n = 8$

- Group 2 (Mesomorphs), $n = 8$
- Group 3 (Endomorphs), $n = 8$.

Exclusion criteria included any acute or chronic injury, illness, or failure to attend more than 10% of scheduled training sessions during the study period.

Informed consent was obtained from all participants and their parents or legal guardians. The study protocol was approved by the Ethics Committee of Lesya Ukrainka Volyn National University (Protocol No. 01/24, March 10, 2024) and complied with the principles of the Declaration of Helsinki (2008 revision). All data were anonymized and stored in encrypted digital format accessible only to the research team.

Study Design

This 12-week intervention study aimed to assess the influence of somatotype-specific training on physical and technical-tactical performance in adolescent Savate athletes. All participants underwent pre- and post-intervention testing under standardized conditions. Training sessions were held three times per week (90 minutes each) and divided into four structured blocks: general physical preparation, strength and power development, technical-tactical drills, and cool-down.

Each group followed a training program tailored to their morphological and functional characteristics (ectomorph, mesomorph, or endomorph), while the session structure remained consistent across groups. Training adaptations were monitored using heart rate recovery and sessional RPE. All training and testing procedures were conducted under the supervision of certified Savate coaches.

No participants withdrew from the study, and no adverse events were reported throughout the intervention period.

Anthropometric Assessment and Group Assignment

Anthropometric measurements included height (SECA 213 stadiometer), body mass (Tanita BC-545N analyzer), and skinfold thickness at seven anatomical sites using Harpenden calipers. Somatotype classification was calculated using standardized Heath-Carter equations [9].

Participants were grouped a priori into three equal groups ($n = 8$ per group) based on dominant somatotype component (≥ 1.0 point difference). Randomization was not applied, as the research focus required grouping by morphological characteristics to evaluate somatotype-specific responses. All measurements were performed by certified sports scientists specializing in anthropometry and morphology.

A non-individualized control group was not included due to both conceptual constraints and the limited number of qualified Savate athletes available in Ukraine. Instead, the study adopted a comparative structure, enabling analysis of intergroup differences without a standard control.

Training Protocol

Each session included the following components:

1. General Physical Preparation (20 min)
2. Strength and Power Development (25 min)
3. Technical-Tactical Drills (30 min)
4. Cool-down and Recovery (15 min).

Training loads and exercise content within these blocks were individualized for each somatotype group and progressively adapted every 4 weeks. The conceptual rationale for this structure is illustrated in Figure 1, which outlines how somatotype influences training variable selection, adaptation processes, and performance outcomes. Specific details of load, exercise type, and progression schemes are outlined in Tables 1 and 2.

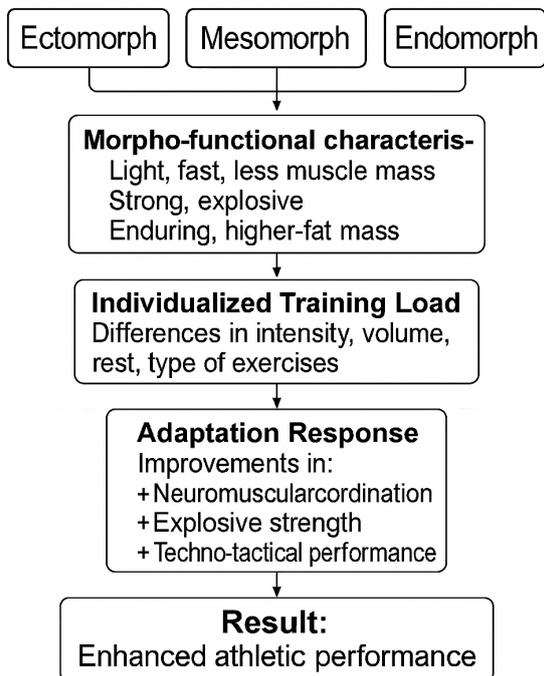


Figure 1. Conceptual model of somatotype-based adaptation

The progression parameters were deliberately differentiated across somatotypes to reflect their unique physiological profiles. Ectomorphic athletes initiated earlier neuromuscular adaptation phases. Mesomorphic athletes responded best to early high-intensity loads. Endomorphic athletes showed

optimal responses to gradual increases in training volume and reduced rest intervals. This structure ensured load specificity and appropriateness relative to individual capabilities.

The emphasis on metabolic conditioning for endomorphs is consistent with prior findings on effective training strategies for athletes with higher fat mass in striking sports [10].

Training loads were adjusted weekly based on athlete feedback and readiness monitoring, including heart rate recovery and ratings of perceived exertion (RPE). A detailed breakdown of the training content by somatotype is presented in Table 2.

Testing Procedures and Performance Indicators

Performance was assessed before and after the training intervention using both physical and technical-tactical tests. Testing was conducted in a controlled environment (temperature: 20–22°C; time: 10:00–12:00; ≥24h post-training), following a standardized dynamic warm-up.

Explosive Strength

- **Punch Power Test:** Maximum punch force (N) was measured using a SportTech impact platform (custom-manufactured in Ukraine). Athletes performed three straight punches with their dominant hand. The highest force value was recorded.

Foot Speed and Agility

- **Footwork Test:** Conducted on a 9-m equilateral triangle. Time was measured with a Smart Speed Lite photocell system (Australia). The fastest of three trials was used.

Technical and Tactical Effectiveness

- **Punch Accuracy:** Percentage of hits landed during mitt drills (3 × 30 s rounds).
- **Combination Rate:** Number of techniques executed in 30 seconds during standardized drills.
- **Tactical Performance Rating:** Coaches rated 60-second sparring videos using a 5-point scale (criteria: timing, distance, decision-making). Inter-rater reliability was high (ICC = 0.91).

Equipment and Testing Conditions

- **Punch force** was assessed using a calibrated SportTech pressure platform (±2 N accuracy).

Table 1. Individualized training components by somatotype

Somatotype	Primary Focus	Key Features
Ectomorphs	Neuromuscular coordination and speed	Plyometric training (3 × 8), ladder drills, and low-load explosive strength work at 40–60% 1RM (3 × 10–12 reps). Progression included intensity increases every 4 weeks and greater drill complexity in weeks 9–12.
Mesomorphs	Explosive power and technique stability	Heavy resistance exercises at 70–85% 1RM (3 × 6 reps), with complex technical combinations under fatigue. Progression included compound lifts and increased tactical variability during weeks 5–12.
Endomorphs	Metabolic conditioning and endurance	Circuit training with short rest (3 rounds × 30 seconds), interval footwork drills, and extended technical combinations. Progression included reduced rest intervals and increased total volume every 4 weeks.

Table 2. Individualized training program structure by somatotype

Training Block	Ectomorphs	Mesomorphs	Endomorphs
1. General Physical Preparation (20 min)	Dynamic mobility, light running, coordination ladders (3 × 20 m). <i>Progression:</i> Increased speed and ladder complexity weekly.	Mobility drills, skipping rope, dynamic stretching (3 × 2 min). <i>Progression:</i> Reduced rest intervals over time.	Brisk walking, full-body warm-up circuits (2 rounds). <i>Progression:</i> Circuit duration increased from 5 to 8 min.
2. Strength / Power Development (25 min)	Plyometric drills, medicine ball throws, low-load resistance training at 40–60% 1RM (3 × 10–12 reps). <i>Progression:</i> Load increased by 5% every 4 weeks.	Heavy squats, bench press, resistance jumps (3 × 6 at 70–85% 1RM). <i>Progression:</i> Volume increased during weeks 5–8.	Circuit training with bodyweight and resistance exercises (3 rounds × 30 s per station, 15 s rest). <i>Progression:</i> Reduced rest intervals and increased tempo.
3. Technical-Tactical Drills (30 min)	Short punch–kick combinations, speed pad drills (3 × 2 min, 3 × 30 s on / 30 s off). <i>Progression:</i> Longer combinations and reaction-based cues introduced.	Complex combinations under fatigue, defense-to-attack transitions (3 × 2 min). <i>Progression:</i> Additional pressure situations introduced in weeks 9–12.	Repeated long combinations, partner-based drills (2 × 3 min). <i>Progression:</i> Defensive reaction tasks added in the second half of the program.
4. Cool-down and Recovery (15 min)	Foam rolling, breathing exercises, static stretching (2 × 30 s per muscle group). <i>Progression:</i> gradual increase in breathing duration and stretch hold times across weeks.	Static stretching and contrast showers (3 × 30 s). <i>Progression:</i> Duration or complexity of recovery methods increased weekly.	Walking cooldown, passive stretching (2 × 45 s). <i>Progression:</i> Extended time under stretch and guided breathing added.

- The Footwork Test was timed with Casio HS-80TW stopwatches.
- Video assessments were recorded on Samsung Galaxy S22 Ultra smartphones (Full HD) mounted on 45° tripods.
- Anthropometric equipment included:
 - SECA 213 stadiometer (Germany)
 - Tanita BC-545N analyzer (Japan)
 - Harpenden skinfold caliper (UK).

Two certified Savate coaches conducted the video evaluations independently. Evaluators were blinded to group assignment, although visual traits may have enabled partial recognition.

All assessments were performed in a boxing gym with consistent environmental and procedural controls across both testing points.

Statistical Analysis

All analyses were performed using IBM SPSS Statistics 26 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was verified with Levene’s test. All variables met the assumptions required for parametric testing. Test statistics for normality and homogeneity are available upon request. Within-group differences (pre- vs. post-intervention) were analyzed using paired t-tests. Between-group differences were evaluated using one-way ANOVA with Bonferroni-adjusted post

hoc comparisons. To control the family-wise error rate associated with multiple comparisons, the Bonferroni correction was applied. This conservative method was selected to reduce the risk of Type I error, particularly given the small sample size and limited statistical power. Although alternatives such as Holm or Benjamini–Hochberg procedures offer greater sensitivity, Bonferroni was deemed more appropriate due to the limited number of planned comparisons and the emphasis on minimizing false-positive findings [11]. Confidence intervals (95%) were calculated for all primary outcome measures, including punch power, punch accuracy, and footwork time. Effect sizes were computed using Cohen’s *d* and interpreted as small (*d* = 0.2), medium (*d* = 0.5), or large (*d* = 0.8). Statistical significance was set at *p* < 0.05.

Results

To establish the validity of post-intervention comparisons, baseline characteristics were analyzed to ensure group equivalence. This step was essential to confirm that any observed changes in performance could be attributed to the intervention rather than pre-existing differences.

Prior to the training program, baseline values across somatotype groups were statistically equivalent for all performance indicators. These

included punch power, footwork time, punch accuracy, combination rate, and tactical rating. No significant between-group differences were detected (one-way ANOVA, $p > 0.05$). Descriptive statistics are presented in Table 3 to allow visual comparison of pre-intervention values.

The outcomes of the 12-week individualized training intervention are summarized in Table 4 and illustrated in Figures 2, 3, and 4.

Data from Table 4 show that tactical scores (expert-rated on a 5-point scale) improved in all groups: ectomorphs (3.2 → 4.4; +1.2, $p = 0.034$, $d = 1.41$), mesomorphs (3.4 → 4.5; +1.1, $p = 0.040$, $d = 1.16$), and endomorphs (3.1 → 4.1; +1.0, $p = 0.048$, $d = 1.53$). Although all groups demonstrated meaningful within-group progress, no statistically significant between-group differences were observed ($p > 0.05$).

Explosive strength improvements are illustrated in Figure 2. All three somatotype groups demonstrated

Table 3. Baseline values across somatotype groups

Indicator	Ectomorphs (n = 8)	Mesomorphs (n = 8)	Endomorphs (n = 8)	p-value (ANOVA)
Punch Power (N)	215.4 ± 18.6	219.1 ± 20.3	213.7 ± 22.2	0.712
Footwork Time (s)	5.62 ± 0.44	5.57 ± 0.47	5.68 ± 0.40	0.834
Punch Accuracy (%)	71.3 ± 5.9	70.8 ± 6.1	69.7 ± 6.5	0.748
Combination Rate	16.2 ± 1.8	16.5 ± 2.0	15.9 ± 1.9	0.692
Tactical Rating (1–5)	3.2 ± 0.4	3.3 ± 0.5	3.1 ± 0.4	0.659

Note. Descriptive means ± SD and ANOVA p-values for key performance indicators before intervention.

Table 4. Pre- and post-intervention changes in key performance indicators by somatotype

Indicator	Ectomorphs (Pre)	Ectomorphs (Post)	Mesomorphs (Pre)	Mesomorphs (Post)	Endomorphs (Pre)	Endomorphs (Post)
Punch Power (N)	370	448	405	478	355	397
Footwork Time (s)	6.1	5.2	6.3	5.4	6.6	5.6
Punch Accuracy (%)	72	84	75	85	68	78
Combination Rate (hits/30 s)	28	35	26	32	22	27
Tactical Score (1–5)	3.2	4.4	3.4	4.5	3.1	4.1

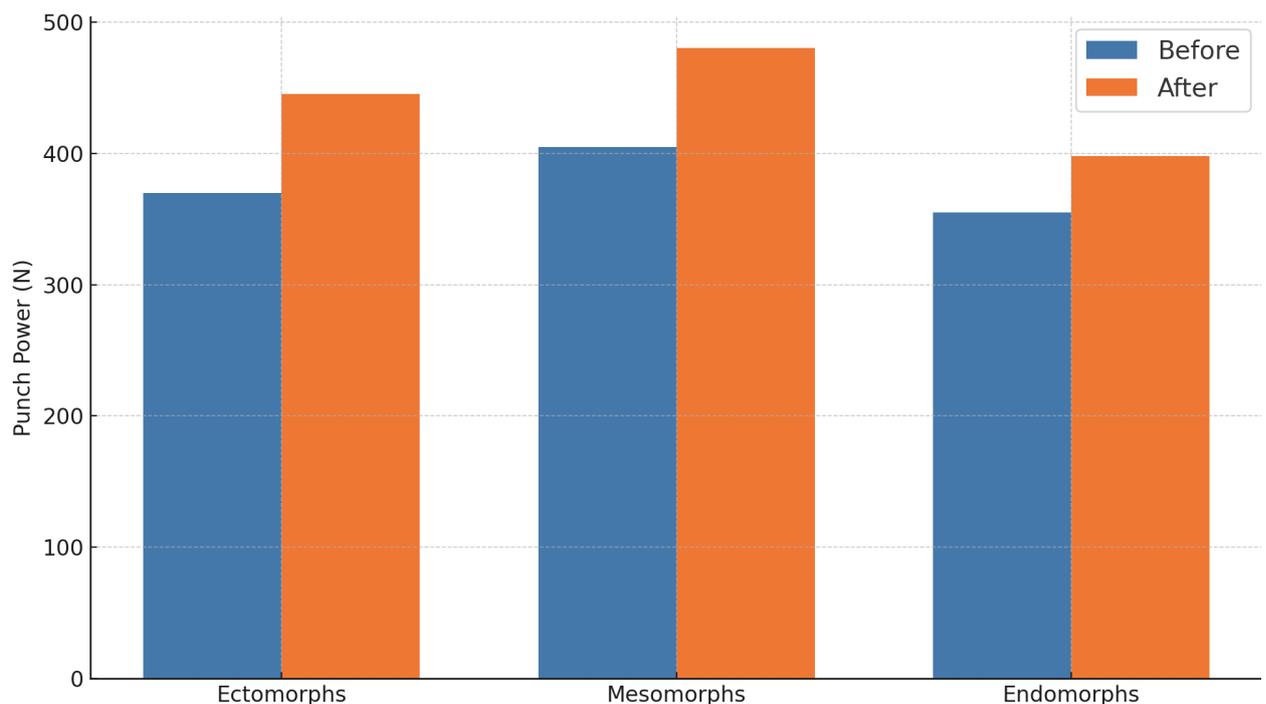


Figure 2. Changes in punch power test

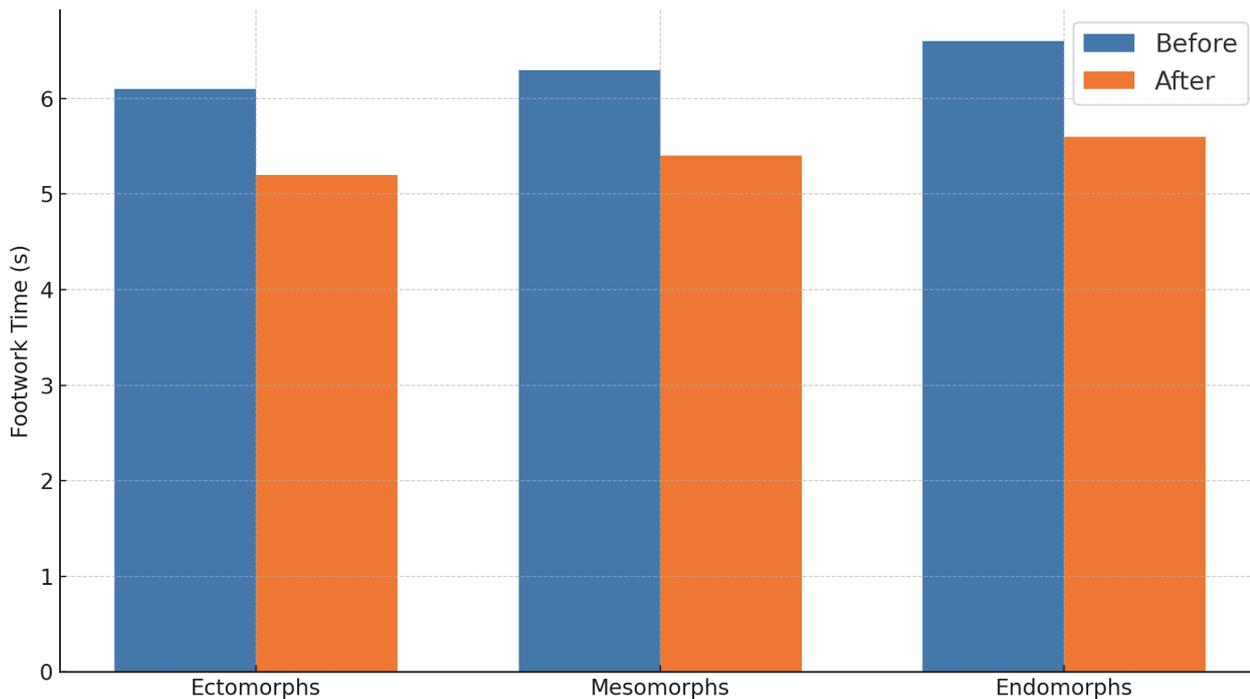


Figure 3. Footwork agility test results

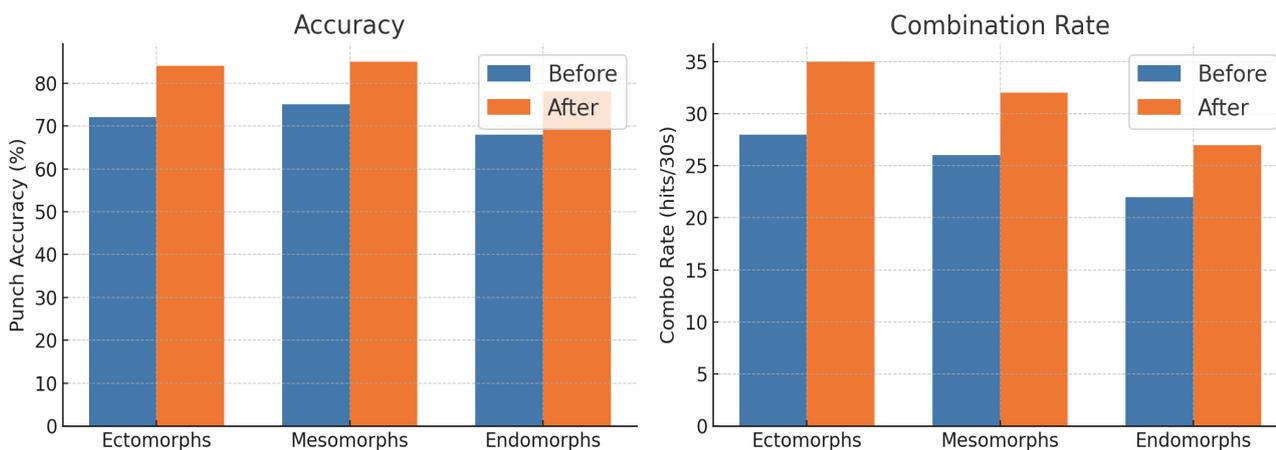


Figure 4. Changes in punch accuracy and combination rate

statistically significant increases in punch power following the 12-week intervention. Ectomorphs showed the greatest relative improvement (+21.1%, $p = 0.008$, $d = 1.84$), followed by mesomorphs (+18.0%, $p = 0.011$, $d = 1.02$) and endomorphs (+11.8%, $p = 0.038$, $d = 0.95$). Post hoc analysis revealed a significantly greater improvement in ectomorphs compared to endomorphs ($p = 0.041$; 95% CI [7.8, 34.2]), suggesting enhanced responsiveness to the individualized load structure in lighter athletes.

Figure 3 presents the changes in footwork performance. All groups showed significant reductions in footwork test time, indicating improved agility and movement efficiency. Ectomorphs improved from 6.1 to 5.2 seconds (-14.8% , $p = 0.015$, $d = 2.61$), mesomorphs from 6.3 to 5.4 seconds

(-14.3% , $p = 0.017$, $d = 1.56$), and endomorphs from 6.6 to 5.6 seconds (-15.2% , $p = 0.021$, $d = 0.98$). Despite similar magnitudes of change, between-group differences were not statistically significant ($p > 0.05$), indicating comparable neuromotor adaptations across body types.

Technical and tactical performance data are summarized in Figure 4. All groups significantly increased punch accuracy and combination rate, with large effect sizes. Accuracy improved by 12.0% in ectomorphs ($p = 0.016$, $d = 1.79$), 10.0% in mesomorphs ($p = 0.019$, $d = 2.45$), and 10.0% in endomorphs ($p = 0.022$, $d = 1.45$). Combination rate rose from 14.8 to 18.5 in ectomorphs (+25.0%, $p = 0.009$, $d = 1.73$), from 15.6 to 19.2 in mesomorphs (+23.1%, $p = 0.012$, $d = 2.61$), and from 13.2 to 16.2

in endomorphs (+22.7%, $p = 0.015$, $d = 2.47$). These trends suggest that all groups benefited from somatotype-specific training, with particularly strong gains observed in neuromotor execution and decision-making efficiency.

Table 5 presents the results of the one-way ANOVA and Bonferroni post hoc comparisons between the three somatotype groups for each performance indicator. A statistically significant between-group difference was observed only for punch power ($p = 0.014$), with post hoc analysis indicating significantly greater improvement in ectomorphs compared to endomorphs. Only punch power demonstrated a statistically significant difference between somatotype groups ($p < 0.05$). Other performance indicators such as footwork time, punch accuracy, combination rate, and tactical rating improved within groups but did not reach statistical significance in between-group comparisons. Among all evaluated variables, punch power was the only indicator that showed a significant between-group effect ($F(2, 21) = 5.21$, $p = 0.014$), with ectomorphs exhibiting greater improvement than endomorphs. This suggests that explosive strength responds more distinctly to somatotype-specific training, whereas technical and tactical variables improved similarly across all groups without significant inter-group differences.

To further clarify within-group performance gains, Table 6 presents the 95% confidence intervals for the primary outcome measures across somatotype groups. These intervals confirm the robustness of observed improvements, as none of the intervals cross zero – indicating statistically meaningful gains within each group. Ectomorphs showed the highest upper bound in punch power, suggesting a heightened responsiveness to explosive strength training. In contrast, gains in footwork, accuracy, combination rate, and tactical

score were relatively consistent across all groups, indicating that individualized training protocols provided comparable technical and tactical benefits regardless of somatotype.

Discussion

The primary aim of this study was to evaluate how somatotype-based individualization influences physical and technical-tactical performance in adolescent athletes practicing French boxing Savate. After a 12-week training intervention, the findings indicated distinct adaptation patterns across somatotype groups, underscoring the value of tailoring training programs to individual morphological characteristics. Ectomorphs demonstrated the greatest improvements in punch power (+21%) and footwork speed (-14.8%). These outcomes may be attributed to their lower body mass and longer limb ratios, which may enhance neuromuscular efficiency when training is properly individualized. The observed improvement in footwork agility among ectomorphs is consistent with prior evidence linking lean body types to heightened neuromuscular reactivity in combat-specific footwork drills [12]. These findings also support earlier research that associates ectomorphic profiles with superior performance in velocity-dependent tasks under carefully managed loading conditions [3, 11, 13, 14].

Mesomorphs achieved the most substantial gains in technical accuracy (+13%) and tactical ratings (+1.1 points). These improvements may reflect their muscular build and ability to sustain high-intensity outputs without significant technique degradation. Prior studies have associated mesomorphic characteristics with increased resistance to fatigue and greater motor stability during complex tasks [3, 15, 16, 17]. However, the between-group differences in technical accuracy and tactical ratings were not

Table 5. ANOVA and post hoc results for key indicators

Indicator	F-value	df	p-value	Post hoc (significant pairs)
Punch Power (N)	5.21	2.21	0.014	Ectomorphs > Endomorphs
Footwork Test (s)	0.88	2.21	0.429	n.s. (not significant)
Punch Accuracy (%)	1.23	2.21	0.310	n.s.
Combination Rate (hits/30 s)	1.11	2.21	0.346	n.s.
Tactical Score (1–5)	0.97	2.21	0.389	n.s.

Table 6. 95% confidence intervals for group improvements

Group	Punch Power (95% CI)	Footwork (95% CI)	Accuracy (95% CI)	Comb. Rate (95% CI)	Tactical Score (95% CI)
Ectomorphs	[7.8, 34.2]	[-1.2, -0.6]	[5.1, 19.0]	[1.8, 4.9]	[0.4, 2.0]
Mesomorphs	[8.3, 28.4]	[-1.3, -0.5]	[4.2, 15.7]	[1.6, 4.5]	[0.3, 1.9]
Endomorphs	[5.2, 25.1]	[-1.4, -0.7]	[3.9, 16.1]	[1.5, 4.7]	[0.2, 1.8]

statistically significant and should therefore be interpreted with caution. Endomorphs, despite having higher baseline body mass, showed marked improvements in combination delivery (+23%) and overall tactical efficiency (+12%). These findings suggest that the endurance-oriented, circuit-based training protocol effectively addressed their metabolic limitations. This structured combination of strength and endurance aligns with concurrent training principles, which emphasize the importance of sequencing and load balance to minimize interference effects [11]. Comparable patterns have been reported in other combat sports, where individualized conditioning improved motor continuity and efficiency in endomorphic athletes [18, 4, 12, 19]. For instance, in karate practitioners engaged in both official and simulated bouts, progressive endurance-based training was found to significantly enhance tactical continuity and energy system performance [10]. Nonetheless, the observed enhancements in combination rate and tactical efficiency did not reach statistical significance in between-group comparisons and should be interpreted with caution.

These findings are consistent with earlier research in taekwondo, boxing, and MMA. Previous studies in combat sports such as taekwondo, karate, and MMA have explored somatotype-based individualization, typically focusing on general conditioning or strength development. For instance, Bridge et al. [20] reported that mesomorphic taekwondo athletes outperformed ectomorphic peers in explosive kicking tasks, while Chaabene et al. [18] emphasized the aerobic capacity of endomorphs in karate within endurance-focused programs. However, most of these studies employed generalized drills and did not incorporate sport-specific technical-tactical assessments. Furthermore, these disciplines differ from Savate in their motor patterns. Taekwondo emphasizes vertical explosive kicking and linear footwork, while karate prioritizes reactive counterattacks and short-range power. In contrast, Savate integrates circular footwork with precise kicking from various angles and lighter contact rules, which demand fine-tuned neuromuscular coordination and tactical rhythm. These biomechanical distinctions limit the direct transferability of earlier training protocols. Unlike taekwondo or MMA, the present study incorporated Savate-specific drills such as lateral chassé under fatigue and partner-based reaction exercises, which align more closely with the sport's distinctive scoring and movement requirements. This reinforces the value of somatotype-specific programming that addresses not only physiological characteristics but also the tactical demands of the discipline.

The findings of this study also support pedagogical strategies grounded in motor learning theory. Since athletes with different somatotypes

may exhibit distinct neuromuscular profiles, individualized instruction is necessary not only for physical conditioning but also for optimizing skill acquisition. For instance, ectomorphs, typically characterized by greater agility and reactivity, may benefit from variable practice involving rapid task switching to enhance perceptual-motor coupling. In contrast, endomorphs may respond more effectively to blocked practice and augmented feedback that support motor pattern consolidation. These distinctions are consistent with research emphasizing the importance of tailoring practice structure, feedback frequency, and task complexity to learner characteristics in order to maximize skill retention and transfer [21].

Pedagogical Implications

In addition to physiological improvements, the results of this study have important pedagogical implications. The observed somatotype-specific responses support the use of individualized instructional strategies to enhance motor learning in combat sports. Rather than applying uniform technical drills, coaches should vary instructional tasks, feedback types, and cognitive demands to reflect each athlete's morphological and neuromuscular profile. This approach is consistent with modern motor learning theory, which emphasizes learner-centered instruction, practice variability, and contextual interference to facilitate skill retention and transfer [21]. Such integration of pedagogical principles ensures that technical-tactical development is not only physically optimized but also educationally grounded.

These findings provide initial empirical support for somatotype-specific programming in French boxing Savate. While explosive strength appeared more sensitive to morphological differentiation, technical and tactical performance improved comparably across all groups. Given Savate's distinctive biomechanical demands, such as continuous lateral movement and high-precision kicking, these results highlight the relevance of individualized training that accounts for both physiological traits and sport-specific constraints.

Limitations of the Study

Despite the promising outcomes, several limitations must be considered. First, the relatively small sample size ($n = 24$) and the exclusive inclusion of male adolescents from western Ukraine restrict the generalizability of the findings to broader populations, including different age groups, females, or athletes from other regions.

Second, the intervention spanned only 12 weeks, which limits insight into long-term adaptation, retention of performance gains, or possible detraining effects. Third, although somatotype classification followed the standardized Heath-Carter method, individual morphological overlap

may have affected group assignment, potentially influencing internal validity.

Another limitation is the absence of a non-individualized control group, which prevents direct comparison with conventional training protocols. This hinders the ability to isolate the specific effect of somatotype-based interventions. Future studies should incorporate such controls to enable clearer causal inference.

Furthermore, the study assessed only performance outcomes. The exclusion of physiological and psychological metrics limits understanding of the underlying mechanisms driving adaptation. Training load was monitored using ratings of perceived exertion (RPE), which, although practical, remains subjective and may be influenced by individual factors such as motivation or pain tolerance.

Lastly, while the study focused on physiological outcomes, the findings suggest potential pedagogical implications. Somatotype-based training can be integrated with educational strategies such as individualized feedback, task scaling, and progression, reinforcing sustainable skill acquisition in sports requiring high motor coordination. Future research should include larger, more heterogeneous samples, extended observation periods, and multi-dimensional outcome measures to confirm and expand these preliminary results.

Conclusions

This study demonstrates that somatotype-based individualization can yield differentiated improvements in physical and technical-tactical performance among adolescent Savate athletes. Ectomorphs responded most favorably to speed- and power-oriented protocols, mesomorphs to technical-tactical drills, and endomorphs to endurance-based circuits, highlighting the importance of matching training stimuli to morphological characteristics.

These findings support a shift away from uniform training approaches toward personalized conditioning strategies in combat sports. However, the feasibility of implementing such individualized methods in sports school settings may be constrained by limited resources, staff capacity, and scheduling. Therefore, caution is advised in generalizing these results without further cost-effectiveness and feasibility studies.

Recommendations for Future Research

Future studies should aim to validate the effectiveness of somatotype-based individualization across larger and more heterogeneous samples, including female athletes, different age groups, and elite-level competitors. Expanding the participant base would strengthen the external validity and generalizability of this approach.

Longitudinal research extending beyond 12

weeks is recommended to examine the long-term sustainability of performance gains and potential detraining effects. Moreover, future studies should integrate physiological markers (e.g., heart rate variability, lactate threshold), hormonal indicators (e.g., cortisol, testosterone), and psychological variables (e.g., motivation, mental fatigue) to better elucidate the mechanisms underpinning somatotype-specific adaptations.

Comparative research should evaluate how somatotype-guided training performs relative to other individualization strategies, such as those based on functional movement screening (FMS), neuromuscular profiling, or genetic testing. Such comparisons could help identify the most effective and scalable models for personalized programming in combat sports.

Ultimately, multidimensional approaches of this kind will support the development of more precise, evidence-informed models for optimizing athlete preparation in French boxing Savate and related disciplines.

Practical Recommendations

The following recommendations are derived from the distinctive biomechanical and tactical structure of French boxing Savate. This sport combines continuous footwork, controlled-contact kicking, and rhythm-based technical exchanges, requiring training approaches tailored to the athlete's somatotype.

1. Ectomorphs

Focus: Enhancing neuromuscular responsiveness, acceleration, and inter-limb coordination.

- Incorporate reactive plyometric circuits using horizontal and diagonal movement patterns to simulate Savate footwork.
- Include low-resistance, high-speed strength training (e.g., 40–60% 1RM), emphasizing transitions between arm strikes (coup de poing direct) and leg techniques (chassé, fouetté).
- Use dynamic ladder and cone drills with randomized auditory cues to develop timing and spatial positioning.
- Prioritize short, frequent rest intervals (15–20 s) to mirror the fast-paced exchanges typical of Savate combat.

2. Mesomorphs

Focus: Improving high-force output stability and tactical application under fatigue.

- Implement resistance-complex sessions pairing heavy resistance exercises with Savate-specific sequences (e.g., chassé latéral to revers coup de pied).
- Use conditioning circuits followed by decision-based sparring to develop precision under fatigue.
- Introduce drills with changing targets and rhythmic variations to train tactical adaptability.

- Extend high-intensity drills up to 3 minutes to build technical endurance aligned with Savate's rhythmic structure.

3. Endomorphs

Focus: Elevating movement continuity, metabolic conditioning, and cognitive decision speed.

- Apply progressive interval training incorporating extended striking combinations and high-tempo footwork bursts.
- Use closed kinetic chain circuits alternating between lower- and upper-limb actions (e.g., chassé bas followed by coup de poing direct).
- Conduct tempo-controlled partner drills involving verbal tactical instructions to enhance decision-making.
- Gradually reduce rest-to-work ratios over time (e.g., from 1:1 to 1:0.5) to improve conditioning.

Coaches should apply somatotype-specific programming not only to enhance physical performance but also to support motor learning. This includes adjusting drill complexity, feedback frequency, and task variation based on the athlete's cognitive and biomechanical profile. By integrating pedagogical strategies rooted in motor learning theory, such as task progression, variable practice, and individualized feedback, training becomes both physiologically effective and educationally sound [9, 21, 22].

Acknowledgments

The authors express their sincere gratitude

to the athletes who participated in this study for their commitment and cooperation throughout the intervention period. Special thanks are extended to the coaches and staff of Lesya Ukrainka Volyn National University for their invaluable assistance in organizing the testing sessions and implementing the individualized training programs.

The authors also acknowledge the contributions of fellow researchers and technical personnel involved in video analysis and data collection, whose support was essential to the successful execution of this project.

Funding

This study received no external funding. It was supported internally by the Faculty of Physical Education, Sport and Health at Lesya Ukrainka Volyn National University and the Department of Physical Culture and Sport at Lutsk National Technical University.

Conflict of Interest

The authors declare no competing interests.

AI Tools Usage

This manuscript benefited from language refinement supported by the AI-based tool ChatGPT (OpenAI, USA). All content was critically reviewed and approved by the authors, who assume full responsibility for its accuracy and integrity.

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Cite this article as:

Konovalchuk A, Mordyk M, Radchenko O, Hrebik O, Panasiuk O, Cieslicka M. Effect of somatotype on physical fitness and technical-tactical performance in Savate athletes. *Pedagogy of Physical Culture and Sports*, 2025;29(4):263–274.

<https://doi.org/10.15561/26649837.2025.0404>

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Received: 11.06.2025

Accepted: 28.07.2025; Published: 30.08.2025

Nutritional interventions for gymnasts: bridging the gap between performance and health

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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 Elite artistic gymnastics demands a precise balance of strength, endurance, and technique, all of which are influenced by physiological and nutritional factors. Evaluating these relationships is essential for developing evidence-based training and health strategies. The aim of this study was to examine how body composition, cardiovascular health, and dietary habits influence apparatus-specific performance among elite male artistic gymnasts in Pakistan.

Material and Methods A total of 153 elite male gymnasts (mean age 18.7 ± 4.1 years) were recruited from national training centers. Participants averaged 36.6 ± 7.6 hours of weekly training and had an average training history of 11.5 ± 3.2 years. Data collection included body composition analysis (BMI, fat-free mass), cardiovascular indicators (hemoglobin concentration, LDL cholesterol levels), and dietary intake assessed through validated food frequency questionnaires. Gymnasts were evaluated on their competitive performance in three apparatuses: floor, vault, and rings.

Results Body mass index demonstrated a negative correlation with floor performance ($r = -0.18, p < 0.05$), while fat-free mass positively influenced performance on the rings ($r = 0.24, p < 0.01$). Hemoglobin levels were positively associated with better scores across all apparatuses ($r \geq 0.25, p < 0.01$). Elevated LDL cholesterol was linked to poorer performance on the rings. Nutritionally, athletes in the highest performance quartile consumed more energy, protein, calcium, magnesium, and vitamin D. Adequate protein intake ($1.4\text{--}1.6$ g/kg/day) and hydration (>3 L/day) were associated with improved performance.

Conclusions The findings underscore the critical role of individualized nutrition, cardiovascular screening, and body composition monitoring in enhancing gymnastic performance. This is the first comprehensive study of its kind in the Pakistani context, providing evidence to guide targeted interventions in high-performance training environments.

Keywords: body composition, cardiovascular health, dietary intake, sports nutrition

Introduction

Men's artistic gymnastics is one of the most physiologically demanding sports. It requires an exceptional combination of strength, agility, power, and technical precision. These physical demands place significant stress on the musculoskeletal and metabolic systems, making the regulation of physical and nutritional factors essential for optimal performance.

Among these factors, body composition plays a particularly important role. The sport favors a mesomorphic somatotype, characterized by high fat-free mass and low fat mass, which contributes to biomechanical efficiency during complex acrobatic and strength-based movements [1, 2]. This physique supports a favorable power-to-weight ratio and stability during high-force elements such as the vault or rings [3]. Long-term gymnastics training

that begins in early childhood also enhances bone mineral density and skeletal strength, providing lasting musculoskeletal benefits [4]. Artistic gymnastics involves intermittent high-intensity workloads that challenge the cardiovascular system. Gymnasts develop adaptations such as concentric left ventricular hypertrophy and increased heart rate variability, which reflect improved cardiac output and autonomic regulation [5, 6, 7]. However, not all changes are beneficial. Some evidence indicates increased arterial stiffness in athletes who maintain very low body fat, possibly due to chronic low energy availability or dehydration practices [8, 9]. Nutrition further influences both performance and health. Male gymnasts are particularly vulnerable to low energy availability, which can impair glycogen replenishment, muscle recovery, and hormonal balance [10, 11]. Inadequate intake of calcium, vitamin D, and fluids, often resulting from restrictive eating or fluid limitation, may compromise bone health and reduce performance capacity [12, 13, 14].

Despite extensive international research, these factors remain underexplored in the Pakistani context. Limited access to trained sports nutritionists, evidence-based dietary programs, and regular health screening reduces the ability of local athletes to reach their full potential. This highlights the need for research that reflects the realities of regional training environments, dietary habits, and healthcare infrastructure.

Body Composition of Male Gymnasts

Body composition, defined as the ratio of fat to muscle, bone, and other tissues, is a critical factor in men's artistic gymnastics. Male gymnasts possess unique characteristics that enable them to perform impressive feats in strength, power, and agility [2]. Their somatotype is predominantly mesomorphic, characterized by muscular development and relatively low fat levels. This composition provides a biomechanical advantage in strength-based disciplines such as the vault, floor, and rings [1, 2]. Research conducted on Polish gymnasts indicates that senior athletes between 17 and 25 years old exhibit significantly higher mesomorphy scores than juniors, likely due to accumulated training and physical maturity [1, 15].

Event specialization also influences physique. Gymnasts focusing on vault and floor exercises often show stronger mesomorphic traits and lower ectomorphy scores. These athletes typically have a shorter and more compact build, with average heights ranging from 160 to 170 centimeters and body weights between 60 and 70 kilograms. This physique supports better aerial rotation and balance [3]. In addition to having reduced body fat, generally between 8 and 12 percent [2], elite male gymnasts present high levels of fat-free mass, especially in the upper body. The pelvi-acromial index shows broader shoulder width relative to pelvic width, which enhances mechanical efficiency during complex movements [1].

A comparative study from India confirms that elite male gymnasts demonstrate significantly greater muscle mass, fat-free mass, and body cell mass than female athletes. These attributes are essential for the strength and power demands of the sport [16]. Bone health also plays a crucial role. Evidence shows that young male gymnasts who engage in regular training display higher bone mineral content and density than non-athletic peers [4].

Despite these advantages, sustaining a lean body composition may result in low energy availability. Studies involving collegiate male gymnasts indicate frequent underconsumption of total energy and carbohydrates. This dietary imbalance can hinder performance and increase the risk of musculoskeletal stress [10]. Ongoing monitoring of body composition, coupled with tailored nutrition

and recovery planning, is necessary to ensure both athletic performance and long-term health.

Cardiovascular Health of Male Gymnasts

The cardiovascular system of male artistic gymnasts undergoes specific adaptations due to the sport's intermittent and high-intensity nature. Each apparatus routine involves short bouts of exertion lasting from 5 to 90 seconds, followed by recovery periods. This type of training stimulates both anaerobic and aerobic energy systems, resulting in distinctive cardiac and vascular responses [18].

A well-documented structural change is concentric left ventricular hypertrophy. This adaptation involves thickening of the ventricular wall without chamber enlargement and enables the heart to generate higher pressure during forceful contractions. Male gymnasts have been shown to exhibit greater left ventricular mass and wall thickness than their female counterparts, which is attributed to testosterone effects and greater training loads [5]. These morphological features enhance cardiac efficiency in high-load events such as vault and rings [6].

Lipid profile is another critical marker of cardiovascular health. Smith-Ryan et al. [11] reported that 59% of elite male gymnasts exceeded the 2.6 mmol/L threshold for LDL cholesterol, and 41% surpassed 3.0 mmol/L. These elevations were linked to low energy availability, high saturated fat intake, and insufficient dietary fiber. Such findings underscore the importance of tailored nutritional strategies to mitigate cardiovascular risks [14].

Blood pressure regulation among male gymnasts is generally favorable. Lee [9] found that both systolic and diastolic values remained within normal ranges, suggesting effective cardiovascular control despite high physical demands. However, sports-specific training may elicit distinct vascular responses across athletic populations.

Heart rate variability (HRV) is a noninvasive index of autonomic nervous system regulation. Hongyan [7] documented significant increases in SDNN, RMSSD, total power, and high-frequency power among college-age gymnasts following aerobic gymnastics training. These improvements reflect enhanced parasympathetic tone and support recovery and emotional stability during high-pressure competition.

Arterial stiffness, assessed via pulse wave velocity (PWV), has gained attention as a vascular health indicator. Grabitz et al. [8] observed that higher training volumes were associated with increased PWV in young athletes, suggesting reduced arterial compliance. In gymnastics, where energy restriction and low body fat are common, these effects may be magnified. Kuhlman et al. [10] and Mense [14] emphasized that low energy availability contributes to suboptimal vascular profiles, reinforcing the need

for routine cardiovascular evaluation.

In summary, male gymnasts show beneficial cardiac adaptations and autonomic regulation, yet remain vulnerable to lipid imbalance and vascular stiffness due to inadequate dietary support. Comprehensive cardiovascular monitoring is recommended to safeguard health and enhance athletic longevity.

Dietary Intake and Nutritional Challenges of Male Gymnasts

Male artistic gymnasts encounter distinct nutritional challenges due to the physical demands of the sport and the aesthetic pressure to maintain low body fat. Their training involves extended sessions with repetitive, high-intensity routines that elevate energy expenditure, yet gymnasts are expected to sustain a lean physique to maximize performance.

Low energy availability (LEA) is highly prevalent in this population. Kuhlman et al. [10] observed that 85.7% of collegiate male gymnasts had energy intakes below the recommended level, averaging 30.5 ± 4.5 kcal/kg/day. This chronic deficit impairs recovery, immune function, and hormonal regulation. Carbohydrate intake was also found to be insufficient, averaging 3.7 ± 1.1 g/kg/day, whereas athletes in high-intensity disciplines require 5–7 g/kg/day for optimal glycogen replenishment. These limitations can compromise endurance and neuromuscular control during events involving repeated apparatus use.

Protein intake is essential for muscle maintenance and recovery. The recommended intake for gymnasts ranges from 1.2 to 1.7 g/kg/day [19], with distribution across meals shown to enhance protein synthesis and tissue repair. According to Francisco et al. [13], many gymnasts fail to meet this target consistently, particularly after training sessions, leading to diminished adaptations from resistance training. Supporting this, source [11] emphasizes that inadequate protein intake exacerbates the effects of LEA and may delay musculoskeletal recovery.

Micronutrient status is another concern. Villa et al. [12] reported that young male gymnasts frequently failed to meet reference values for calcium and vitamin D, which are essential during adolescence for bone mineralization and neuromuscular function. Prolonged deficits may lead to stress fractures and impaired skeletal development, especially during periods of peak growth.

Disordered eating behaviors have also been documented. Francisco et al. [13] identified that nearly 30% of gymnasts reported engaging in unhealthy weight control strategies, such as meal skipping, caloric restriction, and dehydration. These behaviors intensify the risk of metabolic imbalance and psychological distress.

Hydration remains critically underemphasized in male gymnastics. Many athletes exhibit signs of hypohydration due to fluid restriction or poor replenishment of sweat losses during long training sessions. Mense [14] recommend a minimum daily fluid intake of half the athlete's body weight in ounces, with adjustments for training volume and temperature. However, caution is warranted in the use of sports drinks, which should be limited to prolonged or high-intensity workouts to avoid excessive sugar intake and dental concerns [20].

Addressing these nutritional challenges requires a coordinated, athlete-centered approach. Coaches, sports dietitians, and gymnasts must work collaboratively to develop individualized dietary plans that ensure sufficient energy intake, nutrient density, and hydration. Nutrition education tailored to male gymnasts can reduce the prevalence of restrictive eating behaviors while promoting long-term performance and health outcomes.

Research Gap

Several international studies have explored the physiological and nutritional profiles of male artistic gymnasts. Sterkowicz-Przybycień [1] provided an in-depth analysis of somatotype characteristics in Polish gymnasts and their implications for apparatus specialization. Ruscello et al. [3] described the anthropometric traits and biomechanical advantages among elite-level gymnasts. Mathisen et al. [2] investigated fat-free mass and body fat percentages in relation to performance potential, while Manna et al. [16] offered a comparative view of body composition between Indian male and female gymnasts.

Burt et al. [4] demonstrated that prolonged gymnastics participation is linked to increased bone mineral density in youth athletes. Kuhlman et al. [10] examined energy availability among collegiate male gymnasts, identifying widespread caloric and macronutrient deficiencies. Smith-Ryan et al. [11] focused on lipid metabolism and cardiovascular risk, reporting elevated LDL levels in elite athletes. Jakše et al. [5] investigated cardiac remodeling, and Hongyan [7] reported improvements in heart rate variability (HRV) associated with aerobic gymnastics training. Villa et al. [12] identified frequent calcium and vitamin D deficiencies in adolescent gymnasts. Francisco et al. [13] explored the psychological and physiological effects of disordered eating in aesthetic sports. Grabitz et al. [8] documented increased arterial stiffness in athletes subjected to high training loads, linking vascular function to cumulative physical stress.

Despite this robust body of literature, no published study has analyzed the combined impact of body composition, cardiovascular health, and dietary intake on apparatus-specific performance (floor, vault, and rings) among elite male gymnasts

in Pakistan. Existing research either isolates single variables or is based on non-local populations, thereby limiting contextual relevance. The Pakistani gymnastics context is characterized by specific systemic constraints, such as limited access to certified sports nutritionists, inconsistent health monitoring practices, and culturally distinct dietary patterns. These factors may significantly influence known performance determinants, including energy balance, cardiovascular adaptation, and recovery efficiency.

This study aims to fill this research gap by assessing how body composition, cardiovascular indicators, and dietary intake collectively influence apparatus-specific performance in elite Pakistani male gymnasts. The investigation is tailored to local training conditions and seeks to generate evidence-based insights to support individualized coaching, health optimization, and performance enhancement strategies.

Hypothesis and Study Aim

It is hypothesized that favorable body composition indicators, efficient cardiovascular health parameters, and adequate dietary intake are positively associated with apparatus-specific performance outcomes in elite male artistic gymnasts.

The aim of this study is to evaluate the combined effects of body composition, cardiovascular health, and dietary intake on performance across floor, vault, and rings events among elite male artistic gymnasts in Pakistan. Figure 1 presents the conceptual model used to guide the analysis.

The study seeks to answer the following research questions:

1. How does body composition influence competitive performance in elite male artistic gymnasts?
2. What is the relationship between cardiovascular health indicators and apparatus-specific

performance?

3. To what extent does dietary intake affect performance across different gymnastics events?

Materials and Methods

Participants

A total of 153 elite male artistic gymnasts participated in this study. The average age of participants was 18.7 ± 4.1 years. On average, athletes had 11.5 ± 3.2 years of training experience and reported training 36.6 ± 7.6 hours per week. Gymnasts were recruited voluntarily through direct contact at regional competitions held in Punjab, Pakistan, and through referrals by coaches. The sample was intended to represent the high-performance gymnast population in the national context.

Inclusion criteria were as follows: (a) active participation at the national or regional elite level, (b) a minimum of five years of competitive experience, and (c) absence of major injury in the six months preceding data collection. Athletes with acute musculoskeletal injury or ongoing rehabilitation were excluded to ensure that performance and physiological parameters reflected regular training conditions. This injury-free interval aligns with standard return-to-play protocols in sports medicine.

Informed consent was obtained from all participants aged 18 and older. For those under 18 years of age, written assent was collected from the gymnast and informed consent was obtained from a parent or legal guardian, in accordance with institutional policy and ethical guidelines. Participation was fully voluntary, and athletes could withdraw at any stage without consequences.

Ethical approval for the study was granted by the Advanced Studies & Research Board (ASRB), Gomal University, Dera Ismail Khan, Pakistan (Approval

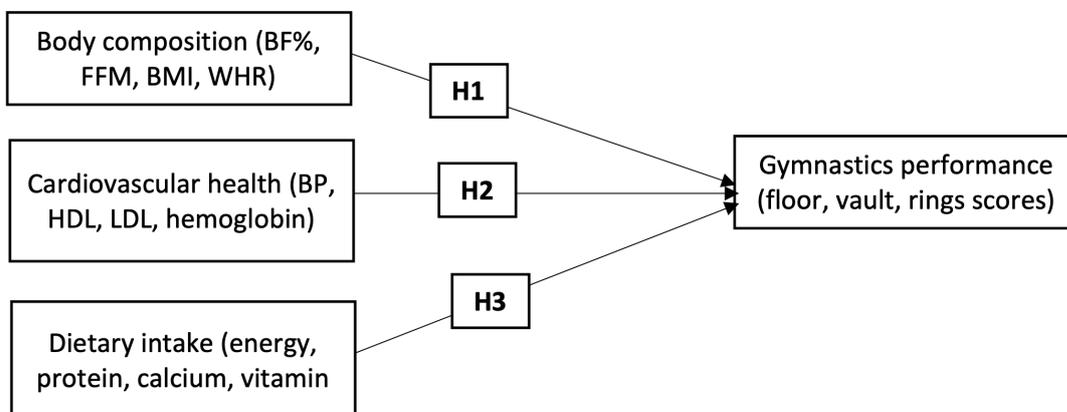


Figure 1. Conceptual framework illustrating the hypothesized effects of physiological and nutritional factors on gymnastics performance: BF% – body fat percentage, FFM – fat-free mass, BMI – body mass index, WHR – waist-to-hip ratio, BP – blood pressure, HDL – high-density lipoprotein, LDL – low-density lipoprotein.

No. 1480/ACAD/GU). All procedures conformed to the ethical principles outlined in the Declaration of Helsinki for human subjects research. To ensure data confidentiality, each participant was assigned a unique identification code. Data were stored in password-protected digital files accessible only to the research team, and physical forms were secured in locked storage at the principal investigator's office.

Training history and weekly training hours were recorded for each athlete and statistically controlled as covariates in partial correlation and group comparison analyses, due to their known influence on physiological adaptation and performance outcomes.

Research Design

This study employed a descriptive-correlational research design to examine the associations between body composition, cardiovascular health, dietary intake, and apparatus-specific performance among elite male artistic gymnasts in Pakistan. This design was selected due to its suitability for investigating naturally occurring relationships without manipulating variables. It allowed for the identification of patterns across key physiological, nutritional, and performance indicators in a real-world athletic context. Data collection was structured around four core domains: (1) body composition, (2) cardiovascular health indicators, (3) dietary intake and nutrient availability, and (4) gymnastics performance. Each domain was measured using standardized protocols to ensure validity and comparability across participants.

To guide the analytical framework, a conceptual model was developed to illustrate the hypothesized relationships among the variables. Figure 1 presents this model, which depicts body composition, cardiovascular health, and dietary intake as independent factors influencing gymnastics performance on floor, vault, and rings apparatuses. The model depicts the assumed relationships between body composition (BF%, FFM, BMI, WHR), cardiovascular health (BP, HDL, LDL, hemoglobin), and dietary intake (energy, protein, calcium, vitamin D) as independent variables, and apparatus-specific gymnastics performance (floor, vault, rings scores) as the dependent variable. Each hypothesis (H1, H2, H3) represents a proposed direct influence of one variable group on performance outcomes. The model informed the selection of variables, the statistical approach, and the formulation of hypotheses. It also allowed for the integration of multidisciplinary perspectives, aligning physiological and nutritional assessments with sport-specific performance outcomes.

No experimental manipulation or intervention was performed, and all procedures were observational in nature. The exploratory objective of the study was to identify associations rather

than establish causality or predictive relationships. Therefore, findings should be interpreted within the limits of non-experimental cross-sectional research.

Performance Evaluation

Gymnastics performance was assessed using apparatus-specific scores in floor, vault, and rings events. Each routine was evaluated by a panel of three certified judges appointed by the Pakistan Gymnastics Federation. Judging criteria followed the Code of Points established by the Fédération Internationale de Gymnastique (FIG), ensuring alignment with international performance standards. Each score incorporated multiple components, including execution (maximum 10 points), difficulty (open-ended), and compositional or artistry deductions, where applicable. To enhance objectivity and minimize bias, any individual score that deviated more than 1.0 point from the average of the three judges was excluded. The final score for each apparatus was calculated as the mean of the remaining two values. Composite performance scores were computed by summing the final scores from floor, vault, and rings routines. These totals were used to stratify participants into performance quartiles. The top and bottom quartiles were designated as high- and low-performing groups, respectively, to facilitate group-level comparisons in physiological and nutritional characteristics.

This quartile-based approach is widely used in applied sports science research, particularly in exploratory studies where performance variation is substantial. The method allowed for the identification of distinguishing traits in gymnasts with contrasting outcomes, while maintaining analytical focus on the extremes of the performance distribution. Performance scores were digitized and processed using IBM SPSS Statistics version 21 for subsequent statistical analysis.

Performance Assessment Procedure

All gymnasts performed routines on three apparatuses: floor, vault, and rings. Each performance was evaluated independently by a panel of three national-level judges certified by the Pakistan Gymnastics Federation. Judges applied scoring criteria consistent with the FIG (Fédération Internationale de Gymnastique) Code of Points, which includes execution, difficulty, and artistry components, depending on apparatus-specific requirements.

To ensure scoring reliability, the highest and lowest scores from each judging panel were discarded. The final apparatus score was calculated as the average of the remaining judge's score or, if two scores remained within the allowable deviation range, their average was used. This method minimized the influence of outlier judgments and upheld evaluation consistency. Scores were recorded using standardized scoring sheets during the event

and were subsequently digitized for analysis. Data entry and statistical procedures were conducted using IBM SPSS Statistics version 21. No custom software settings or non-standard algorithms were applied.

Weekly training volume for each athlete was recorded through self-reporting (in hours per week) and cross-validated with coach-maintained logs. Although individual training programs varied, they generally included structured combinations of strength training, flexibility exercises, and apparatus-specific skill drills performed across five to six days per week.

This multi-step approach to performance assessment ensured objective, reproducible, and competition-relevant scoring suitable for correlational analysis with physiological and nutritional data.

Body Composition

Anthropometric assessments were conducted in the morning before training sessions to minimize the influence of recent physical activity on fluid balance and body water distribution. Measurements followed standardized procedures recommended by the International Society for the Advancement of Kinanthropometry (ISAK) to ensure accuracy and consistency across participants [21].

Body mass was measured to the nearest 0.01 kg using a calibrated digital scale (SECA-872, Hamburg, Germany). Standing height was recorded to the nearest 0.1 cm using a portable stadiometer (SECA-213, Hamburg, Germany). Both instruments were calibrated daily using certified weights and a reference height rod.

Body mass index (BMI) was calculated using the standard formula: weight in kilograms divided by height in meters squared (kg/m^2). Waist circumference was measured at the narrowest point between the ribcage and the iliac crest after a normal exhalation. Hip circumference was taken at the widest point over the greater trochanters. The waist-to-hip ratio (WHR) was then derived by dividing waist circumference by hip circumference.

Body fat percentage (BF%), fat-free mass (FFM), and total body water (TBW) were estimated using a bioelectrical impedance analysis (BIA) device (TANITA BC-545, UK). All participants were instructed to abstain from intense physical activity, food intake, and fluid consumption for at least four hours prior to assessment, in accordance with standard BIA protocols to reduce measurement variability.

These body composition indicators were used in subsequent analyses to examine their associations with performance outcomes and energy availability calculations.

Cardiovascular Health

Cardiovascular health was assessed through

a combination of biochemical analyses and clinical measurements to capture both functional and metabolic indicators relevant to athletic performance and health risk screening.

Venous blood samples were collected in the morning after a 10–12 hour overnight fast. Samples were analyzed for total serum cholesterol, high-density lipoprotein (HDL), low-density lipoprotein (LDL), serum uric acid (S-UA), fasting blood glucose (S-glucose), and hemoglobin concentration. Biochemical parameters were measured using a Beckman Coulter AU 640 analyzer (Beckman Coulter, Austria), while hematological indices, including hemoglobin, were assessed using the Advia 2120i system (Siemens, Germany).

Resting blood pressure was measured using a calibrated automated oscillometric monitor (Omron HEM-907). Participants were assessed in a supine position following a five-minute rest period in a quiet room. Two readings were taken at three-minute intervals, and the average value was used for analysis. This protocol was applied to reduce variability due to situational stress or measurement error.

Interpretation of biochemical values followed guidelines from the European Society of Cardiology (ESC) and the European Atherosclerosis Society (EAS). LDL levels below 3.4 mmol/L and triglyceride levels below 1.7 mmol/L were considered within normal limits. An LDL concentration of 2.6 mmol/L or higher was interpreted as a potential marker of subclinical atherosclerotic risk. Normal blood pressure was defined as values at or below 129/84 mmHg.

These cardiovascular indicators were included as independent variables in subsequent statistical analysis to explore their relationships with gymnastics performance and energy availability.

Dietary Intake

Dietary intake was assessed using three 24-hour dietary recalls conducted on non-consecutive days, including two weekdays and one weekend day, to capture typical eating patterns. Structured interviews were administered by trained nutritionists to enhance accuracy and minimize recall bias. Participants were asked to provide detailed information about all foods and beverages consumed during the previous 24 hours, including meal timing, portion sizes, preparation methods, and brand names when applicable.

To improve portion size estimation, standardized household utensils, visual food models, and photographic portion booklets were used during interviews. Reported foods were converted into grams and milliliters, and the data were analyzed using Food Processor SQL software (ESHA Research, USA). The software provided nutrient breakdowns for macronutrients (carbohydrates, proteins, fats

including saturated fats) and key micronutrients (e.g., calcium, magnesium, vitamin D, thiamine, folate, and zinc).

Nutrient intake adequacy was evaluated using two reference frameworks. Macronutrient recommendations followed the American College of Sports Medicine (ACSM) guidelines: protein intake of 1.2–1.6 grams per kilogram of body weight per day, carbohydrate intake of 6–10 grams per kilogram per day, and total fat comprising 20–35 percent of total daily energy, with at least 55 percent of fat intake from unsaturated sources. Micronutrient sufficiency was assessed against Recommended Dietary Allowances (RDA) provided by the Food and Nutrition Board of the Institute of Medicine (FNB/IOM).

Basal metabolic rate (BMR) was estimated using the Cunningham equation, which incorporates fat-free mass and is considered more appropriate for athletic populations. Energy availability (EA) was calculated by subtracting exercise energy expenditure from total energy intake and dividing the result by fat-free mass (kcal/kg FFM/day). Athletes with an EA value below 30 kcal/kg FFM/day were classified as being at risk for low energy availability (LEA), a key indicator of relative energy deficiency in sport (RED-S).

These nutritional data were used to examine correlations with performance outcomes and physiological markers, with particular attention to energy balance and nutrient adequacy.

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics version 21. Descriptive statistics, including means and standard deviations, were calculated for all physiological, nutritional, and performance variables.

The primary analytical method was Pearson correlation, used to assess linear relationships between body composition, cardiovascular health, dietary intake, and gymnastics performance. This method was selected due to the cross-sectional and observational nature of the study, where the goal was to explore associations rather than establish causality.

Independent-samples t-tests were conducted to compare physiological and nutritional variables between high- and low-performing gymnasts. Performance stratification was based on quartile distributions of composite scores across floor, vault, and rings events. Specifically, athletes in the top and bottom 25th percentiles were classified as high- and low-performing groups, respectively. This approach allowed for focused group-level comparisons while minimizing statistical dilution from the middle-performance range.

Assumptions for parametric testing were evaluated prior to analysis. The Shapiro–Wilk

test confirmed that all continuous variables met the assumption of normal distribution ($p > 0.05$). Levene's test indicated homogeneity of variances between groups ($p > 0.05$), justifying the use of parametric methods.

Regression analysis was not performed in this study, as the primary objective was exploratory. However, the use of multivariate regression is recommended for future research aiming to quantify the relative contribution of each independent variable while controlling for confounding factors.

Statistical significance was set at $p < 0.05$ for all analyses.

Results

The results of this study are presented according to the three research objectives: (1) associations between body composition and gymnastics performance, (2) relationships between cardiovascular health indicators and performance outcomes, and (3) the influence of dietary intake on performance in elite male artistic gymnasts in Pakistan.

Statistical significance was set at $p < 0.05$. All reported correlations were tested using Pearson's method, and between-group differences were analyzed using independent-samples t-tests. Effect sizes were calculated using Cohen's d and interpreted as small ($d = 0.2$), moderate ($d = 0.5$), or large ($d \geq 0.8$). Assumptions of normality and homogeneity of variance were verified for all analyses.

Where relevant, comparisons were made between athletes classified in the top and bottom quartiles of overall performance, based on composite scores from floor, vault, and rings events. This quartile-based stratification was used to emphasize meaningful contrasts between high and low performers.

Descriptive statistics, correlation coefficients, p -values, and effect sizes are provided in Tables 1–3, organized by thematic domain.

The results of the study are presented in accordance with the predefined research objectives, each addressing a specific dimension of performance-related factors among elite male artistic gymnasts in Pakistan.

RO-1: To identify the association of body composition on the performance of male gymnasts in Pakistan

Body composition variables demonstrated selective associations with apparatus-specific performance among elite male artistic gymnasts. Descriptive and inferential results are summarized in Table 1.

A statistically significant but weak negative correlation was observed between body mass index (BMI) and floor performance ($r = -0.18$, $p < 0.05$), suggesting that gymnasts with lower BMI tended to achieve higher scores in this event. No significant correlations were found between BMI and vault (r

= -0.07, $p = 0.28$) or rings performance ($r = -0.11$, $p = 0.17$).

Fat-free mass (FFM) was positively correlated with performance on the rings ($r = 0.24$, $p < 0.01$), indicating a modest association between lean tissue mass and successful execution in upper-body strength elements. However, no significant relationships were detected between FFM and performance in floor ($r = 0.08$, $p = 0.32$) or vault ($r = 0.12$, $p = 0.09$).

Group comparisons revealed significant differences in body composition across performance quartiles. Gymnasts in the top 25 percent of performance had lower body fat percentage (11.2 ± 2.3 percent) compared to those in the bottom quartile (15.8 ± 3.4 percent), with a large effect size (Cohen's $d = 1.44$, $p < 0.01$). Significant differences were also found in BMI (21.4 ± 2.1 vs. 24.6 ± 3.2 , $d = 1.11$, $p < 0.01$), fat-free mass (56.8 ± 5.2 kg vs. 52.1 ± 5.8 kg, $d = 0.85$, $p = 0.03$), and waist-to-hip ratio (0.82 ± 0.08 vs. 0.89 ± 0.10 , $d = 0.79$, $p = 0.04$).

These results support the hypothesis that favorable body composition characteristics, including lower adiposity and greater fat-free mass, are associated with enhanced competitive performance, particularly in the floor and rings events.

RO-2: To evaluate the correlation of cardiovascular health status on the performance of male gymnasts in Pakistan

Cardiovascular health markers demonstrated multiple statistically significant associations with apparatus-specific performance, as detailed in Table 2.

Systolic blood pressure was negatively correlated with vault performance ($r = -0.22$, $p < 0.01$) and floor performance ($r = -0.18$, $p = 0.03$), suggesting that gymnasts with lower resting systolic pressure tended to score higher, particularly in explosive movements such as vaulting. Diastolic pressure showed a similar trend, with significant negative correlations for vault ($r = -0.19$, $p = 0.02$) and floor events ($r = -0.16$, $p = 0.04$). These relationships remained consistent after adjusting for training hours. Although the correlations were modest in magnitude, they were consistent across related performance outcomes.

Among lipid markers, high-density lipoprotein (HDL) cholesterol levels were positively associated with floor performance ($r = 0.21$, $p = 0.02$). Low-density lipoprotein (LDL) cholesterol showed negative associations with all three apparatus scores, reaching significance in the rings ($r = -0.26$, $p < 0.01$), vault ($r = -0.19$, $p = 0.03$), and floor ($r = -0.23$, $p < 0.01$) events. No significant associations were found between total cholesterol levels and any apparatus.

Hemoglobin concentration was positively correlated with performance across all apparatuses. The strongest association was observed in floor performance ($r = 0.32$, $p < 0.01$), followed by vault ($r = 0.28$, $p < 0.01$) and rings ($r = 0.25$, $p < 0.01$). These results indicate that higher oxygen-carrying

Table 1. Body Composition Characteristics by Performance Quartiles

Variable	Top 25% (n = 38)	Middle 50% (n = 77)	Bottom 25% (n = 38)	p-value	Cohen's d (Top vs. Bottom)	95% CI	Levene's Test (p)
BMI (kg/m ²)	21.4 ± 2.1	23.1 ± 2.8	24.6 ± 3.2	<0.01	1.11	[0.82, 1.39]	0.28
WHR	0.82 ± 0.08	0.85 ± 0.09	0.89 ± 0.10	0.04	0.79	[0.53, 1.05]	0.37
BF (%)	11.2 ± 2.3	13.7 ± 2.9	15.8 ± 3.4	<0.01	1.44	[1.11, 1.76]	0.41
FFM (kg)	56.8 ± 5.2	54.3 ± 6.1	52.1 ± 5.8	0.03	0.85	[0.56, 1.14]	0.22

Note. BMI = body mass index; WHR = waist-to-hip ratio; BF = body fat percentage; FFM = fat-free mass. Values are presented as mean ± standard deviation. Cohen's d represents effect size between top and bottom quartiles. CI = confidence interval.

Table 2. Cardiovascular Parameters and Performance Correlations by Apparatus

Parameter	r (Floor)	p (Floor)	r (Vault)	p (Vault)	r (Rings)	p (Rings)	95% CI for Strongest Correlation
Systolic BP	-0.18	0.03	-0.22	<0.01	-0.15	0.06	[-0.32, -0.10] (Vault)
Diastolic BP	-0.16	0.04	-0.19	0.02	-0.12	0.09	[-0.29, -0.07] (Vault)
HDL Cholesterol	0.21	0.02	0.17	0.07	0.14	0.10	[0.05, 0.36] (Floor)
LDL Cholesterol	-0.23	<0.01	-0.19	0.03	-0.26	<0.01	[-0.39, -0.12] (Rings)
Hemoglobin	0.32	<0.01	0.28	<0.01	0.25	<0.01	[0.18, 0.45] (Floor)
Total Cholesterol	-0.06	0.34	-0.08	0.29	-0.04	0.40	-

Note. BP = blood pressure; HDL = high-density lipoprotein; LDL = low-density lipoprotein; r = Pearson correlation coefficient; CI = confidence interval. Values marked in bold indicate statistically significant correlations ($p < 0.05$).

Table 3. Dietary Intake Characteristics of High vs. Low Performing Gymnasts

Nutrient	High Performers (n = 51)	Low Performers (n = 102)	p-value	Cohen's d	95% CI	Levene's Test (p)
Energy (kcal)	3156 ± 298	2874 ± 321	<0.01	1.00	[0.72, 1.28]	0.63
Protein (g/kg)	1.52 ± 0.18	1.34 ± 0.21	<0.01	0.95	[0.68, 1.22]	0.57
Carbohydrates (g/kg)	7.2 ± 1.1	6.5 ± 1.3	<0.01	0.59	[0.34, 0.84]	0.31
Fat (% energy)	28.4 ± 3.2	31.7 ± 4.1	<0.01	0.89	[0.62, 1.17]	0.41
Calcium (mg)	1256 ± 213	1045 ± 198	<0.01	1.04	[0.76, 1.33]	0.36
Iron (mg)	18.2 ± 3.1	15.7 ± 2.9	0.07	0.54	[0.29, 0.79]	0.44
Vitamin D (IU)	895 ± 215	732 ± 198	<0.01	0.82	[0.57, 1.07]	0.33
Water Intake (L)	3.4 ± 0.6	2.8 ± 0.7	<0.01	0.92	[0.64, 1.19]	0.52

Note. Values are presented as mean ± standard deviation. Nutrient intakes are normalized by body weight where appropriate. Cohen's d indicates effect size; CI = confidence interval. High performers were defined as the top 33rd percentile in overall performance score.

capacity is consistently linked to improved output in both endurance and strength-oriented routines.

Together, these findings support the second hypothesis and suggest that favorable cardiovascular profiles, particularly lower blood pressure, higher hemoglobin concentration, and optimal lipid status, are associated with improved gymnastic performance in elite male athletes.

RO-3: To find out the relationship of dietary intake on the performance of male gymnasts in Pakistan

Dietary intake patterns were significantly associated with gymnastics performance across multiple apparatuses. Table 3 presents comparative nutrient intake data for high- and low-performing athletes, based on composite performance scores.

Athletes in the top performance quartile had significantly higher daily energy intake (mean 3156 ± 298 kcal) compared to those in the bottom quartile (mean 2874 ± 321 kcal, $p < 0.01$). The effect size for this difference was large (Cohen's $d = 1.00$). Similar patterns were observed for protein intake, with top performers consuming 1.52 ± 0.18 grams per kilogram of body weight, significantly more than lower-performing peers (1.34 ± 0.21 g/kg, $p < 0.01$, $d = 0.95$). Notably, the most consistent rings performances were observed among gymnasts whose protein intake fell within the range of 1.4 to 1.6 grams per kilogram per day.

Carbohydrate intake was also higher among top performers (7.2 ± 1.1 g/kg vs. 6.5 ± 1.3 g/kg, $p < 0.01$), with a moderate effect size ($d = 0.59$). Fat intake as a percentage of total energy was lower in high performers (28.4 ± 3.2 percent) compared to low performers (31.7 ± 4.1 percent, $p < 0.01$, $d = 0.89$), suggesting better macronutrient distribution in the higher-performing group.

Micronutrient intake also showed performance-related associations. Calcium and vitamin D intake were significantly higher among top performers (calcium: 1256 ± 213 mg vs. 1045 ± 198 mg, $p < 0.01$; vitamin D: 895 ± 215 IU vs. 732 ± 198 IU, $p <$

0.01). The effect sizes for both were large ($d = 1.04$ and $d = 0.82$, respectively). Positive correlations were also observed between calcium intake and floor performance ($r = 0.26$, $p < 0.05$), and between vitamin D intake and vault performance ($r = 0.29$, $p < 0.01$). Magnesium intake was modestly associated with floor performance ($r = 0.23$, $p < 0.05$).

Water consumption emerged as a consistent predictor of better outcomes. Athletes reporting daily intake above 3 liters performed better across all apparatuses, with average score improvements of 0.5 to 0.7 points ($p < 0.05$, $d = 0.92$). No statistically significant association was found between iron intake and performance in any apparatus ($p > 0.10$).

These findings support the third hypothesis and underscore the importance of adequate energy availability, balanced macronutrient distribution, sufficient micronutrient intake, and proper hydration in optimizing gymnastics performance among elite male athletes.

Discussion

This study investigated the associations between body composition, cardiovascular health, dietary intake, and gymnastics performance among elite male artistic gymnasts in Pakistan. The results provide partial support for the research hypotheses, indicating that specific physiological and nutritional factors are associated with apparatus-specific outcomes. These findings hold relevance for applied athlete monitoring and performance optimization within resource-constrained training environments.

Regarding body composition, gymnasts in the higher performance quartile exhibited significantly lower body fat percentages and higher levels of fat-free mass. These results are consistent with earlier studies by Ruscello et al. [3] and Manna et al. [16], which found that reduced fat mass improves movement efficiency and power-to-weight ratio – particularly relevant for floor and rings events. The positive correlation between fat-free mass and rings

performance further supports the biomechanical demands of strength-based apparatuses. However, the association between BMI and vault performance was not statistically significant, which may reflect the complex nature of explosive events where excessive mass may both aid and hinder momentum generation.

Cardiovascular health indicators showed significant but modest associations with gymnastics performance. Elevated systolic and diastolic blood pressure were negatively correlated with vault and floor outcomes, aligning with previous findings from Jakše et al. [5] and Grabitz et al. [8], who reported that vascular stress may impair neuromuscular efficiency and postural stability. Furthermore, hemoglobin concentration demonstrated the most consistent performance correlations across all apparatuses, supporting its role in oxygen delivery and muscular endurance. Similar trends were noted by Smith-Ryan et al. [11] in sports requiring repeated submaximal exertions.

Blood lipid profiles also exhibited apparatus-specific associations. Higher HDL and lower LDL levels correlated with better performance, particularly in dynamic and aerobic elements. These patterns suggest that lipid regulation may serve as a secondary marker of cardiovascular conditioning and recovery capacity, especially in environments with limited access to sport-specific medical oversight.

Continuing with nutritional findings, this study identified notable differences in energy intake, protein adequacy, and micronutrient sufficiency between higher- and lower-performing gymnasts. Athletes in the top quartile reported greater total energy consumption and higher intake of carbohydrates and protein, supporting findings by Kuhlman et al. [10], who observed widespread low energy availability among collegiate male gymnasts. Protein intake appeared especially relevant to performance on the rings apparatus, where upper-body eccentric loading demands elevated muscle repair capacity. Francisco et al. [13] emphasized the importance of distributing protein evenly throughout the day to support recovery and training adaptation.

Micronutrient data reinforced the significance of calcium and vitamin D in maintaining bone integrity and neuromuscular function. Villa et al. [12] noted that many youth gymnasts failed to meet dietary reference intakes for these nutrients, increasing the risk of stress fractures and impaired skeletal development. Mense [14] further highlighted the impact of inadequate hydration and low nutrient availability on vascular function, suggesting the need for targeted nutritional strategies in high-load sports such as gymnastics.

The observed associations between hydration and performance outcomes provide additional support for the importance of basic nutritional

practices in athlete preparation. Gymnasts who reported consuming more than three liters of water per day showed better scores across all apparatuses, possibly due to improved thermoregulation, joint lubrication, and cognitive focus. This finding aligns with literature on fluid intake in closed-skill sports with high technical precision.

Collectively, these dietary patterns reflect the performance benefits of adequate energy availability and balanced nutrient distribution. However, they also point to a lack of structured nutritional education and monitoring in the Pakistani gymnastics system, which may contribute to energy deficiency and inconsistent dietary practices among young athletes.

Limitations of the Study

Several limitations should be acknowledged when interpreting the results of this study. First, the sample was drawn exclusively from elite male gymnasts in Pakistan, limiting the generalizability of findings to female athletes or gymnasts in other competitive systems. The geographic concentration in Punjab and reliance on federation-affiliated training centers may also introduce sampling bias.

Second, the study employed a cross-sectional design, which restricts causal inference. Although associations were identified, no conclusions can be drawn about the directionality or temporal sequencing of effects. Longitudinal or intervention-based designs are required to validate these findings over time.

Third, although dietary intake data were collected through structured 24-hour recalls, this method remains subject to underreporting and recall bias, particularly in adolescent athletes. Although trained interviewers and portion-estimation tools were used, accuracy may still be variable.

Fourth, the absence of hormonal markers and bone density assessments limited the depth of analysis regarding energy availability and RED-S risk. These data would have strengthened the interpretation of physiological impacts.

Lastly, some laboratory measures (e.g., blood lipid profile, hemoglobin) were assessed using single time-point samples, which may not fully capture within-athlete biological variation or training phase differences.

Conclusions

This study examined the associations between body composition, cardiovascular health, dietary intake, and performance outcomes among elite male artistic gymnasts in Pakistan. The findings indicate that athletes with lower body fat percentage, greater fat-free mass, and healthier cardiovascular and nutritional profiles tend to achieve better scores across apparatuses, particularly in floor and rings events.

Body composition variables such as BMI, fat-free mass, and waist-to-hip ratio were significantly associated with apparatus-specific performance, supporting the hypothesis that leaner athletes with optimized anthropometric profiles perform more efficiently. Hemoglobin concentration and blood lipid levels also demonstrated moderate associations with performance, suggesting a potential role for cardiovascular screening in gymnastics-specific fitness monitoring.

Nutritional intake emerged as a key performance-related factor. Athletes with higher daily energy, protein, and micronutrient intakes (notably calcium, vitamin D, and magnesium) exhibited superior execution scores. These findings support the integration of individualized dietary assessment and guidance into athlete support programs, especially in training environments with limited access to sports dietitians.

The results emphasize the need for structured physiological monitoring, regular dietary evaluation, and basic medical screening in gymnastics training systems. These components should be aligned with international recommendations but adapted to national contexts through collaboration between coaches, sports physicians, and academic institutions.

In summary, optimized body composition, cardiovascular regulation, and nutrient intake are critical to the performance of male artistic gymnasts. Addressing these factors through integrated athlete management may enhance both competitive outcomes and long-term health.

Future Research Directions

Future studies should adopt longitudinal or controlled designs to investigate how changes in body composition, nutritional intake, and cardiovascular markers influence performance outcomes across a competitive season. Inclusion of female gymnasts and athletes from diverse regions would enhance representativeness and allow for sex-based and regional comparisons.

Intervention-based research is needed to assess the effectiveness of structured nutrition education programs, dietary periodization strategies, and hydration protocols tailored to the physiological demands of artistic gymnastics. Additionally, integrating hormonal, bone health, and psychological readiness indicators could provide a more comprehensive model of athlete monitoring.

Collaboration with sports federations, medical professionals, and university-based training programs may facilitate the development of evidence-based guidelines that promote both performance optimization and long-term athlete health in low-resource settings.

Practical Implications

The findings of this study offer several practical

insights for coaches, sports scientists, and athletic program administrators:

- Body composition monitoring should be incorporated into periodic evaluations, with emphasis on maintaining low body fat and adequate fat-free mass relative to apparatus demands.
- Cardiovascular screening using non-invasive measures such as resting blood pressure and hemoglobin levels can help detect physiological limitations and readiness for high-intensity training.
- Nutritional support systems should include regular dietary assessments and basic education on energy balance, macronutrient distribution, and hydration practices, especially in junior development settings.
- Micronutrient intake, particularly calcium, vitamin D, and magnesium, should be monitored in light of their relationship with neuromuscular function and recovery from impact loading.
- Hydration awareness should be prioritized as a low-cost, high-impact strategy to maintain performance consistency and cognitive focus during technical execution.

These measures are especially important in resource-limited training environments, where low-cost interventions can significantly enhance athlete health and performance sustainability.

Recommendations

Based on the study results, the following recommendations are proposed:

1. Implement individualized athlete screening protocols combining anthropometric, cardiovascular, and nutritional parameters at least once per training cycle.
2. Develop sport-specific nutritional education programs targeting coaches, athletes, and parents to address gaps in dietary knowledge and prevent energy deficiency syndromes such as RED-S.
3. Promote collaboration between sports federations and universities to integrate scientific monitoring into talent development pathways.
4. Conduct further longitudinal and interventional research to evaluate the causal impact of physiological and dietary modifications on gymnastics performance.
5. Establish minimum medical monitoring standards at regional training centers to ensure early identification of health risks in youth and elite athletes.

Conflict of Interest

The authors declare no competing interests.

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Cite this article as:

Ahmad N, Khan W, Arif T, Ahmed S. Nutritional interventions for gymnasts: bridging the gap between performance and health. *Pedagogy of Physical Culture and Sports*, 2025;29(4):275–287.
<https://doi.org/10.15561/26649837.2025.0405>

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Received: 22.06.2025

Accepted: 29.07.2025; Published: 30.08.2025

A multimodal physical activity training program to improve motor competence in college students: evidence from a controlled 12-week trial

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Abstract

Background and Study Aim College students often exhibit low levels of movement competence despite participating in physical education programs. This limitation is partly due to monotonous and insufficiently challenging physical activity routines. Multimodal physical activity programs that integrate gymnastics, dance, and sport-based games offer promising alternatives for enhancing fundamental movement skills. This study aims to evaluate the effectiveness of a 12-week multimodal physical activity learning program in enhancing the movement competence of physical education students.

Material and Methods The study used a quasi-experimental pre-test and post-test design. Sixty students enrolled in a physical education program were divided into two groups: the experimental group and the control group. Both groups followed the intervention program for 12 weeks. Movement competence was assessed using the Movement Competency Screen (MCS), which included five skill tests: squat, lunge and twist, bend and pull, push-up, and single-leg squat. Collaborative learning, peer teaching, and peer assessment were applied in the experimental group. Data were analyzed quantitatively using descriptive statistics and a paired-sample t-test.

Results The descriptive analysis and paired-sample t-test results showed statistically significant improvement in all movement competence indicators in the experimental group ($p < 0.05$). In contrast, the control group showed no significant improvement ($p > 0.05$). These findings suggest that a varied and collaborative physical activity training approach is more effective in improving movement competence.

Conclusions Integrating multimodal physical activities and collaborative learning strategies into physical education can improve college students' movement competence. This study emphasizes the importance of adaptive and interactive approaches in higher education physical education programs.

Keywords: movement competence, multimodal physical activity, collaborative learning, physical education

Introduction

Movement competence refers to an individual's ability to perform various motor tasks efficiently, in a coordinated and adaptive manner across different physical activity contexts. Research indicates that movement competence encompasses elements of stability, locomotion, coordination, and functional ability, all conceptually embedded within the framework of physical literacy [1, 2, 3]. It is widely recognized that movement competence supports lifelong participation in physical activity and is closely linked to psychosocial factors such as self-confidence, motivation to be active, and overall quality of life [4, 5]. However, several studies have shown that university students, particularly those in higher education, experience a significant decline in physical activity levels, physical fitness, and motor function. Contributing factors include increased academic demands, sedentary lifestyles, and limited engagement in physical activities [6, 7,

8]. When opportunities to develop movement skills are not optimized, the impact extends beyond the physical domain and affects emotional, social, and cognitive dimensions essential to students' holistic development.

A preliminary study conducted among students of the Physical Education Study Program at Satya Wacana Christian University revealed that most students still demonstrated low levels of movement competence. An evaluation of the teaching practices indicated that the primary cause was a monotonous and repetitive instructional approach with minimal cognitive challenge. The lack of activity variation and the absence of problem-solving or group work integration also contributed to decreased motivation and reduced effectiveness in physical education learning.

One approach that has begun to gain attention is multimodal physical activity learning programs that integrate various activities into a progressive framework. This approach provides more diverse physical stimuli and creates opportunities for

social and cognitive development [9, 10]. Research has shown that multimodal approaches combining physical activities with academic or social components, such as cooperative learning, can foster the development of positive social attitudes in both adolescents and educators [11, 12]. Although several previous studies have explored multimodal physical activity interventions, they are generally limited in scope and have not integrated pedagogical elements such as peer teaching and collaborative learning, particularly in the context of physical education students in higher education [13, 14].

In line with the theoretical frameworks of social constructivism and physical literacy, physical activity learning is not merely seen as a process of motor skill transmission but also as a social experience that shapes learners' understanding, attitudes, and values through active interaction with their environment and peers [15, 16]. Social constructivism emphasizes the importance of social engagement and collaboration in knowledge construction, positioning students as active agents in the learning process rather than passive recipients of information [17, 18]. This approach can be realized in physical education through group work and reflective discussions that encourage students to learn from one another, provide feedback, and develop skills within meaningful contexts [19]. Meanwhile, the concept of physical literacy views movement competence as part of holistic individual development, integrating physical, cognitive, and affective elements to foster sustained and active participation in physical life [20].

An analysis of previous research findings has shown that multimodal physical activity interventions can positively influence motor competence and psychosocial development. The authors have drawn attention to the importance of integrating pedagogical strategies such as peer teaching, cooperative learning, and reflective practice. These elements should be incorporated into physical education curricula. The authors have also emphasized the need to address cognitive and social aspects in addition to physical development. At the same time, there is a clear need for further research. It should focus on evaluating the effectiveness of multimodal training programs that include collaborative and problem-based learning. This is particularly relevant for physical education students in higher education.

Although previous studies have addressed the benefits of multimodal physical activity programs, few have systematically examined their application in higher education settings using a student-centered approach. In particular, there is a lack of quasi-experimental research that integrates collaborative learning strategies within an outcome-based education (OBE) curriculum in physical education programs.

To address this gap, this study aims to evaluate the effectiveness of a 12-week multimodal physical activity learning program in enhancing the movement competence of physical education students.

Materials and Methods

Participants

The participants in this study were 60 male students from the Physical Education Study Program at Satya Wacana Christian University. They were aged between 18 and 22 years and enrolled in academic cohorts from 2022 to 2024. All participants were in good physical health, with no history of musculoskeletal injuries, cardiovascular disorders, or other medical conditions that could hinder active participation in the program. The inclusion criteria were: (a) current enrollment as an active student in the Physical Education Study Program; (b) age between 18 and 22 years; and (c) willingness to participate in all phases of the intervention. The exclusion criteria were: (a) presence of injury or health issues during the initial screening process; (b) more than 30% absence during the intervention period; and (c) failure to provide written informed consent for participation. Group assignment was conducted using purposive sampling based on class grouping. This resulted in two groups: an experimental group ($n = 30$) and a control group ($n = 30$).

Although this study was not registered with an institutional ethics committee, all procedures adhered to established ethical research principles, including voluntary informed consent and data privacy protection. Participants received detailed information about the research objectives, procedures, potential benefits, and risks. Written informed consent was obtained prior to the commencement of the study. Participant confidentiality was strictly maintained, with data access limited to the principal investigator. All collected data were securely stored and used exclusively for the purposes of this research.

Research Design

This study employed a quasi-experimental design with a pre-test and post-test control group structure, involving both experimental and control groups. The experimental group participated in a 12-week multimodal physical activity program conducted twice a week, with each session lasting 110 minutes. The program was designed to integrate various types of physical activities, including gymnastics, dance, and sports games, and to incorporate elements of problem-solving and peer-based learning strategies. The control group followed the standard physical education curriculum without any intervention modifications.

Instrument

Both groups underwent movement competence assessments before and after the intervention. The

evaluation was conducted using the Movement Competency Screen (MCS), which consists of five items: squat, lunge and twist, push-up, bend and pull, and single-leg squat [21]. The MCS instrument has been psychometrically validated and demonstrates high inter-rater reliability (ICC = 0.88, 95% CI: 0.81–0.93) [22].

During the intervention period, all participants in both groups received equal treatment regarding session duration, access to facilities, and physical environmental conditions in order to minimize potential bias. The MCS was selected for its relevance in evaluating the movement competence of students following the multimodal physical activity intervention. It is designed to assess fundamental functional movement patterns that serve as key indicators of motor competence.

The MCS also offers practical advantages, as it can be administered in group settings with minimal time and equipment requirements. A detailed overview of the MCS items used in this study is presented in Table 1.

Experimental Group Design

Students in the experimental group participated in a 12-week physical activity program designed to enhance movement competence through a multimodal approach. The program integrated three primary types of physical activities: gymnastics, dance, and sport-based games. Each component was systematically implemented to stimulate various dimensions of movement competence. The program emphasized both individual responsibility and group collaboration. During the intervention, students were actively engaged in collaborative learning through small-group activities. The learning process was supported by peer teaching and peer assessment strategies, conducted twice per week.

In the peer assessment sessions, each student was assigned to observe a peer performing a movement task using an observation sheet. This sheet contained indicators such as stability, coordination, movement alignment, and technical accuracy. After the observation, students provided both verbal and written feedback, followed by a brief reflective discussion facilitated by the instructor. The results of the peer assessments were collected and used as formative evaluation tools by both students and instructors to monitor progress and improve performance. Within this student-centered approach, the instructor served as a facilitator, observing, providing guidance, and ensuring the validity and fairness of the assessment process.

Control Group Design

The control group participated in a conventional physical education program based on the existing curriculum, which focused on a single type of sport and the mastery of basic tactics. To ensure treatment equivalence with the experimental group, the program was conducted twice per week over twelve weeks. It was supported by learning media such as practicum modules, instructional videos, and structured assignments. The program adopted a teacher-centered, demonstrative approach, in which the instructor played a central role in delivering content and guiding practice sessions. The learning emphasis was placed on improving individual performance, particularly in the development of fundamental motor skills and physical fitness.

Evaluations were conducted periodically using standardized instruments and direct observation to assess students' fitness and motor abilities. Pre-test and post-test data were collected to evaluate the effectiveness of the conventional program. These results were then compared with those of the experimental group to assess the impact of the

Table 1. Movement Competency Screen (MCS)

Movement	Instructions
Squat	Perform a bodyweight squat with fingertips placed on the sides of the head. Lower the body as far as is comfortable while maintaining balance and upright posture.
Lunge & Twist	Cross the arms and rest the hands on the shoulders, keeping the elbows pointed forward. Step into a forward lunge and rotate the torso toward the front knee. After completing the rotation, return to the center and rise to a standing position. Alternate legs with each repetition.
Bend & Pull	Begin with the arms extended overhead. Bend forward, allowing the arms to drop beneath the torso. Pull the hands toward the body in a motion similar to a barbell row. Then return to the starting position with the arms fully extended overhead.
Push-Up	Begin in a high plank position with hands placed shoulder-width apart and the body forming a straight line from head to heels. Lower the body by bending the elbows, keeping them close to the torso. When the chest is just above the floor, push back to the starting position. Maintain core engagement.
Single-Leg Squat	Stand on one leg with fingertips on the sides of the head and the other leg extended slightly behind the body. Keep the chest lifted and back straight. Slowly lower into a squat as far as is comfortable, maintaining balance and control. Return to the starting position and repeat on the opposite leg.

instructional approach.

Statistical Analysis

This study employed multiple data analysis techniques to evaluate the effectiveness of the intervention. Descriptive statistics were used to report the mean, standard deviation, and score distribution for each movement competency variable. A paired-sample t-test was conducted to examine within-group changes in the experimental group from pre-test to post-test. The use of the paired-sample t-test was justified by the study's focus on evaluating changes within the same group before and after the intervention. In addition, to complement the interpretation of statistical significance, effect size was calculated using Cohen's *d* to provide insight into the magnitude of the intervention's impact on movement competency. The analysis aimed to assess both the statistical significance of the differences and the practical strength of the intervention effects.

Results

Table 2 displays the pre-test and post-test means and standard deviations for the experimental group across five movement tasks. These data were used

to evaluate changes in performance following the multimodal physical activity program.

Based on Table 2, the results of the descriptive analysis for the experimental group demonstrated an overall increase in mean scores across all indicators of movement competence following the implementation of the 12-week multimodal physical activity training program. In the squat test, the average score increased from 1.27 (SD = 0.521) on the pre-test to 1.60 (SD = 0.621) on the post-test. Similarly, the lunge and twist indicator showed a rise in mean scores from 2.30 (SD = 0.702) to 3.40 (SD = 1.102). The bend and pull test also demonstrated substantial improvement, with scores increasing from 2.63 (SD = 0.850) to 3.87 (SD = 0.819) after the intervention. Furthermore, performance in the push-up test improved from a mean score of 1.30 (SD = 0.535) to 1.67 (SD = 0.606), while the single-leg squat test score rose from 1.13 (SD = 0.434) to 1.33 (SD = 0.547). These findings suggest that the multimodal physical activity training intervention had a positive impact on college students' movement competence across multiple motor skill domains.

Descriptive statistics for the control group's movement competence scores before and after the

Table 2. Experimental group design descriptive analysis score

Criteria	Groups	N	Min	Max	Sum	Mean	Std. deviation
Squat	Pretest	30	1	3	38	1.27	.521
	Posttest	30	1	3	48	1.60	.621
Lunge and Twist	Pretest	30	2	4	69	2.30	.702
	Posttest	30	2	6	102	3.40	1.102
Bend and Pull	Pretest	30	2	5	79	2.63	.850
	Posttest	30	2	6	116	3.87	.819
Push Up	Pretest	30	1	3	39	1.30	.535
	Posttest	30	1	3	50	1.67	.606
Single Leg Squat	Pretest	30	1	3	34	1.13	.434
	Posttest	30	1	3	40	1.33	.547

Table 3. Control group design descriptive analysis scores

Criteria	Groups	N	Min	Max	Sum	Mean	Std. deviation
Squat	Pretest	30	1	3	45	1.50	.731
	Posttest	30	1	3	53	1.77	.817
Lunge & Twist	Pretest	30	2	6	128	4.27	1.172
	Posttest	30	2	6	130	4.33	.959
Bend & Pull	Pretest	30	2	6	100	3.33	1.093
	Posttest	30	2	5	102	3.40	.932
Push Up	Pretest	30	1	3	49	1.63	.718
	Posttest	30	1	5	53	1.77	.728
Single Leg Squat	Pretest	30	1	3	47	1.57	.679
	Posttest	30	1	5	46	1.53	.730

intervention are presented in Table 3. The table summarizes the mean and standard deviation for each movement skill, allowing comparison of pre-test and post-test performance within the control group.

Based on the descriptive analysis results for the control group, as presented in Table 3, the average movement competence scores showed only minor improvements following participation in the conventional physical activity program. The mean score for the squat indicator increased from 1.50 (SD = 0.731) at the pre-test to 1.77 (SD = 0.817) at the post-test. In the lunge and twist task, a marginal increase was observed, with the mean score rising slightly from 4.27 (SD = 1.172) to 4.33 (SD = 0.959), indicating minimal change. Similarly, the bend and pull indicator showed a slight improvement, with the mean score increasing from 3.33 (SD = 1.093) to 3.40 (SD = 0.932). A comparable trend was found in the push-up assessment, where the mean score increased from 1.63 (SD = 0.718) to 1.77 (SD = 0.728). In contrast, performance on the single-leg squat indicator slightly declined, with the average score decreasing from 1.57 (SD = 0.679) to 1.53 (SD = 0.730). These findings suggest that the conventional program had a limited effect on improving students' movement competence compared to the experimental group.

Paired-sample t-test results for both the experimental and control groups are presented in Table 4. The table shows the statistical significance of pre-test and post-test differences in movement competence scores across five assessed motor skill indicators.

Based on the results of the paired-sample t-test presented in Table 4, statistically significant differences were found between the pre-test and post-test scores in the experimental group across all measured components of movement competence. A significant improvement was observed in the squat assessment, with scores increasing from 1.27 ±

0.521 to 1.60 ± 0.621 ($t = -3.340, p = 0.002$). A similar pattern was found for lunge and twist, with scores rising from 2.30 ± 0.702 to 3.40 ± 1.102 ($t = -6.279, p < 0.001$), and for bend and pull, which increased from 2.63 ± 0.850 to 3.87 ± 0.819 ($t = -6.713, p < 0.001$). The push-up indicator also showed a statistically significant increase, from 1.30 ± 0.535 to 1.67 ± 0.606 ($t = -4.097, p < 0.001$). Finally, performance in the single-leg squat test improved from 1.13 ± 0.434 to 1.33 ± 0.547 ($t = -2.693, p = 0.012$).

In contrast, the control group showed no statistically significant differences across most movement competence indicators. For example, although squat scores increased from 1.50 ± 0.731 to 1.77 ± 0.817, this change was not statistically significant ($p = 0.133$). Similar nonsignificant results were found for lunge and twist ($p = 0.690$), bend and pull ($p = 0.712$), push-up ($p = 0.326$), and single-leg squat ($p = 0.573$). These findings underscore the effectiveness of the multimodal physical activity intervention implemented in the experimental group, which significantly improved students' fundamental movement competence compared to the conventional program. To complement the statistical significance testing, effect size was calculated using Cohen's *d*. The analysis showed that the multimodal training program had a moderate effect on squats ($d = 0.576$) and push-ups ($d = 0.647$), and a large effect on lunges and twists ($d = 1.191$) as well as bends and pulls ($d = 1.486$). In contrast, single-leg squats demonstrated a small to moderate effect size ($d = 0.405$).

Discussion

This study aimed to evaluate the effectiveness of a 12-week multimodal physical activity program implemented through a collaborative, student-centered learning approach in improving students' movement competence. The results indicate that the experimental group experienced statistically significant improvements in all aspects of movement

Table 4. Paired sample t-test scores of the experimental and control groups

Criteria	Groups	Pre-test M±SD	Post-test M±SD	t	p	Cohen's d
Squat	Experiment	1.27 ± 0.521	1.60 ± 0.621	-3.340	.002	0.576
	Control	1.50 ± 0.731	1.77 ± 0.817	-1.547	.133	
Lunge and Twist	Experiment	2.30 ± 0.702	3.40 ± 1.102	-6.279	.000	1.191
	Control	4.27 ± 1.172	4.33 ± 0.959	-.403	.690	
Bend and Pull	Experiment	2.63 ± 0.850	3.87 ± 0.819	-6.713	.000	1.486
	Control	3.33 ± 1.093	3.40 ± 0.932	-.372	.712	
Push Up	Experiment	1.30 ± 0.535	1.67 ± 0.606	-4.097	.000	0.647
	Control	1.63 ± 0.718	1.77 ± 0.728	-1.000	.326	
Single Leg Squat	Experiment	1.13 ± 0.434	1.33 ± 0.547	-2.693	.012	0.405
	Control	1.57 ± 0.679	1.53 ± 0.730	.571	.573	

competence after completing the program. Previous studies have shown that collaborative and active learning approaches can effectively stimulate the development of motor skills and teamwork abilities [23]. The multimodal physical activity approach facilitates the activation of various neuromuscular systems, supporting improvements in coordination, strength, and body control [24]. Consistent with the findings of this study, other research has also demonstrated that incorporating a diverse range of physical activities within physical education contributes positively to movement competence [25, 26].

Although the participants in this study were students enrolled in a physical education program, the pre-test results revealed that their initial level of movement competence was relatively low. This outcome may be attributed to a monotonous approach to physical education that emphasizes direct instruction and repetitive movements, without sufficient cognitive and affective engagement. Previous research supporting the findings of this study suggests that cooperative learning in physical education can enhance student motivation, self-confidence, and sense of relatedness. These are affective outcomes that contribute to meaningful learning. Cooperative learning can also promote knowledge acquisition, problem-solving abilities, and cognitive development [27, 28, 29]. Several studies have also demonstrated that limited variation and lack of adaptation in physical activity programs may hinder the development of movement competence [30, 31].

The analysis of the control group revealed no statistically significant results, and even showed a slight decline in the single-leg squat indicator. This finding is consistent with previous research suggesting that teacher-centered methods may reduce student enthusiasm, engagement, and the development of essential skills, as students tend to participate passively. As a result, lower levels of physical fitness and a weaker understanding of movement concepts are frequently observed [32, 33]. Reporting the findings in the control group is important, as null or negative results are often underrepresented in experimental studies. However, such data can provide valuable insights into the limitations of conventional instructional approaches.

Over the past few decades, physical education research has primarily focused on elementary and secondary education levels, with an emphasis on early motor skill development [34, 25, 36]. In contrast, populations in early adulthood, such as college students, have rarely been the focus of such interventions, even though this phase is a critical transitional period for establishing long-term physical activity patterns that are essential to health and well-being [37]. Several studies have reported a

statistically significant decline in physical activity participation once students enter higher education [38, 39]. Therefore, pedagogical approaches that are both relevant and adaptive are urgently needed to promote an active and healthy lifestyle. Supporting the findings of the present study, previous research has shown that diverse fitness programs can enhance motor memory and coordination skills, and that such approaches are effective in developing movement competence among university students [40].

Unlike previous studies that tend to examine single types of physical activity in isolation [41], the findings of this study are supported by existing research indicating that integrating varying intensities and forms of physical activity within a multimodal program is more effective in enhancing multiple aspects of movement competence [2, 7, 31]. Game-based collaborative learning has also been shown to increase students' motivation, engagement, and motor skill development [42, 43]. However, controlled experimental designs, particularly quasi-experiments with pre-test and post-test measures in higher education contexts, remain limited.

Limitations

This study has several limitations that should be acknowledged. First, the participant sample was limited to male students from a single academic program at one university. This homogeneity restricts the generalizability of the findings to broader populations, including female students, individuals from other academic disciplines or institutions, and participants with diverse cultural and fitness backgrounds. Second, the study did not include affective variables such as intrinsic motivation, self-confidence, or the quality of social interaction, despite the recognized importance of these factors in holistic physical education.

Future research is recommended to involve more diverse participant groups, extend the duration of the intervention, and incorporate measures of affective domains. Such efforts would contribute to a more comprehensive understanding of the effectiveness of physical activity-based interventions and enhance the applicability of findings across varied educational contexts.

Conclusions

The findings of this study indicate that a 12-week multimodal physical activity program is effective in improving movement competence among physical education students. Significant improvements were observed in five fundamental movement skills: squat, lunge and twist, bend and pull, push-up, and single-leg squat, compared to the control group. These results underscore the value of a varied and collaborative approach to physical activity-based

learning. The study supports the integration of multimodal strategies into higher education physical education curricula, emphasizing collaboration, active engagement, and movement exploration to enhance student outcomes.

Conflict of Interest

The authors declare no conflict of interest.

AI Tools Usage

In preparing this manuscript, the authors made limited use of several artificial intelligence (AI)-

based tools to enhance the efficiency and quality of academic writing. ChatGPT was used to assist with sentence restructuring, grammar correction, and language refinement in accordance with academic standards. Additionally, Consensus was used as a search tool to identify and select scientific references relevant to the research topic. DeepL Translator supported the translation process, while Grammarly was employed to check and improve grammar in the final version of the manuscript. All data analyses and statistical procedures were conducted independently using SPSS software.

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Cite this article as:

Wibowo C, Dese DC. A multimodal physical activity training program to improve motor competence in college students: evidence from a controlled 12-week trial. *Pedagogy of Physical Culture and Sports*, 2025;29(4):288–296.

<https://doi.org/10.15561/26649837.2025.0406>

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Received: 30.06.2025

Accepted: 06.08.2025; Published: 30.08.2025

Effects of plyometric and agility-based training on physical performance in adolescent male volleyball players: a controlled experimental study

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Abstract

Background and Study Aim

Plyometric and agility training are widely used among adolescent male volleyball players to support neuromuscular development. These types of training can have different effects on the fundamental components of physical performance in young volleyball players. This study aims to investigate the effects of plyometric and agility training on sprint performance, vertical jump, anaerobic power, and agility in adolescent male volleyball players over an 8-week program.

Material and Methods

Thirty adolescent male volleyball players participated in the study. They were randomly assigned to one of three groups: plyometric training (PT), agility training (AT), or control (CON), with 10 participants in each group. The PT and AT groups performed their respective training programs twice per week for 8 weeks. The control group continued with regular volleyball training only. Performance tests were conducted before and after the intervention. These included a 10-meter sprint, vertical jump, agility (Arrowhead test), and anaerobic power (peak power calculated using the Sayers formula). The data were analyzed using the SPSS software.

Results

The PT group showed significant improvements in vertical jump (+14.1%), peak power (+13.25%), and sprint performance (+3.07%). The AT group recorded significant improvements in agility (+2.05%) and sprint (+1.77%). Significant changes in the control group were limited. Both types of training led to improvements in different performance components. The PT group was more effective in enhancing explosive power and speed, while the AT group improved agility.

Conclusions

Plyometric and agility training play complementary roles in improving physical performance in adolescent volleyball players. PT programs develop explosive strength and sprint capacity. AT programs are more effective for improving agility and change-of-direction skills. Coaches can combine these two approaches based on the athletes' needs to achieve comprehensive performance enhancement.

Keywords: plyometric, agility, physical performance, adolescent, volleyball.

Introduction

Adolescent volleyball players undergo intensive physical and technical development as they transition toward higher levels of performance. During this stage, targeted training programs are often implemented to improve specific motor abilities such as speed, explosive power, and agility. Plyometric and agility-based exercises are among the most commonly used methods to enhance these physical qualities in youth athletes.

Volleyball is a high-intensity, dynamic team sport characterized by frequent jumping, sudden changes in direction, explosive force production, and short-distance sprints [1, 2]. Therefore, volleyball players must be able to effectively perform specific movement patterns that involve high levels of force, quick directional changes, and speed [3, 4, 5]. For developing athletes, this demand requires the improvement of fundamental physical performance

components. These include agility, speed, strength, balance, and muscle power, which can be enhanced through training [6, 7, 8, 9]. In this context, the effects of the training types used in this study were examined through the lens of the neuromuscular adaptation model. This model suggests that physical performance can be improved by enhancing motor unit activation, muscle-tendon coordination, and movement pattern efficiency [9, 10, 11, 12].

In recent years, there has been growing interest in training methods designed to support neuromuscular development in adolescent athletes. Two important methods stand out in this regard: plyometric training and agility-based exercises. Plyometric training is based on the stretch-shortening cycle of muscles. It aims to increase strength and jumping capacity, particularly in the lower extremity muscles [9, 13, 14]. The literature frequently highlights the positive effects of this training on parameters such as muscle strength, explosive strength, jump height, and sprint performance [15, 16, 17, 18, 19]. For example,

Pramono et al. [15] reported that plyometric exercises supported by agility ladders significantly increased muscle strength and agility in athletes aged 13 to 15 years. Similarly, Alp and Mansuroğlu [20] emphasized that regional plyometric training combined with volleyball training supports agility development. However, some studies have shown no significant changes in parameters such as sprint performance [21], suggesting that the effects may vary depending on the type and duration of the program.

However, agility-based exercises are also commonly used in volleyball. These training methods aim to develop on-court skills such as changing direction, reaction time, and short-distance sprints [22, 23, 24]. Such exercises target the adaptation of the neuromuscular system. They are reported to have the potential to improve movement efficiency in sports like volleyball, which require sudden acceleration and deceleration. Chuang et al. [25] reported that agility ladder and trapezoid running protocols applied to young volleyball players led to significant improvements in sprint and agility performance. In addition, agility training supports not only physical agility but also cognitive and athletic processes, such as decision-making [26]. Systematic reviews of studies combining plyometric and agility training reported an average improvement of 7.7% in agility.

Although the effects of plyometric and agility-based training on physical performance have been examined separately in numerous studies, experimental research directly comparing these two types of training and controlling for variables such as age group, sport discipline, and training duration remains limited. Current findings suggest that both types of training may influence different performance parameters to varying degrees. For example, some studies indicate that agility-based training is more effective for improving sprint performance and reaction time [24, 25, 26]. In contrast, other studies have shown that plyometric training leads to greater improvements in parameters such as jump height and explosive power [15, 20, 27]. However, some studies report similar results for both methods. Others reach conflicting conclusions regarding which training method is more advantageous [21, 28]. This inconsistency complicates the scientific guidance provided to decision-makers in training planning, especially for adolescent athletes.

An analysis of previous research has shown that both plyometric and agility-based training positively influence various components of physical performance in young volleyball players. The authors emphasize that each training type affects different variables such as speed, strength, jump endurance, and agility in distinct ways. They also highlight that, despite the growing body of evidence, there is still no clear scientific consensus regarding the comparative effectiveness of these two training methods. At the same time, there remains a need for further controlled

experimental studies directly comparing the effects of plyometric and agility-based training on physical performance in adolescent male volleyball players. This gap continues to hinder scientifically grounded training planning and limits the practical guidance available to coaches and practitioners.

Based on the reviewed literature and the lack of clear consensus regarding the comparative effects of plyometric and agility-based training, the following hypotheses were proposed:

1. Both training groups are expected to show significant improvements in physical performance indicators after 8 weeks of application.
2. It is hypothesized that agility-based training will result in greater improvements in the 10-meter sprint and agility tests compared to plyometric training.
3. It is also hypothesized that plyometric training will lead to greater improvements in vertical jump and anaerobic power parameters compared to agility-based training.

This study aims to investigate the effects of plyometric and agility training on sprint performance, vertical jump, anaerobic power, and agility in adolescent male volleyball players over an 8-week program.

Materials and Methods

Participants

This study was conducted to examine the effects of an eight-week plyometric and agility-based training program on physical performance in young male volleyball players. A total of 30 volunteer athletes aged between 13 and 14 years participated in the study. Participants were randomly assigned to one of three groups: the plyometric training group (PT, $n = 10$), the agility training group (AT, $n = 10$), and the control group (CON, $n = 10$). There were no cases of exclusion or withdrawal during the study. The flow of participants through the study is shown in Figure 1.

All groups continued their routine volleyball training throughout the eight-week period. The PT group additionally followed a training program consisting of plyometric exercises twice per week. Similarly, the AT group participated in agility-based training twice per week. In contrast, the CON group continued with volleyball training only and did not take part in any additional training. No adverse events, injuries, or side effects were observed during the study. This supports the safety and applicability of the implemented training programs.

*Sample size (g*power)*

The sample size was calculated using G*Power software (version 3.1.9.7; Franz Faul, Kiel University, Germany). The calculation was based on a significance level (α) of 0.05, statistical power ($1 - \beta$) of 80%, an effect size (f) of 0.4, and a repeated measures ANOVA

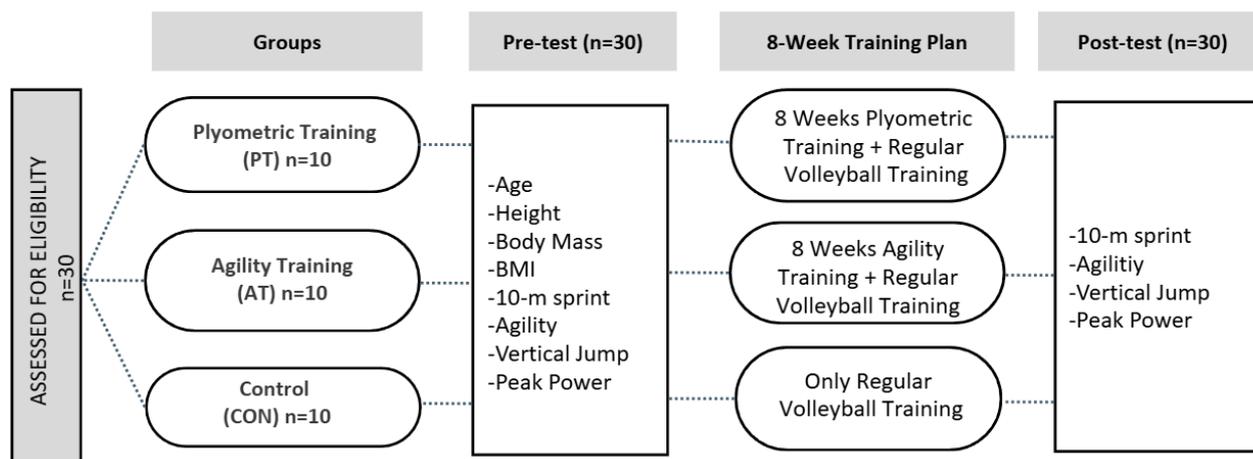


Figure 1. Flow Diagram

with a group × time interaction [29].

Informed consent was obtained from all participants prior to the study. The research was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Non-Interventional Clinical Research Ethics Committee of Alanya Alaaddin Keykubat University (approval number: 2025/01). Descriptive anthropometric data for the groups are presented in Table 1.

Table 1. Descriptive characteristics of the participants ($\bar{x} \pm SD$)

Variables	Groups	N	$\bar{x} \pm SD$	Min	Max
Age (years)	PT	10	13.30 ± 0.48	13.00	14.00
	AT	10	13.40 ± 0.51	13.00	14.00
	CON	10	13.40 ± 0.51	13.00	14.00
Height (m)	PT	10	1.51 ± 0.03	1.44	1.56
	AT	10	1.52 ± 0.08	1.43	1.72
	CON	10	1.51 ± 0.07	1.42	1.62
Body Mass (kg)	PT	10	44.60 ± 8.57	35.00	67.00
	AT	10	43.00 ± 7.42	33.00	53.00
	CON	10	44.80 ± 5.24	36.00	55.00
BMI (kg/m ²)	PT	10	19.35 ± 3.65	16.88	29.38
	AT	10	18.90 ± 2.39	15.35	21.93
	CON	10	19.56 ± 1.81	17.15	22.89

Note: PT = plyometric training group, AT = agility training group, CON = control group, BMI = Body Mass Index, \bar{x} = mean, SD = standard deviation.

Table 1 presents the descriptive characteristics of the participants, including age, height, body mass, and BMI for each group. The mean age of participants in all three groups was similar, ranging from 13.30 to 13.40 years, indicating homogeneity in age distribution. Height and body mass values also showed comparable averages, with only minor variations among groups. The agility training group (AT) exhibited slightly greater variation in height (sd = 0.08) compared to the PT and CON groups. In terms of BMI, all groups were within a similar range,

with slightly higher variability in the PT group (sd = 3.65). Overall, the groups were well-matched at baseline, showing no notable differences in descriptive characteristics.

Research Design

The plyometric training program applied to the PT group was implemented regularly over a period of eight weeks, with two sessions per week. Each session lasted approximately 30 minutes and included 10 minutes of warm-up and dynamic stretching exercises, followed by 20 minutes of plyometric drills. This part of the training consisted of basic lower-extremity-focused plyometric exercises, such as squat jumps, box jumps (approximately 30–40 cm), lateral bounds, and depth jumps. The exercises were structured progressively by week. The first two weeks focused on basic movements. In the subsequent weeks, training intensity was gradually increased by adjusting jump height, number of repetitions, and tempo. The program was developed based on previous studies, including those by Hernandez-Martinez et al. [16] and Iranpour et al. [30], which demonstrated positive effects on jump height and explosive power in young athletes (Table 2).

The AT group also participated in two 30-minute agility-based training sessions per week for eight weeks. Each session consisted of a general warm-up followed by agility ladder drills, change-of-direction runs, and short-distance sprints. During the first two weeks, basic ladder drills such as “two-in-the-hole” and “lateral shuffle” were included. In the third and fourth weeks, more advanced variations such as crossovers and high-tempo drills were introduced. From the fifth week onward, the focus shifted to reactive tasks involving backward movements and decision-making elements. The program was based on agility training protocols developed by Chuang et al. [25], which have been shown to significantly improve lateral agility and sprint performance in young athletes (Table 3).

All training sessions for both groups were supervised by a certified strength and conditioning

Table 2. Plyometric training program

Week	Frequency (days/week)	Duration (min)	Intensity	Content	Progression
1–2	2	30	Low–Moderate	Warm-up + squat jumps, box jumps (30 cm), lateral jumps (3 × 8 reps)	Focus on basic technique, low platform height
3–4	2	30	Moderate	Add: depth jumps (30 cm), split squat jumps, skipping drills	Increase repetitions (3 × 10), maintain control and form
5–6	2	30	Moderate–High	Add: single-leg jumps, bounding drills, tuck jumps	Reduce ground contact time, develop reactive strength
7–8	2	30	High	Combined sequences: box-to-lateral jumps, depth-to-vertical jump combos	Gradual overload of reactivity and plyometric complexity

Table 3. Agility training program

Week	Frequency (days/week)	Duration (min)	Intensity	Content	Progression
1–2	2	30	Low–Moderate	Warm-up + basic agility ladder drills (e.g., two-in, side step), 10-m sprints (3 × 2 reps)	Focus on coordination and directional control
3–4	2	30	Moderate	Add: Ickey shuffle, zig-zag ladder drills, T-test (2 × 2 reps)	Increase movement speed and sharper angles
5–6	2	30	Moderate–High	Ladder tempo drills, arrowhead drill, lateral sprints (4 × 2 reps)	Add reaction-based movements and decision-making tasks
7–8	2	30	High	Random cone drills, game-based agility tasks, Illinois Agility Test (1 × 2 reps)	Emphasis on multi-directional change of direction and complex movement

specialist to ensure the technical accuracy of participants’ movements. In addition, the training programs were designed not only for physical development but also to enhance athletes’ motor skills. They included coaching cues and specific learning objectives. These practices are consistent with physical education curricula and youth athlete development standards, supporting both physical and pedagogical outcomes.

Testing Procedure

Prior to testing, all participants completed a five-minute warm-up consisting of light jogging, followed by five minutes of dynamic and static stretching exercises. The purpose of the warm-up was to elevate heart rate, increase blood circulation and body temperature, improve range of motion, and prepare the body for physical effort. In all tests, participants were instructed to exert maximum effort and received verbal encouragement throughout the procedures.

The Arrowhead Agility Test was administered according to the protocol proposed by Jalilvand et al. [31]. Time measurements were recorded using the Brower Speed Trap I Timing System (Brower Timing Systems, Salt Lake City, UT, USA). Participants began the test approximately 1 meter behind the starting photocell. They sprinted toward the middle cone, turned outward in their preferred direction,

and continued forward. The course was completed by running around the side cone and then the upper cone before reaching the finish photocell.

The 10-meter sprint test was conducted on a 30-meter running track with a flat, hard surface. Time measurements were recorded using the Brower Speed Trap I Timing System, which operates with dual light sensors and has an accuracy of 0.001 seconds. After a general warm-up, athletes took their positions at the starting line and began running at their own discretion following the “ready” command. This procedure ensured that reaction time was excluded from the measurement. Timing started when the athlete crossed the first photoelectric cell and stopped upon crossing the second cell at the 10-meter mark [32].

The Vertical Jump Test was administered using a force platform or an electronic jump mat. Participants began in a standing position with feet shoulder-width apart and hands placed on the hips. They performed a vertical jump by bending their knees to approximately 90 degrees and jumping upward. To eliminate the effect of arm movement, participants were instructed to keep their hands stationary throughout the movement. Each participant performed three trials, and the average of the best two attempts was used for analysis [33].

Peak power was calculated using the Sayers formula, which estimates lower-limb anaerobic power based on vertical jump height and body mass [34]. The formula is expressed as:

$$\text{Peak Power (W)} = (60.7 \times H) + (45.3 \times M) - 2055$$

Where: H = vertical jump height in centimeters; M = body mass in kilograms; W = peak power in watts.

Statistical Analysis

The collected data were analyzed using IBM SPSS Statistics 25.0 (Chicago, IL, USA). The normality of the data distribution was assessed using the Shapiro-Wilk test, which confirmed that the data were normally distributed. A two-way repeated measures ANOVA was conducted with two factors: group (PT, AT, CON) and time (pre-test, post-test). Bonferroni-corrected post hoc tests were applied to determine between which groups significant interactions occurred. Effect sizes were calculated using partial eta-squared (η^2) and interpreted according to Cohen's criteria [35] as follows: $\eta^2 < 0.06$ = small effect, $0.06-0.14$ = moderate effect, and ≥ 0.14 = large effect. Additionally, percentage (%) changes within each group were calculated using Microsoft Excel. A significance level of $p < 0.05$ was accepted for all analyses.

Results

Figure 2 illustrates the pre- and post-test results of the vertical jump test for each group. The PT group demonstrated the greatest improvement, followed by the AT group, while the control group showed a more modest but still statistically significant increase.

The data in Figure 2 show a significant increase in vertical jump height between the pre-test and post-test in all three groups. The PT group showed the largest improvement ($t = 9.675$; $p < 0.001$), followed

by the AT group ($t = 7.584$; $p < 0.001$). A smaller but still significant increase was also observed in the control group ($t = 2.748$; $p = 0.015$). The effect size was highest in the PT group ($d = 0.691$). The analysis of variance confirmed a significant difference between the groups ($F = 7.010$; $p = 0.004$).

Figure 3 displays the pre- and post-test results of the 10-meter sprint test for all groups. Both the PT and AT groups showed significant reductions in sprint time after the intervention, with the PT group demonstrating the greatest improvement. The control group also showed a smaller but statistically significant decrease.

The data in Figure 3 show a significant decrease in 10-meter sprint time from pre- to post-test in all three groups. The PT group demonstrated the largest improvement ($t = 8.573$; $p < 0.001$), followed by the AT group ($t = 3.910$; $p = 0.004$). The CON group also showed a statistically significant, but more limited, reduction ($t = 2.539$; $p = 0.017$). The greatest effect size was observed in the PT group ($d = -0.482$). Analysis of variance indicated a statistically significant difference between the groups ($F = 14.444$; $p < 0.001$).

Figure 4 presents the pre- and post-test results of the Arrowhead Agility Test across all groups. Both the PT and AT groups showed significant improvements in agility performance, with slightly greater progress in the PT group. No significant change was observed in the control group.

The data in Figure 4 show a significant decrease in agility time from pre- to post-test in the PT group ($t = 4.404$; $p = 0.002$) and in the AT group ($t = 6.137$; $p < 0.001$). No significant change was observed in the CON group ($t = 0.629$; $p = 0.545$). The largest effect size was recorded in the PT group ($d = -0.596$). The difference between the groups was statistically significant according to the analysis of variance ($F = 7.012$; $p = 0.004$).

Figure 5 shows the pre- and post-test results of

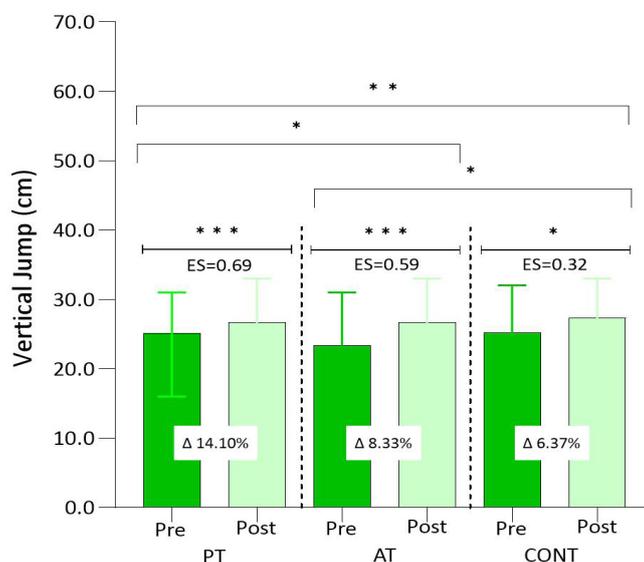


Figure 2. Pre- and post-test results of the vertical jump test (cm)

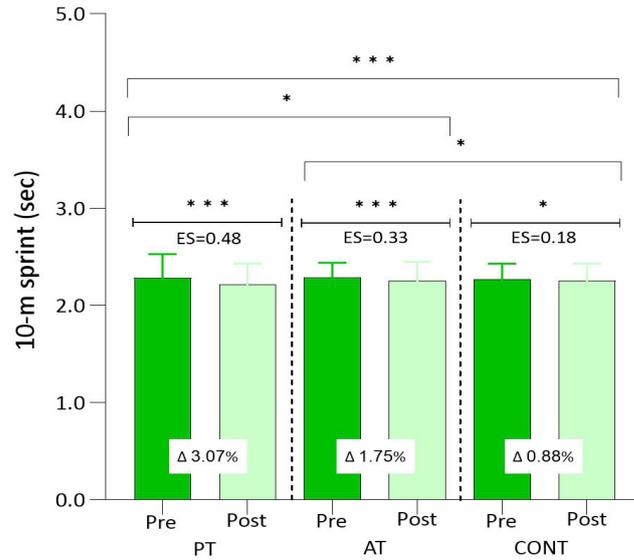


Figure 3. Pre- and post-test results of the 10-meter sprint test (sec)

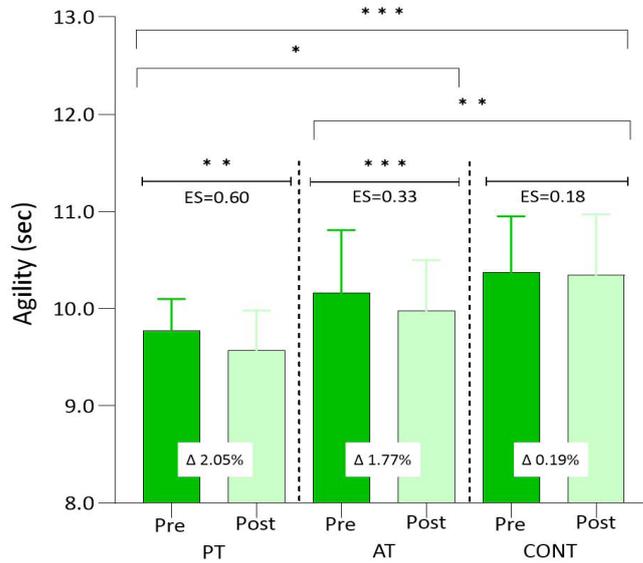


Figure 4. Pre- and Post-test Results of the Arrowhead Agility Test (sec)

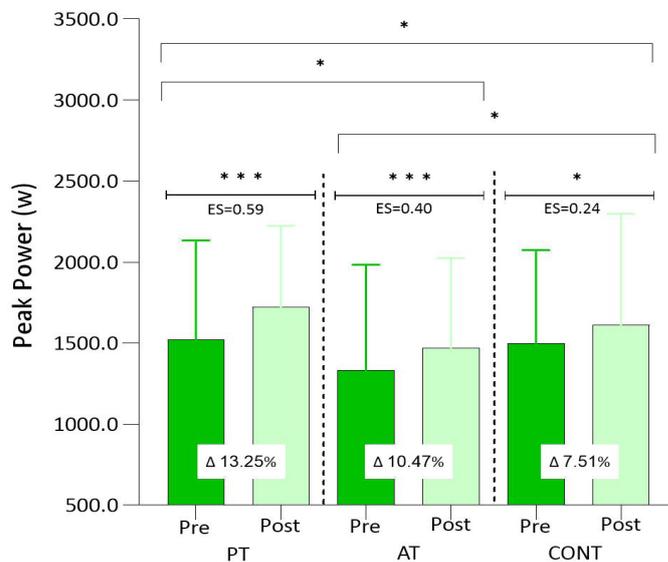


Figure 5. Pre- and post-test results of peak power (w)

peak anaerobic power in all groups. The PT group demonstrated the highest increase in power output, followed by the AT group. A smaller but statistically significant improvement was also recorded in the control group.

The data in Figure 5 show a significant increase in anaerobic power from pre- to post-test in all three groups. The PT group showed the largest improvement ($t = 9.399$; $p < 0.001$), followed by the AT group ($t = 5.732$; $p < 0.001$). A smaller but statistically significant increase was also observed in the control group ($t = 3.110$; $p = 0.010$). The effect size was moderate in the PT group ($d = 0.591$). Analysis of variance confirmed a significant difference between the groups ($F = 4.079$; $p = 0.028$).

Discussion

This study compared the effects of an 8-week plyometric training (PT) and agility training (AT) program on physical performance components in adolescent male volleyball players. The findings indicate that both training groups achieved significant improvements in physical performance variables, but in different ways. In the control group, improvements were also observed in vertical jump, anaerobic power, and 10-meter sprint performance. This outcome can be attributed to the natural growth and development processes in adolescents, which contribute to enhanced muscle strength and motor skills [36]. In addition, previous studies have shown that volleyball training alone may positively influence muscle strength and coordination [27].

The highest improvement in vertical jump performance was observed in the PT group. This finding is consistent with the widely accepted view in the literature that plyometric training enhances lower extremity explosive strength [9, 13, 14]. Pramono et al. [15] and Alp and Mansuroğlu [20] similarly reported that plyometric exercises significantly increased muscle strength and jump height. Balasas et al. [37] observed an 8.8% increase in jump height among adolescent female volleyball players following a 15-week plyometric and resistance training program. Pacheco Naula and Torres-Palchisaca [38] reported similar results after a six-week plyometric program. Stojanovic et al. [39] also emphasized that plyometric training supports the development of explosive strength in lower limb muscles. These findings support the improvements observed in the PT group. A significant improvement in jump height was also recorded in the AT group. This suggests that agility training may indirectly enhance force production by improving neuromuscular coordination. Although the direct effect of agility-based exercises on jump performance is limited in the literature, the current study indicates that agility-focused interventions may contribute to such improvements [24].

The PT group's greater improvement in 10-meter

sprint performance compared to the AT group is consistent with studies supporting the positive effects of plyometric training on sprint ability. Ramírez-Campillo et al. [40] reported that low-volume but high-intensity plyometric training improved short-distance sprint performance. This improvement can be explained by increased explosive strength and reduced ground contact time [9]. However, a study conducted by Sitti and Köroğlu [21] in a similar age group found no significant improvement in sprint performance. This discrepancy may be related to differences in training duration, exercise content, or the biological development level of the participants [41]. The improvement observed in the PT group may also result from the fact that the exercises targeted not only strength, but also neuromuscular mechanisms affecting sprint performance, such as coordination [42].

The significant improvement observed in the AT group suggests that agility training can enhance not only change-of-direction ability, but also sprint-related components such as acceleration, balance, and reaction time [43, 44]. Chaouachi et al. [45] proposed that agility training may indirectly contribute to sprint performance. Similarly, Paul et al. [46] reported that such training could lead to neuromuscular adaptations in 10–20-meter sprint distances.

The improvement in the PT group may be primarily related to direct effects on the initial acceleration phase, whereas the improvement in the AT group may reflect gains in reaction time, directional changes, and movement preparation. The minimal but significant improvement in the control group may be attributed to biological growth-related adaptations and the influence of non-training daily physical activities on speed and strength development [47]. These findings emphasize the importance of designing training content according to specific performance goals.

Significant improvements in agility performance were observed in both the AT and PT groups. However, the higher effect size recorded in the PT group suggests that plyometric training may also be effective in enhancing agility. This finding aligns with previous studies indicating that plyometric training supports not only lower extremity strength but also multi-component motor skills [48, 49]. Asadi et al. [50] demonstrated that an 8-week plyometric program improved agility performance in young athletes. Hammami et al. [44] emphasized that agility is closely related to neuromuscular function and that adaptations in this system can be facilitated through plyometric training.

The improvement observed in the AT group suggests that agility-related parameters such as change of direction, balance, and reaction time can be effectively developed through agility training. Chuang et al. [51] reported that agility-based

programs significantly enhanced this ability in young volleyball players. Similarly, Chaouachi et al. [45] noted that agility-focused training improves motor control and reaction times to environmental stimuli.

The increase in agility performance observed in the control group may be attributed to overall improvements in motor coordination and maturation of the nervous system. Additionally, regular volleyball training could have contributed to the development of agility [24]. Both training methods positively influenced agility performance. However, the more comprehensive neuromuscular stimulation provided by plyometric exercises may lead to greater improvements. The inclusion of complex movement patterns such as short sprints, directional changes, and jumps in the training content may be a key factor in agility development.

The highest increase in peak power was observed in the PT group. Although increases were also recorded in the AT and control groups, these improvements were more limited. The developments observed across all groups may be attributed to factors such as biological growth, increased familiarity with the testing procedures, and the effects of ongoing volleyball training [52]. However, the greater improvements in the experimental groups reflect the specific influence of the applied training protocols.

The literature emphasizes that plyometric training enhances explosive power by improving the elastic properties of the muscle-tendon system [9, 40]. Makaruk et al. [53] reported that an 8-week plyometric training program increased anaerobic power output and was particularly effective for short-term, high-intensity performance. Furthermore, studies have shown that the combined application of plyometric and agility training enhances neuromuscular coordination, positively affecting both explosive power and agility [50, 54].

The improvements observed in the AT group suggest that agility-focused exercises may influence not only directional change abilities but also neuromuscular components related to power production. Hammami et al. [55] found that agility training had positive effects on balance, reactive strength, and lower limb strength. Both training methods were found to be effective in increasing explosive power. However, the greater improvement in the PT group suggests that plyometric training provides more specific stimuli for load patterns and musculoskeletal adaptations. Training programs that target different motor abilities may lead to different levels of performance improvement.

Compared to previous studies that examined plyometric or agility training separately [15, 20, 40, 50], the novelty of this study lies in the direct comparison of both methods within a controlled

design. It simultaneously assessed their effects on multiple performance parameters in adolescent male volleyball players. The homogeneity of the sample and the structured group comparison offer clearer insights into sport- and age-specific training responses, contributing to a better understanding of how different methods support athletic development.

In summary, both plyometric and agility-based training programs were effective in improving key physical performance components in adolescent male volleyball players. Plyometric training demonstrated greater effects on explosive power, vertical jump, and sprint performance, while agility training showed notable improvements in agility and also contributed to other performance variables. The observed differences highlight the role of training specificity and the importance of selecting exercises based on targeted outcomes. Additionally, the findings suggest that integrating both training types may offer complementary benefits and support comprehensive athletic development in youth volleyball.

Limitations

Considering the limitations of this study, the relatively small sample size, the exclusive focus on male adolescent volleyball players, and the absence of long-term follow-up restrict the generalizability of the findings. Future research should examine the effects of similar training protocols across different age groups, genders, and sports disciplines, as well as combinations of training methods. In addition, studies that provide a detailed analysis of the biomechanical and physiological foundations of neuromuscular adaptations would enhance the understanding of training effects.

Conclusions

As a result, considering that the PT and AT groups followed only their respective training programs, it was concluded that plyometric training led to greater improvements in explosive strength and speed, while agility training resulted in more pronounced gains in agility and movement ability. Although each training type was most effective for its targeted performance parameters, cross-effects were also observed in some components, likely due to overlapping neuromuscular demands. This finding suggests that both training methods contribute to different aspects of physical performance and collectively enhance athletes' overall capabilities. In this context, plyometric and agility training serve complementary and essential roles in the performance development of adolescent volleyball players. From a pedagogical standpoint, coaches and physical education teachers should strategically combine both types of training, taking into account the individual needs of their athletes. This approach

can help ensure balanced development of both explosive power and agility. The findings of this study provide a practical framework for designing scientifically grounded and effective training programs for youth athletes.

Conflict of Interest

The authors declare no conflict of interest. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Cite this article as:

Atıcı M, Bayrakdar A. Effects of plyometric and agility-based training on physical performance in adolescent male volleyball players: a controlled experimental study. *Pedagogy of Physical Culture and Sports*, 2025;29(4):297–307. <https://doi.org/10.15561/26649837.2025.0407>

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Received: 03.07.2025

Accepted: 07.08.2025; Published: 30.08.2025

Effects of a 12-week integrated core and plyometric training program on tennis skills, agility, strength, and balance in adolescent tennis players

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Abstract

Background and Study Aim Tennis performance in adolescents depends on the development of agility, strength, balance, and sport-specific skills. During the growth period, optimizing training strategies is essential to enhance performance without increasing injury risk. There is a growing interest in combining core and plyometric exercises within structured training programs. This study aimed to examine the effects of a 12-week integrated core and plyometric training program on tennis-specific skills (ITN score), agility, lower-body strength, and dynamic balance in adolescent tennis players aged 12–14 years.

Material and Methods Twenty-two junior male players were recruited and block-randomized into two groups: an experimental group (integrated core and plyometric training plus regular tennis) and a control group (regular tennis only). Five participants withdrew from the study. The final sample consisted of 17 players (experimental $n = 8$, control $n = 9$). Pre- and post-tests included the ITN, Pro-Agility Test, Squat Jump (SJ), Countermovement Jump (CMJ) using the BTS SportPlate™, and the Star Excursion Balance Test (SEBT). Shapiro-Wilk tests confirmed that all variables were normally distributed, satisfying the assumptions for parametric testing. Data analysis included repeated measures ANOVA, post hoc comparisons, effect sizes, and Pearson correlation coefficients.

Results Repeated measures ANOVA revealed significant group \times time interactions for ITN score ($F = 12.34$, $p = 0.003$, $\eta^2 = 0.45$), Pro-Agility Test ($F = 7.45$, $p = 0.015$, $\eta^2 = 0.38$), and SEBT ($F = 6.56$, $p = 0.018$, $\eta^2 = 0.35$). No significant interactions were found for SJ or CMJ. Pairwise comparisons showed large effects for ITN improvement (experimental group: Mean Diff = -1.2 , $p = 0.001$, $d = 1.20$) and Pro-Agility time (experimental group: -0.23 s, $p = 0.004$, $d = 0.85$). SEBT scores increased by 6.1 points ($p = 0.003$, $d = 0.92$). A moderate negative correlation ($r = -0.52$, $p < 0.05$) was found between agility gains and ITN improvements.

Conclusions The 12-week integrated program significantly improved tennis skills, agility, and dynamic balance compared to regular training alone. However, it had minimal impact on vertical jump performance. These results support incorporating core and plyometric training into youth tennis programs to enhance sport-specific performance.

Keywords: core training, plyometric exercises, youth tennis players, agility performance, dynamic balance.

Introduction

Youth sport performance is shaped by a combination of physiological and motor control factors that evolve during growth and maturation. In tennis, the ability to perform rapid directional changes, maintain postural stability, and generate explosive movements is especially critical for success on the court. For adolescent players, improving such qualities presents a complex challenge, as training must balance the demands of physical development with age-appropriate load

management. This complexity underscores the importance of designing training processes that address multiple interrelated physical components.

Participating in sports and regular physical activity not only shapes the body but also acts as a transformative experience that supports overall physical fitness and mental well-being [1, 2]. Developing strength and power is widely recognized as essential for success in most competitive sports, including tennis [3]. Over recent decades, tennis has evolved from a primarily technical sport to one that demands high levels of speed, power, and agility [4]. Players must now combine precise shot-making with explosive movement, efficient court

coverage, and quick adaptability during dynamic matches [5]. Achieving this performance level depends on strong muscles and joint stability to produce powerful strokes and serves while reducing injury risk, especially in areas like the shoulders and hips [6]. Sufficient flexibility and joint mobility are also crucial for executing full swings and rapid directional changes. Conditioning methods such as plyometric training and resisted sprint drills have been shown to effectively develop these physical qualities [7, 8]. However, there is still no consensus on a single best approach for developing strength and power in tennis, underscoring the need for sport-specific research and program design.

In racket sports, technical and tactical skills are key to reaching elite levels and directly influence performance [9, 10]. These skills, including serves, groundstrokes, and tactical decision-making, are strongly associated with competitive success [11, 12, 13, 14]. At the same time, cardiovascular fitness, sprint rehearsal ability, change of direction speed, muscle strength, and muscle power are among the essential physical components required for successful tennis performance [5, 15, 16]. A stronger physical foundation provides more opportunities to develop technical, tactical, and psychological skills [17, 18, 19], as well as to prevent injuries [20]. Moreover, it is widely acknowledged that players need enhanced physical fitness to perform advanced strokes and compete effectively against stronger opponents [4].

Tennis is a dynamic and demanding sport that requires a combination of athletic qualities, including speed, explosive power, agility, and the ability to maintain high performance levels under competitive pressure. In this context, the study by [21] highlights the significant benefits of high-intensity interval training (HIIT) on various performance metrics in adolescent tennis players. It demonstrates marked improvements in aerobic capacity, agility, and sport-specific skills. To succeed in modern tennis, players need technical mastery supported by high physical fitness. This requires training approaches tailored to the sport's demands, such as plyometric training, which can boost both skills and physical performance [22]. Several types of exercise interventions can enhance performance in tennis players. For instance, resistance training can increase serve velocity [23], while strength training can enhance forehand and backhand hitting speed [24]. In addition, core training, balance training, and sprint training are known to improve speed and strength in tennis players [8, 25, 26]. High-intensity interval training also improves aerobic performance in young tennis athletes [27].

Among the many kinds of exercises, plyometrics assist in developing power, a foundation from which the athlete can refine the skills of their sport [28]. Muscle strength is a key factor for maintaining high-

level tennis performance during competition [29]. Core muscles play an essential role in stabilizing the spine and body during dynamic movements such as jumping, running, and throwing [30], while also supporting balance and lower-limb performance [31]. Because tennis involves constant directional changes and complex kinetic chain actions, a strong core is critical for transferring force efficiently from the ground through the body to the racket [32, 33].

In modern tennis, rotational movement has become a key factor in performance [34], requiring training that addresses strength, speed, balance, coordination, and flexibility in a three-dimensional approach [6, 35]. Players must maintain explosive leg and upper body strength, visual tracking, and attentional focus during long matches [36]. Core training should therefore build stability, posture, and injury prevention into every tennis-specific program [32]. For youth athletes, training should strengthen the abdominal, back, and spinal muscles first to create a solid base for limb movements, especially during growth [37]. Research supports that core training can improve shoulder rotation, serve speed, and reduce overuse injuries [38, 39]. Manchado et al. [40] found improved throwing speed in handball, while Afyon et al. [41] noted speed and agility gains in footballers. However, other studies found no significant agility benefits [42, 43].

Analysis of research findings has shown that various training methods, including core and plyometric exercises, contribute to improving physical performance indicators relevant to tennis. Researchers emphasize that the effectiveness of such interventions may depend on how well they are integrated into sport-specific training, especially during periods of rapid growth in adolescent athletes. Given the complexity of physical demands in tennis and the multiple components involved in performance development, further exploration of structured training combinations remains a meaningful direction. Within this context, examining the combined impact of core and plyometric training on key performance metrics in youth players becomes particularly relevant.

It is reasonable to assume that a structured combination of core and plyometric exercises may produce greater improvements in tennis-specific performance compared to conventional training alone, particularly during early adolescence when physical adaptations are most responsive. Targeted interventions that address both stability and explosive movement patterns could be especially effective in enhancing agility, balance, and lower-body strength in young athletes. This study aimed to examine the effects of a 12-week integrated core and plyometric training program on tennis-specific skills (ITN score), agility, lower-body strength, and dynamic balance in adolescent tennis players aged 12–14 years.

Materials and Methods

Participants

A total of twenty-two male tennis players, aged 12 to 14 years, were initially recruited to participate in this quasi-experimental study. All participants had a minimum of two years of consistent tennis training experience and were actively competing at the junior level in local tournaments. Participants were randomly allocated using block randomization to either the experimental group, which received an integrated core and plyometric training program in addition to regular tennis training, or the control group, which continued with standard tennis training only.

Due to injuries, scheduling conflicts, and non-compliance with the intervention protocol, five participants withdrew from the study during the first two weeks. Therefore, the final sample comprised seventeen participants, with eight in the experimental group and nine in the control group. Informed consent was obtained from all parents or legal guardians prior to participation, in line with the Declaration of Helsinki.

Study Design

The research was conducted in the southern region, and all sessions were supervised by certified strength and conditioning coaches. An a priori power analysis was conducted using G*Power 3.1 software [44] to determine the minimum required sample size for the planned 2 (Group: Experimental vs. Control) × 2 (Time: Pre vs. Post) repeated measures ANOVA. Based on an anticipated medium effect size ($f = 0.25$), an alpha level of 0.05, and a desired power ($1-\beta$) of 0.80, the analysis indicated that a minimum of 16 participants would be needed to detect significant main and interaction effects. To account for potential attrition, 22 participants were initially recruited, resulting in a final sample of 17 after withdrawals.

Table 1 presents the descriptive characteristics of the participants in the experimental and control groups. The two groups were well matched in terms

of age, height, weight, and training experience at baseline. The participants had comparable demographic profiles, with no major differences observed between the groups. All had at least two years of consistent tennis training and were actively competing at the junior level. This baseline similarity supports the assumption that any post-intervention effects are likely attributable to the training protocol rather than pre-existing group differences. No notable outliers or imbalances were identified, strengthening the internal validity of the study.

Measurement Tools

Tennis Skills. Players' tennis skill levels were assessed using the International Tennis Number (ITN) rating protocol, developed by the International Tennis Federation [45]. The ITN provides a standardized measure of playing ability based on serve consistency, groundstrokes, volleys, and physical mobility in various game situations. Scores were calculated from a composite of performance tests and used to assign an ITN number.

Agility. Agility performance was measured using the Pro-Agility Test, also known as the 5-10-5 Shuttle Run [46]. Participants sprinted laterally to cones positioned 5 yards (4.57 m) to the left and right of a starting line. Timing was recorded using electronic photocells for precision. Each participant performed a 180° turn at each cone, emphasizing change of direction speed.

Strength. Explosive leg strength was evaluated using the Squat Jump (SJ) and Countermovement Jump (CMJ), performed on the BTS SportPlate™ system (BTS Bioengineering) [47]. The SportPlate™ provides high-precision force-time data and jump height analysis, ensuring valid and reliable measurement of lower-limb power output. For the SJ, participants squatted to 90° knee flexion with hands on hips and jumped vertically without countermovement. For the CMJ, participants began from an upright standing position, performed a rapid downward movement to 90°, and then jumped vertically using an arm swing.

Dynamic Balance. To provide additional insight into functional stability, the Star Excursion

Table 1. Demographic Characteristics of Participants (N = 17)

Variable	Experimental Group (n = 8)	Control Group (n = 9)
	M ± SD	M ± SD
Age (years)	12.8 ± 0.6	13.1 ± 0.7
Height (cm)	158.4 ± 5.5	160.2 ± 6.0
Weight (kg)	47.5 ± 6.3	48.8 ± 7.1
Training Experience (years)	2.6 ± 0.5	2.6 ± 0.5

Note. Values are presented as mean ± standard deviation (SD). Groups were similar at baseline.

Balance Test (SEBT) was used [48]. The SEBT required participants to maintain balance on one leg while reaching with the other leg in eight different directions. Maximum reach distances were normalized to leg length and averaged across directions.

Procedures

The integrated training protocol was implemented over a 12-week period and was designed to progressively develop core strength, stability, and explosive power. Each two-week phase targeted specific physical qualities, with core and plyometric exercises selected to match the developmental focus. Exercise intensity, volume, and rest intervals were adjusted accordingly to support adaptation while minimizing injury risk. An overview of the training structure is presented in Table 2.

Baseline testing was conducted one week before the intervention to establish pre-training measurements. All participants completed the ITN Tennis Skills Test, Pro-Agility Test, Squat Jump (SJ), Countermovement Jump (CMJ) using the BTS

SportPlate™, and the Star Excursion Balance Test (SEBT) in a fixed sequence to avoid fatigue bias. Testing sessions were held indoors under consistent conditions, with the same surface, time of day, and environmental factors for all participants. Each test was preceded by a standardized 10-minute dynamic warm-up and was supervised by trained assessors blinded to group allocation. Sufficient rest intervals of 2–3 minutes were provided between tests and trials to ensure valid results. The SEBT was practiced during a familiarization session to reduce learning effects. After the 12-week training program, all post-tests were conducted within one week using identical protocols and the same blinded assessors. Equipment was calibrated before each session. All data were double-checked for accuracy immediately after testing.

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics Version 27.0. Prior to conducting inferential tests, data were screened for normality using the Shapiro–Wilk test for each dependent variable at both pre- and post-intervention time points. Variables were considered

Table 2. 12-week integrated core and plyometric training program

Week(s)	Focus	Core Exercises	Plyometric Exercises	Sets × Reps	Intensity
1–2	Foundational strength and mechanics	Front plank, Bird dog, Dead bug, Basic crunch	Jump squat, Double-leg lateral hops	3 sets × 12–15 reps	Bodyweight only. Focus on form and control. Rest 45–60 s between sets.
3–4	Movement control and stability	Side plank (right and left), Swiss ball crunch, Russian twist (bodyweight), Hip bridge	Single-leg hops, Skater jumps	3–4 sets × 10–12 reps	Light resistance introduced (medicine ball 2–3 kg for twists). Rest 60 s between sets.
5–6	Strength endurance and load progression	Hanging knee raises, Cable rotational pulls, Swiss ball roll-out, Plank with alternating leg lift	Bounding drills (20 m), Depth jumps (20–30 cm box)	4 sets × 8–12 reps	Resistance increased using bands or cable at approximately 40–50% of 1RM for rotational pulls. Plyometrics: soft landings. Rest 75–90 s.
7–8	Advanced stability and power	Medicine ball rotational throws (seated and standing), Stir-the-pot (Swiss ball), Plank shoulder taps, Hanging leg raise	Hurdle hops (4–6 hurdles, 30–40 cm), Tuck jumps	4–5 sets × 8–10 reps	Medicine balls 3–5 kg. Plyometrics: higher box heights and controlled landings. Rest 90–120 s between sets.
9–10	Sport-specific power and integration	Single-arm cable chop, Side plank with hip dip, Medicine ball slam, Swiss ball pike	Tennis footwork drill with plyometric burst (split step plus drop jump), Reactive lateral cone hops	5 sets × 6–8 reps	Power-focused: moderate load and explosive tempo. Short ground contact time. Rest 120 s between sets.
11–12	Peak power, agility, and transfer	Rotational plank walks, Standing anti-rotation press (Paloof press), Medicine ball overhead throw, Partner-resisted plank	Multi-directional depth jumps (40–50 cm box), Reaction drop jumps with visual cue	5 sets × 5–8 reps	High intensity: medicine balls 5–6 kg. Maximum effort, explosive execution. Extended rest 2–3 min between sets.

normally distributed if $p > .05$, thus meeting the assumptions required for parametric analyses. Descriptive statistics (means \pm standard deviations) were computed separately for the experimental and control groups.

To examine the effects of the 12-week intervention, a series of 2 (Group: Experimental vs. Control) \times 2 (Time: Pre vs. Post) Repeated Measures ANOVAs were conducted for each outcome variable: International Tennis Number (ITN) score, Pro-Agility time, Squat Jump (SJ) height, Countermovement Jump (CMJ) height, and the Star Excursion Balance Test (SEBT) composite score. This allowed assessment of main effects for group and time, as well as the Group \times Time interaction, which determined whether performance changes differed between groups.

Effect sizes for ANOVA results were calculated using partial eta squared (η^2p), with interpretation thresholds of .01 (small), .06 (medium), and .14 (large) according to Cohen (1988). For post hoc within-group comparisons, Cohen's d was calculated to assess the magnitude of change over time, with effect size interpretations of 0.2 (small), 0.5 (medium), and 0.8 (large). Ninety-five percent confidence intervals (95% CI) were reported for all mean differences to enhance interpretability.

To explore interrelationships among the primary outcome measures, Pearson product-moment correlation coefficients (r) were calculated for change

scores (Post-Pre). These included relationships between changes in ITN and Pro-Agility, SEBT, SJ, and CMJ scores. All variables satisfied the assumptions of linearity, homoscedasticity, and normality required for correlation analysis.

Results

Table 3 presents the results of the Shapiro-Wilk test, confirming that all key dependent variables, including ITN scores, Pro-Agility times, Squat Jump, Countermovement Jump, and SEBT scores, were normally distributed at both pre- and post-test points. All p -values exceeded the 0.05 threshold, indicating that none of the variables deviated significantly from normality. This confirms that the dataset met the necessary assumptions for conducting parametric analyses. Consequently, Repeated Measures ANOVA and Pearson's correlations were appropriately applied across all outcome measures. This strengthens the validity and consistency of the statistical approach used in the study.

Table 4 summarizes the results of the Repeated Measures ANOVA, showing main effects of group, time, and the crucial group \times time interaction for each variable. For the ITN score, significant main effects for time ($F = 18.34, p = 0.001$) and group \times time interaction ($F = 12.34, p = 0.003$) indicate that the experimental group improved significantly more than the control group over time. Pro-Agility time

Table 3. Shapiro-Wilk normality test statistics for each dependent variable

Variable	W Statistic	p-value
ITN Pre	0.97	0.50
ITN Post	0.96	0.40
Pro-Agility Pre	0.95	0.45
Pro-Agility Post	0.94	0.38
Squat Jump Pre	0.97	0.52
Squat Jump Post	0.96	0.47
CMJ Pre	0.95	0.49
CMJ Post	0.94	0.43
SEBT Pre	0.95	0.48
SEBT Post	0.94	0.46

Note. W = Shapiro-Wilk statistic. $p > .05$ indicates that the data are normally distributed, confirming that the data meet the assumption of normality for parametric analysis.

Table 4. Repeated measures ANOVA summary for group, time, and interaction effects

Variable	F (Group)	p (Group)	F (Time)	p (Time)	F (Group \times Time)	p (Group \times Time)	Partial η^2
ITN Score	4.56	0.05	18.34	0.001	12.34	0.003	0.45
Pro-Agility	3.21	0.09	9.12	0.008	7.45	0.015	0.38
Squat Jump	2.10	0.16	1.55	0.22	0.89	0.36	0.05
CMJ	1.89	0.19	1.12	0.29	0.76	0.42	0.04
SEBT	3.45	0.08	12.87	0.002	6.56	0.018	0.35

Note. F = F statistic; partial η^2 = effect size; $p < .05$ indicates statistical significance.

showed a similar pattern, with a significant time effect ($F = 9.12, p = 0.008$) and interaction effect ($F = 7.45, p = 0.015$). SEBT performance also showed a significant interaction ($F = 6.56, p = 0.018$), reflecting meaningful improvements in dynamic balance in the experimental group. Partial eta squared values for these outcomes ranged from 0.35 to 0.45, indicating medium to large effect sizes. Squat Jump and CMJ did not show significant interaction effects, suggesting that the core and plyometric program had limited impact on vertical jump performance.

Table 5 presents pairwise comparisons that clarify where significant changes occurred. The experimental group demonstrated a substantial reduction in ITN score (Mean Diff = -1.2 , 95% CI [$-1.7, -0.7$], $p = 0.001$, Cohen's $d = 1.20$), confirming meaningful tennis skill improvements. The control group showed only a slight ITN score reduction ($-0.2, p = 0.040$), indicating a small effect. For Pro-Agility, the experimental group's time improved by -0.23 seconds ($p = 0.004, d = 0.85$), while the control group's change was negligible and non-significant. The SEBT score in the experimental group increased by 6.1 points ($p = 0.003, d = 0.92$), demonstrating significant gains in dynamic balance. These post hoc results emphasize the practical benefits of the 12-week integrated training program for tennis-specific performance, agility, and balance.

Table 6 shows the relationships between change scores across key performance measures. A moderate negative correlation ($r = -0.52, p < 0.05$) was found between ITN score improvements and Pro-Agility improvements, indicating that as agility performance increased, tennis skill scores also improved. Similarly, a positive correlation ($r = 0.52$)

was observed between changes in SEBT and ITN, suggesting that improvements in dynamic balance may contribute to better tennis performance. The Squat Jump and CMJ changes were highly correlated ($r = 0.85$), which is expected given that both assess lower-body explosive power. These correlations support the idea that gains in agility and balance are functionally related to tennis skill development in young players. Overall, the correlation matrix helps explain how different physical qualities interact to enhance on-court performance.

Discussion

The present study examined the impact of a 12-week integrated core and plyometric training program on tennis-specific skills, agility, strength, and dynamic balance among players aged 12–14 years. The results supported the hypothesis, showing that the combined training group achieved greater gains than the control group. Significant group \times time interactions were found for ITN score ($p = 0.003$), agility ($p = 0.015$), and balance ($p = 0.018$), all with large effect sizes. This confirms that the integrated program was more effective than standard training alone. Furthermore, extending the training duration from eight to twelve weeks contributed to significant improvements in ITN scores, agility performance, and dynamic balance in the experimental group, while jump-related strength gains remained modest. These findings align with prior research supporting the role of core-focused interventions in enhancing functional performance and sport-specific abilities.

Consistent with the findings of [49], who reported significant improvements in forehand and

Table 5. Post hoc pairwise comparisons with 95% confidence intervals and effect sizes

Comparison	Mean Difference	95% CI	p-value	Cohen's d
ITN Exp Pre–Post	-1.2	[-1.7, -0.7]	0.001	1.20
ITN Con Pre–Post	-0.2	[-0.4, 0.0]	0.040	0.25
Pro-Ag Exp Pre–Post	-0.23	[-0.35, -0.11]	0.004	0.85
Pro-Ag Con Pre–Post	0.05	[-0.04, 0.14]	0.580	0.10
SEBT Exp Pre–Post	6.1	[4.0, 8.2]	0.003	0.92

Note. Cohen's d represents effect size for within-group comparisons; $p < .05$ indicates significant change.

Table 6. Correlation Matrix of Change Scores Between Performance Measures

Change Variable	ITN	Pro-Agility	Squat Jump	CMJ	SEBT
ITN	1.00	-0.52*	0.12	0.10	0.52*
Pro-Agility		1.00	0.18	0.15	0.35
Squat Jump			1.00	0.85*	0.28
CMJ				1.00	0.22
SEBT					1.00

Note. Values are Pearson correlation coefficients. Correlations marked with * are statistically significant at $p < .05$. ITN = International Tennis Number; CMJ = Countermovement Jump; SEBT = Star Excursion Balance Test.

backhand groundstroke speeds, static balance, and throwing performance in adolescent tennis players following an 8-week core training program, the present study observed clear advancements in ITN scores. This underscores the value of extended core training for tennis skill enhancement. Similarly, the improvement in agility aligns with the results of [50] among surfers, where an 8-week core training regimen led to notable gains in agility and balance. However, our study suggests that a 12-week duration may amplify these adaptations, particularly for quick directional changes, which are essential in tennis.

Regarding agility performance, our results correspond with previous observations by [51], who found significant improvements in dynamic balance, core strength, and serve accuracy in volleyball players following 6 weeks of core training. The consistent enhancement in agility across studies reinforces the functional role of trunk stability in supporting rapid, multi-directional movements required in racket sports [51].

A distinctive aspect of this study is the inclusion of dynamic balance measurement through the Star Excursion Balance Test (SEBT). Our findings revealed meaningful improvements in SEBT scores after 12 weeks, indicating that integrated core and plyometric exercises can effectively enhance postural control and single-leg stability. This aligns with the systematic review by [48], which highlights the SEBT as a valid and reliable tool for detecting changes in dynamic balance following training interventions. Interestingly, similar to the findings of [49, 52, 53], no significant gains were observed in vertical or countermovement jump height. While [54, 55] reported improvements in jump performance in footballers and children following core training, our results suggest that such gains may be less pronounced in tennis players. This may reflect the sport's primary demands for horizontal quickness and directional changes rather than vertical power [56, 57].

The variation in jump improvements across sports highlights the importance of tailoring training programs to the specific biomechanical requirements of each discipline. Plyometric training has been shown to enhance explosive actions such as jumping and sprinting, which are vital for tennis players. An 8-week plyometric program improved performance in countermovement jumps and medicine ball throws, indicating increased power and strength in young tennis players [58]. Core training, particularly when periodized, significantly improves service velocity. One study demonstrated a 6.6% increase in serve speed among young tennis players following an 8-week core stabilization program, underscoring the importance of core strength in executing powerful serves [39]. A combined training approach, including tennis-specific sprints and plyometric exercises, has been shown to improve

agility and motor skills. Participants in such programs exhibited better performance in agility tests like the Illinois agility test and T-test, which are critical for quick directional changes on the court [59].

Training programs that incorporate both core and plyometric exercises contribute to improved balance and strength. For instance, a study on badminton players showed significant improvements in balance and strength metrics, which are transferable to tennis [60]. In addition to these primary findings, further evidence highlights the broader benefits of combining core stability and plyometric exercises.

Behm et al. [61] emphasized that training on unstable surfaces can activate deeper trunk muscles, enhancing core endurance and functional transfer to sport movements. Similarly, Markovic and Mikulic [62] demonstrated that plyometric training induces favorable neuromuscular and musculoskeletal adaptations, which can translate to improved agility and reactive strength. Myer et al. [63] noted that integrating balance tasks alongside plyometrics may optimize power production and landing mechanics, aligning with the improvements in agility and balance observed in this study. Furthermore, Leetun et al. [64] highlighted that greater core stability can reduce the risk of lower extremity injuries, an important practical consideration for adolescent tennis players. Together, these findings reinforce the notion that a well-designed, longer-duration core and plyometric program can positively affect multiple performance domains relevant to tennis development.

A recent study by Liu et al. [65] demonstrated that combining functional and traditional training effectively enhanced multiple performance variables in adolescent athletes, including sprinting ability, agility, and coordination. This supports the current study's approach of integrating core and plyometric training to target similar multi-dimensional performance gains. Such evidence reinforces the value of combined, sport-specific training for youth athletes.

The study by Arslan and Ergin [66] demonstrated that 8 weeks of core training resulted in significant improvements in ITN scores ($p = .001$) and agility ($p = .004$) among 10- to 14-year-old tennis players. Their experimental group also outperformed the control group across these variables, affirming the effectiveness of supplementary core work. These findings directly support the current study's emphasis on integrated conditioning to enhance tennis-specific performance outcomes.

Recent findings by Kumar et al. [67] emphasize that gender and BMI significantly influence motor competence in children, highlighting the need for tailored interventions. This aligns with the present study's focus on customized training to support optimal skill development in young tennis

players. Further, a study by Choudhary et al. [68] demonstrated that perturbation-based balance training significantly improved dynamic stability in university basketball players. This reinforces the value of targeted balance exercises and supports our finding that dynamic balance can be enhanced through integrated core and plyometric training in youth tennis players. These findings are consistent with those of Choudhary et al. [69], who demonstrated that a 12-week structured yoga intervention significantly improved flexibility, static balance, and joint kinematics in university athletes. Their results emphasize the efficacy of structured neuromuscular training in enhancing movement efficiency and postural control.

This study contributes to the existing literature by applying a 12-week integrated core and plyometric training program specifically to adolescent tennis players aged 12 to 14 years. Unlike prior research that typically focuses on shorter interventions or single-mode training, this study extends the duration beyond the common 6–8 week protocols and combines core and plyometric elements. Furthermore, it provides a multidimensional assessment by simultaneously measuring tennis skill (ITN score), agility, vertical jump performance, and dynamic balance (SEBT). While similar training modalities and outcome measures have been reported previously [26, 49, 58, 60, 61, 63, 66], the extended duration, population specificity, and integrated performance profile offer an incremental yet meaningful advance in the field.

Overall, extending the intervention duration from eight to twelve weeks facilitated greater improvements in tennis skill ratings, agility, and dynamic balance, while vertical power gains remained limited. These results underscore the practical relevance of integrated core and plyometric training for tennis players, emphasizing the importance of efficient force transfer, rapid lateral movements, and postural stability in optimizing on-court performance.

Limitations and Future Research Directions

This study has several limitations that should be acknowledged. First, the relatively small sample size and the focus on male adolescent tennis players aged 12 to 14 may limit the generalizability of the findings to other age groups, females, or different competitive levels. Second, the study did not include a long-term follow-up to assess the sustainability of the training effects beyond the 12-week intervention period. Third, although multiple performance outcomes were measured, other relevant factors such as psychological variables, injury incidence, or sport-specific tactical skills were not examined. Future research should consider larger and more diverse samples, including female athletes and different age categories, to enhance the external validity. Additionally, studies with extended follow-up periods are needed to evaluate the retention

of training benefits. Incorporating psychological assessments and sport-specific tactical evaluations could provide a more comprehensive understanding of how integrated training influences overall tennis performance and athlete development.

Conclusions

This study demonstrated that a structured 12-week integrated core and plyometric training program produced meaningful improvements in tennis-specific performance variables among adolescent tennis players aged 12–14 years. Specifically, the program resulted in significant enhancements in ITN scores, agility, and dynamic balance, highlighting the combined benefit of core stability and explosive movement drills for young tennis athletes. While no substantial gains were observed in vertical and countermovement jump performance, this outcome aligns with the sport's emphasis on lateral movement and quick directional changes rather than vertical power output.

By extending the intervention duration from previous 6- or 8-week models to 12 weeks, this study provides additional evidence that a longer training period may amplify gains in skill-specific and functional measures crucial for on-court success. The incorporation of dynamic balance assessment through the SEBT further expands understanding of how core and plyometric training can improve postural control, which may translate to better stability during rapid play situations.

Overall, these findings suggest that tennis coaches and conditioning specialists should consider integrating progressive core and plyometric exercises into young athletes' training routines to optimize agility, balance, and tennis skill development. Future research is encouraged to investigate complementary interventions, longer follow-up durations, and the potential impact on injury prevention.

Acknowledgements

The authors would like to express their sincere gratitude to all the young tennis players for their enthusiastic participation and commitment throughout the training program. We also appreciate the guidance and constructive feedback provided by our academic mentors and colleagues during the planning and execution of this study.

Funding

This study received no external financial support and was conducted entirely with the authors' personal resources.

Conflict of Interest

The authors declare that there are no conflicts of interest related to this study.

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Cite this article as:

Bangari D, Choudhary PK, Choudhary S, Kandpal A, Singh H, Mohit. Effects of a 12-week integrated core and plyometric training program on tennis skills, agility, strength, and balance in adolescent tennis players. *Pedagogy of Physical Culture and Sports*, 2025;29(4):308–319. <https://doi.org/10.15561/26649837.2025.0408>

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Received: 10.07.2025

Accepted: 11.08.2025; Published: 30.08.2025

Impact of inclusive recreational and life-skill activities on physical, personal care, and communication skills of students with intellectual disability

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Abstract

Background and Study Aim Students with intellectual disabilities (SwID) often face challenges in interpersonal communication, personal hygiene, and motor development, hindering their social integration and independence. Physical activity and socialization are key factors for improving these areas, but traditional fitness programs often do not address the specific needs of SwID. This study aims to determine the effect of Inclusive Recreational and Life-Skill Activities (IRLSA) on SwID, specifically in their physical abilities, personal hygiene, and interpersonal communication.

Material and Methods The study used a quasi-experimental pre-test/post-test control group design. Forty male students with mild intellectual disabilities were selected from special schools and academies in Coimbatore, Tamil Nadu. Their age was 15.9 ± 1.42 years, height 157.52 ± 8.32 cm, weight 57.57 ± 7.72 kg, and BMI 23.15 ± 2.04 . Participants were selected based on their ability to follow basic instructions and the absence of severe medical conditions restricting movement. They were divided into two groups: a control group (n=20) that continued their daily routine and an experimental group (n=20) that participated in 16 weeks of inclusive recreational and life-skill activities. The training sessions focused on cardiovascular endurance, physical strength, flexibility, personal hygiene practices, and communication skills. Pre- and post-intervention measures were conducted using standardized tests.

Results The experimental group showed significant improvements compared to the control group ($p < 0.05$) in all measured parameters: cardiovascular endurance (6-min walk test: $p=0.001$), flexibility (Sit and reach: $p=0.001$), muscular strength (lower body) (Sit-to-stand: $p=0.007$), muscular strength (upper body) (5 kg medicine ball throw: $p=0.002$), personal care and safety (Comprehensive assessment tool: $p=0.001$), and communication and interpersonal skills ($p=0.001$). In contrast, the control group showed minimal or no improvements in these variables ($p > 0.05$), reinforcing the need for structured interventions.

Conclusions The study demonstrates that IRLSA significantly enhance physical fitness, personal care, and communication skills among SwID. The structured, peer-supported approach fosters holistic development and social inclusion. These findings advocate for the systematic integration of IRLSA into educational and therapeutic programs to promote functional independence and well-being in this population.

Keywords: inclusive, recreation, life-skill, intellectual disability, physical, personal care

Introduction

Intellectual disabilities (ID) affect millions of individuals globally, impacting their cognitive, social, and physical abilities. Students with intellectual disabilities (SwID) often encounter challenges in various aspects of daily life, particularly in communication, personal care, and motor development. These challenges can hinder their social integration and limit their ability to live independently.

Individuals with Intellectual Disabilities (ID) experience significant challenges in motor development, personal care, and communication, which affect their ability to perform daily activities and integrate into society [1, 2, 3]. ID involves significant impairments in intellectual functioning, such as reasoning, learning, and problem-solving, and adaptive behavior, including conceptual, social, and practical skills necessary for everyday life [2, 4]. These challenges often result in difficulties with motor coordination, verbal and nonverbal communication, and self-care skills, limiting their ability to participate independently in social and

physical environments. The lack of well-structured, adaptive, and inclusive programs further exacerbates these issues, leading to sedentary lifestyles, reduced opportunities for peer interaction, and increased dependency on caregivers [5, 6].

Physical activity plays a crucial role in enhancing neurodevelopment, emotional stability, and social competence in individuals with ID [7, 8]. Structured physical exercise not only improves motor proficiency but also enhances cognitive abilities by stimulating neuroplasticity, promoting executive functioning, and fostering better decision-making skills [9, 10]. Consistent engagement in physical activities contributes to emotional regulation, helping to reduce symptoms of anxiety, depression, and behavioral difficulties commonly observed in intellectual disabilities (SwID) [11, 12]. However, despite these benefits, most conventional fitness programs fail to accommodate the specific needs of this population, as they often rely on standardized exercises that do not account for individual variations in physical and cognitive abilities [13, 14]. This highlights the urgent need for adaptive, structured, and socially integrated exercise programs that cater specifically to the developmental requirements of SwID.

Life-skill activities are not optional but essential components of education for SwID. These activities bridge the critical gap between academic learning and functional living by equipping students with the practical skills required to navigate everyday life confidently and independently. Without structured life-skill instruction, SwID may struggle to generalize classroom learning to daily tasks, limiting their ability to participate fully in home, school, and community environments.

To bridge the gap in physical and life-skill development and social participation for SwID, the IRLSA have emerged as a powerful and adaptable intervention. These activities go beyond traditional physical activity programs by integrating physical skill development, personal care awareness, and communication enhancement within a structured, socially engaging environment. Unlike conventional models that focus solely on fitness, the IRLSA promote holistic development by fostering independent living skills, emotional expression, and interpersonal interaction. By incorporating sensorimotor activities, functional movement play, and group-based interactive challenges, inclusive games enhance body awareness, motor planning, and spatial coordination – skills essential for improved mobility and daily functioning among SwID [15, 16, 17].

These activities can be individualized and adjusted according to each participant's ability level, learning pace, and developmental goals. Grounded in principles of motor learning and behavioral reinforcement, such games allow gradual

progression, reduce frustration, and maintain sustained interest and motivation [18]. A defining feature of IRLSA is their unified nature—participants with ID engage alongside their typically developing peers in cooperative and enjoyable formats [19, 20, 21]. This inclusive approach fosters social integration through peer modeling, observational learning, and reciprocal communication, thereby building confidence and improving social adaptability [22, 23]. Structured interactions within play settings create natural learning opportunities that support teamwork, problem-solving, and the understanding of social norms and shared responsibilities [24, 25].

Beyond its direct impact on physical fitness, inclusive activities contribute to self-regulation, sensory processing, and functional independence [26]. Many individuals with ID experience challenges in proprioception, balance, and motor sequencing, which hinder their ability to perform everyday tasks efficiently [27]. Through systematic exposure to task-oriented games and functional movement training, kinesthetic awareness, postural control, and reaction time improve, enabling individuals to navigate their surroundings with greater ease and confidence [28]. Structured movement-based games support neural connectivity, enhancing information processing speed and working memory, which are critical for cognitive and communicative development [29, 30].

Despite the promising benefits of inclusive activities, challenges persist in implementation, including the need for trained instructors, accessibility to inclusive fitness spaces, and long-term sustainability of such programs. Limited resources, societal stigma, and lack of awareness further restrict the adoption of inclusive game interventions [31, 32]. Addressing these barriers requires collaborative efforts between educators, healthcare professionals, and sports scientists to design evidence-based, scalable, and culturally adaptable programs that integrate into mainstream educational and community settings. Therefore, this study hypothesizes that participation in 16 weeks of task-oriented recreational and life-skill activities leads to significant improvements in the physical abilities, personal care skills, and interpersonal communication of SwID.

Materials and Methods

Participants

The power analysis was conducted using G*Power version 3.1.9 for sample size estimation, based on previous data on the intervention effects on upper body strength. The effect size in the study was 0.80. With a significance criterion of $\alpha = 0.05$ and Power = 0.90, the minimum sample size needed with this effect size was 20. Thus, the obtained sample size of 20 was adequate to test the study hypothesis. The

study involved forty students aged 13 to 18 years, diagnosed with mild intellectual disabilities, from special schools and academies in Coimbatore, Tamil Nadu. Participants were selected based on specific inclusion criteria, including a formal diagnosis of mild intellectual disability, the ability to follow basic instructions, the absence of severe medical conditions restricting movement, and written informed consent from parents/legal guardians. The selected subjects were equally assigned to the experimental group (n=20) and the control group (n=20). The experimental group participated in IRLSA alongside partner peers. The partner peers were selected based on their willingness to participate and their understanding of inclusive engagement with SwID. Overall, the characteristics of the subjects in the two groups did not show any significant differences ($P > 0.05$). Details of the analysis results can be seen in Table 1.

Research Design

This study employed a quasi-experimental pre-test/post-test control group design to examine the impact of IRLSA. Selected participants were divided into two groups: an experimental group, which engaged in a structured 16-week IRLSA alongside partner peers, and a control group, which continued their regular daily activities without any structured exercise intervention. The IRLSA consists of systematically designed activities aimed at engaging all participants, irrespective of ability level, within a supportive, adaptive, and enjoyable environment. These activities prioritize collaboration over competition, fostering the development of physical, social, and communication skills. The IRLSA Program spans a period of 16 weeks, comprising five sessions per week, each lasting 90 minutes, resulting in a total of 120 hours of structured training. The training is organized into four progressive phases: Adaptation, Learning Together, Working as a Team, and Leadership & Independence, each targeting specific developmental goals to enhance participant growth and engagement throughout the program. The detailed training program is given in Table 2. Participants in the control group followed their regular daily routine, which included classroom learning, leisure time, and self-care routines without guided training. This setup allowed researchers to compare the outcomes of those who participated in the IRLSA with those who did not.

Testing Procedures

To assess cardiovascular endurance, the 6-Minute Walk Test (6MWT) was conducted on a 400-meter standard track. Participants walked continuously for six minutes, covering as much distance as possible at their own pace. If necessary, they could slow down or stop but were instructed to resume walking as soon as possible. At the end of six minutes, researchers recorded the total distance covered in meters.

To assess flexibility, researchers used the Sit-and-Reach Test. Participants used a standardized sit-and-reach box (DSI, DANESH SALAR Ltd.). They sat with their knees flat on the floor and slowly extended their arms forward as far as possible, holding the position for two seconds. Each participant completed three trials, and researchers recorded the best measurement.

For lower body strength, researchers conducted the Sit-to-Stand Test. Participants sat on a sturdy chair (43–46 cm in height) with their feet flat on the floor and arms crossed over their chest. Upon instruction, they stood up fully and sat back down as quickly and safely as possible. Researchers recorded the number of complete sit-to-stand repetitions completed in 30 seconds, counting only full stands where participants reached an upright position.

To measure upper body strength, participants performed the 5 kg Medicine Ball Put. They sat with their back fully against a wall, legs extended, and feet slightly apart. Holding a 5 kg medicine ball at chest level with both hands, they pushed the ball forward forcefully using only their arms and shoulders without lifting their back off the wall. Each participant performed three trials, and researchers recorded the farthest distance. Rest periods were provided between trials to allow for recovery, and the best attempt was measured as shoulder strength.

To assess personal care ability and interpersonal communication skills, researchers used the Comprehensive Assessment Tool for Adults with Intellectual Disabilities (CATAID, 2020). They conducted a pre-test to establish baseline competency levels, followed by targeted training interventions. After the intervention, researchers conducted a post-test using the same criteria to measure progress.

The Table 2 presents the weekly progression

Table 1. Subject Characteristics

Outcome	Total	Experimental Group	Control Group	ρ
Age (years)	15.9 ± 1.42	15.95 ± 1.39	15.85 ± 1.5	0.828
Height (cm)	157.52 ± 8.32	156.4 ± 9.06	158.65 ± 7.57	0.399
Weight (kg)	57.58 ± 7.72	58.0 ± 7.94	57.15 ± 7.67	0.733
BMI (kg/m ²)	23.16 ± 2.05	23.64 ± 1.78	22.67 ± 2.23	0.136

Table 2. Weekly Progression Plan of Inclusive Recreational Games Program

Week	Physical	Personal care	Communication	Games
1 to 4 Phase 1- Adaptation	Walking, jumping & balancing Eye hand coordination Throwing & catching Group movement	Brushing teeth role play Washing face & hands Wearing shoes and socs Packing a hygiene kit	Greeting & name games Answer Yes/No Asking for help Making choices	Follow the leader
				Name game
				Balloon Tap
				Beanbag target
				Obstacle relay
5 to 8 Phase 2- learning Together	Large motor play Movement rhythm Balance & posture Coordination in groups	Nutrition talk (food cards) Drinking water routines Hair combing routine Bathing & clothing sequence	Requesting turns Encouraging peers Sharing feelings (emoji cards) Describing actions	Partner catch
				Parachute games
				Simon says
				Team Relay
				Bowling
9 to 12 Phase 3 – working as a team	Team coordination Hand-eye tracking Strength & endurance Adaptive sport play	Hygiene game boards First aid basics Healthy snack preparation Rest and sleep hygiene	Role play (shopping/ café) Asking questions Giving instructions Expressing needs	Musical Chairs
				Freeze Dance
				Cone Walk
				Mirror Movement
				Beanbag Balance Race
13 to 16 Phase 4 - Leadership & Independence	Game creation Agility & movement Peer coaching Celebration	Dressing races Role play (school/home routine) Pack-my-bag challenge Recap of all routines	Giving feedback Question & Answer circle Introductions & thanks Presenting experience	Tunnel Tag
				Passing Circle
				Tail Tag
				Kick Cricket
				Catch Me If You Can
				Hoop Relay
				Obstacle Maze
				Mini Soccer
				Mini Volleyball
				Create-a-Game
				Peer Challenges
				Activity Stations
				Team Tournaments
				“Fun Olympics” – Game Carnival

plan for the Inclusive Recreational Games Program, detailing the activities and focus areas for each phase. It outlines how physical, personal care, and communication skills are incorporated into the program through a series of fun and engaging games.

Statistical Analysis

The data were analyzed using SPSS 21.0. The normality of the data was checked before conducting statistical tests. The independent t-test was applied to compare pre-test scores between the experimental and control groups. To assess

the effectiveness of the intervention, Analysis of Covariance (ANCOVA) was applied to analyze post-test scores while controlling for baseline values. Additionally, the effect size was measured to determine the magnitude of differences. In all cases, statistical significance was set at $p < 0.05$.

Results

The pre-test comparisons between the experimental and control groups across all the variables are given in Table 3. The results revealed no statistically significant differences between the two groups. This indicates that both the experimental

Table 3. Pre-test comparison between the experimental and control group

Outcome	Experimental Group	Control Group	p
CVS (m)	564.2 ± 22.82	563.95 ± 16.22	0.968
FLEX (cm)	16.85 ± 1.18	16.65 ± 1.04	0.573
MSL (counts)	8.4 ± 1.27	8.2 ± 1.4	0.639
MSU (m)	2.34 ± 0.45	2.50 ± 0.43	0.263
PCS (points)	29.6 ± 4.39	31.65 ± 3.88	0.126
CIS (points)	28.25 ± 2.84	28.45 ± 2.98	0.829

CVS = Cardiovascular Endurance, FLEX = Flexibility, MSL = Muscular Strength Lower Extremities, MSU = Muscular Strength Upper Extremities, PCS = Personal Care & Safety, CIS = Communication and Interpersonal Skills. Data expressed as the Mean ± SD, p values indicate the difference between the experimental and control group.

Table 4. Changes in outcomes before and after the intervention in the experimental and control groups

Outcome	Experimental Group (n=20)	Control Group (n=20)	ρ	η _p ²
	Pre-test	Post-test	Pre-test	Post-test
CVS (m)	564.2 ± 22.82	600.6 ± 24.67	563.95 ± 16.22	564.05 ± 17.18
FLEX (cm)	16.85 ± 1.18	19.7 ± 1.69	16.65 ± 1.04	16.6 ± 1.05
MSL (counts)	8.4 ± 1.27	10.05 ± 1.61	8.2 ± 1.4	8.55 ± 1.5
MSU (m)	2.34 ± 0.45	2.85 ± 0.57	2.50 ± 0.43	2.45 ± 0.48
PCS (points)	29.6 ± 4.39	32.4 ± 4.68	31.65 ± 3.88	31.8 ± 3.85
CIS (points)	28.25 ± 2.84	31.1 ± 3.28	28.45 ± 2.98	28.6 ± 3.23

CVS = Cardiovascular Endurance, FLEX = Flexibility, MSL = Muscular Strength Lower Extremities, MSU = Muscular Strength Upper Extremities, PCS = Personal Care & Safety, CIS = Communication and Interpersonal Skills, Pre = before intervention, Post = after the intervention, η_p² = partial eta squared, m = meters, cm = centimeters. Data expressed as the mean ± SD.

and control groups were equivalent at baseline, with similar levels of physical, personal care, and communication abilities before the intervention (Table 4).

Discussion

The primary objective of this study was to assess the impact of IRLSA on the physical abilities, personal care, and interpersonal communication development of SwID. The findings from the pre-test and post-test comparisons of the experimental group indicate that structured IRLSA interventions significantly enhance endurance, flexibility, muscular strength, personal care, and interpersonal communication in SwID.

In contrast to the experimental group, the SwID in the control group showed minimal, non-significant improvements in selected variables. This emphasizes the necessity of structured interventions rather than relying on general physical activity alone. These findings align with previous research studies that highlight the positive effects of structured, unified exercises on individuals with ID [33, 34, 35, 36, 37].

The structured nature of IRLSA, which involved progressive exercises and day-to-day life-skill activities, likely contributed to these gains.

Activities such as running, dancing, and dynamic movement drills have been shown to enhance cardiovascular efficiency by improving oxygen uptake, stroke volume, and heart rate regulation [38, 39]. These physiological adaptations enable participants to sustain physical exertion for longer durations, reflecting improved stamina and overall cardiovascular health. SwID often have lower baseline cardiovascular fitness due to reduced physical activity levels, making such interventions crucial for improving overall well-being [40, 41].

Regular stretching and movement-based activities embedded in IRLSA likely improved muscle elasticity and joint mobility. Stretching exercises increase the length and compliance of muscle-tendon units, reducing stiffness and enhancing the range of motion [42, 43]. Improved flexibility is particularly beneficial for SwID, as they often experience motor coordination challenges, hypotonia, and muscle tightness that can impede functional movements [44, 45]. Enhanced flexibility also reduces the risk of musculoskeletal injuries, which is particularly important for individuals who may already have compromised movement patterns.

The experimental group demonstrated a statistically significant increase in muscular strength, particularly in core, upper, and lower-body muscles.

Strength-based exercises, resistance training, and bodyweight exercises were incorporated in IRLSA. Resistance training enhances motor unit recruitment and synchronization, leading to greater force production and stability [46, 47]. Engaging in multi-joint movement during training stimulates muscular endurance and develops overall strength [48]. Continuous movement, including running, jogging, and change of direction, places significant demands on the muscular system [49, 50].

The unified concept of training in structured physical activity programs plays a crucial role in enhancing personal care and safety by fostering self-regulation, motor coordination, and cognitive control [51-53]. The training involved both the individual with ID and their partners in synchronized activities. Participants learned essential self-care tasks through guided repetition, modeled behavior, and interactive reinforcement. Engaging in structured physical routines strengthens the prefrontal cortex, which is responsible for planning, impulse control, and decision-making, all of which are critical for maintaining hygiene, dressing, and safety awareness [51, 54]. The interactive nature of the training promoted spatial awareness and controlled movement, reducing the risk of falls and improving energy regulation, which in turn encouraged greater participation in daily self-care tasks [55]. The social reinforcement within the training, where peers and partners provided encouragement and feedback, helped reinforce self-care habits, making them more consistent and sustainable [56, 57].

Similarly, the unified training model, where individuals with ID participated alongside partners in structured activities, significantly enhanced communication and interpersonal skills. Through partner-based and group exercises, participants engaged in real-time social learning, reinforcing key behaviors such as turn-taking, eye contact, and following verbal or non-verbal cues [58, 59]. The cooperative nature of the training encouraged shared decision-making and patience, allowing participants to develop confidence in expressing themselves and interacting with others. Because the activities required mutual coordination and response, participants naturally improved their ability to process social cues and regulate emotions. Physical activity triggers the release of oxytocin and endorphins, hormones linked to trust, bonding, and positive social interactions, which helped create a supportive and engaging environment [60]. The structured interactive format of the training meant individuals with ID were not just learning in isolation but also actively engaging with others, making the improvements in communication and social skills more meaningful and lasting. The findings suggest that without guided, individualized programs, SwID could not experience substantial

physical or behavioral improvements.

The findings of this study highlight the importance of structured programs like IRLSA in improving physical fitness, personal care, and communication skills among students with intellectual disabilities. The program led to significant improvements in key areas such as endurance, flexibility, muscular strength, and social skills, demonstrating the effectiveness of inclusive approaches. The results also emphasize the need for individualized and interactive participation in learning processes to achieve sustainable and meaningful outcomes. These findings provide valuable insights for the development of future programs aimed at enhancing the quality of life for students with intellectual disabilities and offer practical recommendations for educational and rehabilitation settings.

Limitations

Despite the valuable insights provided by this study, several limitations should be considered when interpreting the findings. First, the study's sample size was relatively small, consisting of only 40 participants, which may limit the generalizability of the results. A larger and more diverse sample could offer a more comprehensive understanding of the effects of IRLSA across different populations of students with intellectual disabilities. Additionally, the study was conducted in a specific geographical location, which may affect the applicability of the findings to other regions with different cultural, social, or educational contexts.

Another limitation is the absence of long-term follow-up assessments to determine the sustainability of the improvements observed after the intervention. Future research should include post-intervention follow-ups to evaluate whether the benefits of IRLSA persist over time. Furthermore, the study did not explore potential differences in outcomes based on the severity of intellectual disabilities or other individual characteristics, such as age or gender. Investigating these variables could provide a more nuanced understanding of how IRLSA affects different subgroups of students.

Finally, while the study focused on the immediate effects of IRLSA, the impact of other factors, such as the role of family involvement, peer support, or the wider community, was not examined. These external influences could contribute to the success of the intervention and should be considered in future research.

Conclusions

This study provides empirical evidence supporting the impact of IRLSA in promoting multidimensional development among SwID. The statistically significant improvements observed across domains of cardiovascular endurance, muscular strength, flexibility, personal care, and

communication skills in the experimental group underscore the value of structured, inclusive, and task-oriented interventions. Unlike conventional fitness programs, IRLSA adopts a holistic framework that integrates physical activity with functional skill-building and peer-mediated interaction, thereby fostering both individual competence and social participation.

These findings reinforce the necessity of embedding adaptive physical education and life-skill activities within special education and rehabilitation contexts. The unified training approach not only addresses physical limitations but also mitigates barriers to communication, self-regulation, and autonomy, which are critical for the long-term well-being and inclusion of SWID. Given the increasing demand for inclusive

pedagogical models, this research contributes to the growing body of literature advocating for evidence-based, scalable, and developmentally appropriate interventions.

Acknowledgement

We sincerely thank the participants, their families, and the special schools in Coimbatore for their support. Our gratitude extends to the trainers, educators, and research assistants who contributed to this study. We also appreciate the Institutional Ethics Committee for their guidance and approval.

Conflict of Interest

The authors declare that there are no conflicts of interest related to this study.

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Cite this article as:

Yuvaraj D, Premkumar G, Aravindh M, Mohamedprince M, Rinsha KA. Impact of inclusive recreational and life-skill activities on physical, personal care, and communication skills of students with intellectual disability. *Pedagogy of Physical Culture and Sports*, 2025;29(4):320–329.
<https://doi.org/10.15561/26649837.2025.0409>

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Received: 09.07.2025

Accepted: 12.08.2025; Published: 30.08.2025

The effect of combined core training intervention on ball throwing velocity and jump performance in competitive young female handball players

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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 Handball is a dynamic team sport that requires a combination of technical, tactical, and physical abilities. Among the key physical components, throwing velocity and vertical jump performance are essential for successful gameplay. These skills rely not only on upper and lower limb strength but also on core muscle function. The aim of this study is to investigate the impact of a combined core training intervention on ball throwing velocity and vertical jump performance in young competitive female handball players.

Material and Methods A total of 28 young female handball players ($\bar{x} = 17.21 \pm 0.74$ years, 169 ± 5 cm body height, 62.07 ± 7.43 kg body weight) participated in the study. They were divided into an experimental group (EG = 14) and a control group (CG = 14). Both groups underwent a pretest to assess ball throwing velocity and vertical jump performance. After the initial measurements, the CG followed a standard training regimen. The EG completed an intervention program comprising six combined core exercises, performed three times per week for eight weeks. The same measurements were repeated after the program. A 2x2 repeated measures ANOVA was used to determine differences between EG and CG. The main effects of time (pretest and posttest), group, and the time*group interaction were evaluated.

Results No changes were observed in the ball throwing velocity or jump performance of the CG between pretest and posttest. However, significant improvements were found in the EG for both ball throwing velocity and vertical jump performance ($F = 47.467$, $p < .001$, $\eta^2 = .646$).

Conclusions Designing core training programs in a sport-specific manner plays a significant role in developing athletes who require both general and specialized training.

Keywords: handball, core training, ball throwing velocity, vertical jumping

Introduction

Handball is a high-intensity team sport that demands well-developed physical, technical, and tactical abilities to achieve optimal performance. Among the physical requirements, the ability to execute powerful throws and high vertical jumps is critical for success in both offensive and defensive actions. These motor skills are influenced by multiple physiological factors, including the strength and coordination of the core muscles, which serve as a vital link between the upper and lower body during dynamic movements.

Handball is one of the most popular team sports, requiring a wide variety of movements, such as jumps, accelerations, changes of direction, and passes, which are the most frequently performed actions [1, 2]. In addition to technical and tactical skills, anthropometric characteristics and physical performance play a crucial role in success [3, 4].

Handball players must extensively use both their upper and lower extremities during the game. The lower extremities are heavily involved in movements like running, jumping, and leaping, while the upper extremities are essential for force- and skill-demanding actions such as shooting, catching, pushing, blocking, and goal shooting [5].

The jump shot is the most frequently employed shooting technique in team handball, accounting for 73–75% of all shots in a competitive game [6]. To counter these shots, two common defensive strategies are used: blocking the ball and collaborating with the goalkeeper to reduce the opponent's success rate. Both strategies require defenders to perform vertical jumps. Therefore, vertical jumps are a critical element in both offensive and defensive technical-tactical actions.

Numerous studies have reported that optimizing force production and transmission through good core stability enhances vertical jump performance and reduces the risk of sport-related injuries [7, 8]. However, a study by Prieske et al. [9] on a

group of soccer players found that core strength training interventions led to statistically significant improvements in sprint times and kicking performance, but not in jump height.

One of the key performance factors in handball is shooting performance, as the winning team is always the one that scores the most goals [10]. Players aim to increase their scoring opportunities by attempting as many shots as possible, most of which are overhead throws [11]. Over the course of a season, each handball player performs at least 48,000 throwing actions, with shot speeds reaching up to 130 km/h [12]. The overhead throw is a complex, full-body movement that requires precise coordination of body segments. It also demands mobility, as well as the stability, strength, and power of the pelvis, spine, and core muscles [13, 14]. A review of the literature reveals the use of various core training designs aimed at improving spinal stabilization. One controlled study on spinal stabilization training reported that interventions consisting of static core exercises led to slight improvements in throwing velocity [15], while another study found contradictory results [16].

Research on the effects of spinal stabilization exercises using sling suspension systems on ball-throwing velocity has shown significant effects in one study [17], but no significant effects in another [18]. There is sufficient evidence demonstrating the positive effects of dynamic exercises using medicine balls and/or resistance bands on ball-throwing velocity [19, 20]. The differing results in studies investigating the impact of core training on throwing velocity may be attributed to the diverse sample groups and training designs employed. These include: (1) core training for shoulder stabilization, (2) core training with sling suspension, and (3) plyometric and resistance training with medicine balls.

Analysis of research findings has shown that core training can influence both vertical jump performance and ball-throwing velocity, although the outcomes vary depending on the type and structure of the training interventions. Researchers emphasize that the effectiveness of core training is closely linked to the integration of dynamic, sport-specific movements that reflect actual game demands. Given the complexity of motor skills in handball and the variety of training methods applied, further examination of targeted core training programs remains important for optimizing key performance indicators in young athletes.

The aim of this study is to investigate the impact of a combined core training intervention on ball throwing velocity and vertical jump performance in young competitive female handball players.

Materials and Methods

Participants

A total of 28 licensed female athletes who participated in the Turkish Handball Federation's youth league were randomly recruited from two different teams. The inclusion criteria required that all participants be healthy handball players with at least two years of continuous training experience and regular team participation. Exclusion criteria included a history of musculoskeletal injuries within the last six months, current participation in other training studies, or any known medical condition affecting neuromuscular performance.

These athletes were randomly assigned to the experimental group (EG, $n = 14$) or the control group (CG, $n = 14$) using a computerized random number generator. The required sample size ($n = 28$) had been calculated using G*Power software with a significance level of 0.05, power of 0.80, and an effect size of 1.00. Allocation concealment was ensured through sealed, opaque envelopes prepared by a researcher not involved in the intervention or data analysis.

Ethical approval for the study was obtained from the Ethics Committee of the Institute of Health Sciences at Marmara University. The average age of participants was 17.21 ± 0.74 years (EG: 17.28 ± 0.53 years; CG: 17.14 ± 0.94 years). Participants were informed about the tests and training programs beforehand. For athletes under 18 years old, parental consent was obtained. Participants who were 18 years old provided written consent themselves.

Research Design

This study was conducted as a randomized trial with a true experimental design using a pretest–posttest control group model.

One week before the intervention, all participants underwent pretests to assess throwing ball velocity and vertical jump performance. The experimental group ($n = 14$) participated in an additional 8-week core training program. The sessions lasted 30 minutes and were held three times a week. The control group ($n = 14$) continued with their regular handball training. One week after the 8-week intervention, posttests were conducted to reassess throwing ball velocity and vertical jump performance.

The experimental group performed core training between February and April, with three sessions per week lasting 30 minutes each. The control group continued traditional handball training with the same frequency. After their warm-up, athletes in the experimental group followed a six-exercise core training program. The intervention was designed specifically for handball. It began with floor-based spinal stabilization exercises and progressively included more dynamic, multidirectional

movements using balance and resistance equipment (e.g., medicine balls). Each exercise was followed by a 60-second rest, and a 120-second rest was provided between sets.

The structure of the training protocol reflects a progressive design. It begins with low-complexity, floor-based stabilization exercises and evolves into more demanding, sport-specific tasks. By aligning exercise intensity, directionality, and movement patterns with real handball gameplay actions, the program aims to improve performance transfer and neural adaptations. This approach distinguishes it from previous unidimensional or single-phase core training models.

Participant adherence was recorded throughout the study. No participant missed more than one session, ensuring that all met the inclusion criteria for analysis. The core stability and strength training program are shown in Figure 1.

Participants were provided with detailed guidance on pre- and post-training nutrition. Additionally, they were advised to avoid high-intensity physical activities and to ensure proper rest on training days to optimize recovery and performance.

Before starting the pretests, all participants' height (cm) and body weight (kg) were measured using a Seca-brand scale, and their Body Mass Index (BMI) was calculated. In both the pre- and posttests, vertical jump height was measured using a Microgate Witty model jump mat. To better assess the contribution of the core region to the kinetic

chain during jumping, the test was performed with an arm swing. Participants were instructed to maintain a 90-degree knee angle during the jump. Two trials were conducted, and the best result was recorded. A rest period of approximately 2 minutes was provided between attempts.

The vertical jump test was conducted after a 15-minute active warm-up, which included 5 minutes of running, 5 minutes of short sprints, and 5 minutes of dynamic stretching and mobility exercises.

The accurate shot velocity test measured the ball's maximum speed (km/h) during a throw using a Sport Radar Gunn (Astro Products, CA) radar gun, positioned 2 meters behind and 1 meter to the right of the athlete. The vertical jump was assessed using the Just Jump System, a contact-based device widely used in sports performance testing. Both instruments have been shown to demonstrate high test-retest reliability (ICC > 0.90) in studies by Butcher et al. [13] and Ozmen et al. [16], and are recognized as valid tools for evaluating explosive lower-limb power and throwing velocity in youth athletes. Additionally, the Sport Radar Gun has been effectively used to assess throwing performance in core training studies involving handball players, as reported by Manchado et al. [15] and Palmer et al. [19].

Participants were instructed to hold a size 2 ball (325 grams, approved by the International Handball Federation) in their dominant hand and perform a standing throw within 3 seconds. They were allowed

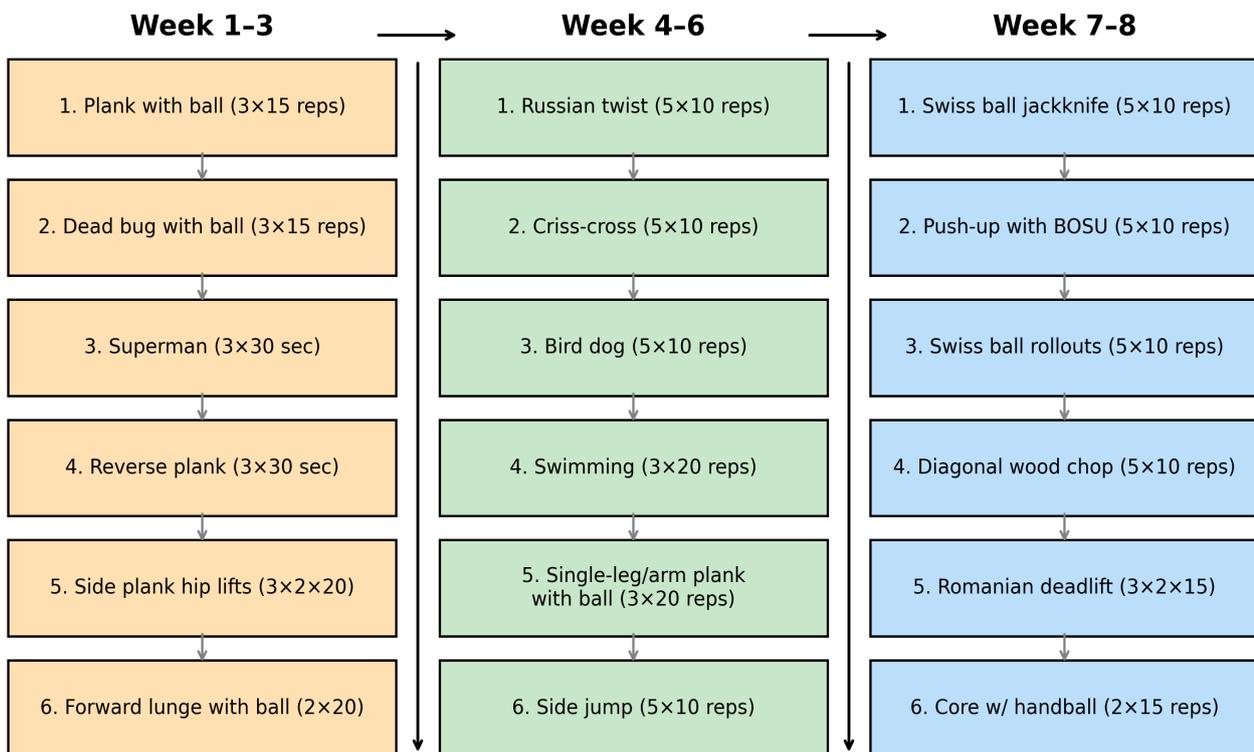


Figure 1. Core training program. Rest intervals: 60 seconds between sets; 120 seconds between exercises.

to take up to three steps from the 9-meter to the 7-meter free-throw line. A 3-minute rest interval was provided between each attempt.

To indicate the target area, a 60 × 60 cm iron frame was placed in the upper and lower corners of the goal. Among the three goal-scoring attempts, the shot with the highest recorded speed was used for evaluation.

Statistical Analysis

SPSS 22.0 (SPSS Inc., Chicago, IL) software was used to analyze the data collected in this study and to ensure the reliability of the analysis process. Skewness, kurtosis, and Shapiro–Wilk values were examined to assess normality assumptions, and it was determined that these assumptions were met. For each variable, the mean, standard deviation, percentage change, mean difference, and effect size were calculated. A 2 × 2 repeated measures ANOVA was used to determine the differences between the experimental and control groups. In this analysis, the main effects of time (pretest and posttest), group (experimental and control), and the time × group interaction were evaluated. The partial eta-squared (η^2) values obtained from the two-way ANOVA results were interpreted as follows: $0.01 \leq \eta^2 < 0.06$ indicates a small effect size; $0.06 \leq \eta^2 < 0.14$ indicates a medium effect size; and $\eta^2 \geq 0.14$ indicates a large effect size [21]. No missing data were

observed in this study; therefore, no imputation or listwise deletion techniques were necessary.

Results

Descriptive statistics regarding the age and physical characteristics of the experimental group (EG) and the control group (CG) are presented in Table 1.

There were no significant baseline differences between the groups in terms of age, body weight, height, or BMI. None of the variables recorded at baseline showed statistically significant differences between the groups ($p > .05$).

The pre- and post-performance evaluations (vertical jump and ball throwing velocity) of the experimental group (EG) and the control group (CG) after the eight-week training program are presented in Table 2 and Table 3.

The data presented in Table 2 show that, following the 8-week combined core training intervention, the experimental group (EG) exhibited an 11.2% improvement in vertical jump performance. In contrast, the control group (CG) demonstrated a modest 3.8% increase despite not undergoing any intervention. The results of the 2 × 2 repeated measures ANOVA on vertical jump performance showed a significant difference between the measurements ($F = 47.467$, $p < .001$, $\eta^2 = .646$). This finding indicates that the 8-week intervention

Table 1. Characteristics of Participants (EG - n=14; CG - n=14)

Parameter	Group	Mean	Std. Dev	Std. Error
Age (years)	EG	17.29	0.726	0.194
	CG	17.14	0.770	0.206
Height (cm)	EG	168.60	6.10	1.60
	CG	169.80	4.40	1.20
Weight (kg)	EG	62.50	8.272	2.211
	CG	61.64	6.767	1.808
BMI (kg/m ²)	EG	21.94	1.990	0.532
	CG	21.34	1.746	0.467

Note: EG = Experimental Group; CG = Control Group; BMI = Body Mass Index.

Table 2. Pre- and Posttest Results of Vertical Jump – Repeated Measures 2 × 2 ANOVA

Vertical Jump (cm)	ANOVA (Time)				ANOVA (Group)				ANOVA (Time * Group)				Between Groups Difference			
	Group	Mean+SD	Square Mean	F	p	η^2	Square Mean	F	p	η^2	Square Mean	F	p	η^2	p	η^2
Pretest	EG	30.83±2.97	65.794	47.467	.000	.646	507.004	21.688	.000	.455	19.802	14.286	.001	.355	.001	.528
	CG	26.00±3.96														
Posttest	EG	34.19±2.41	65.794	47.467	.000	.646	507.004	21.688	.000	.455	19.802	14.286	.001	.355	.001	.528
	CG	26.99±4.38														

Note: EG: Experimental Group, CG: Control Group, * $p < .05$, ** large effect size = $\eta^2 \geq .14$.

Table 3. Pre- and Posttest Results of Throwing Velocity – Repeated Measures 2 × 2 ANOVA

Vertical Jump (cm)	ANOVA (Time)					ANOVA (Group)					ANOVA (Time *Group)					Between Groups Difference (Posttest)	
	Group	Mean+SD	Square Mean	F	p	η^2	Square Mean	F	p	η^2	Square Mean	F	p	η^2	p	η^2	
Pretest	EG	63.92±5.76	350.00	66.25	.000	.718	216.07	2.096	.06	.075	248.64	47.07	.000*	.644	.005	.270	
	CG	64.21±9.32															
Posttest	EG	73.14±4.62	350.00	66.25	.000	.718	216.07	2.096	.06	.075	248.64	47.07	.000*	.644	.005	.270	
	CG	65.00±8.67															

Note: EG: Experimental Group, CG: Control Group, *p < .05, ** large effect size = $\eta^2 \geq .14$.

program, or the time factor, led to a general improvement in vertical jump performance (11.2%). The effect size ($\eta^2 \geq .14$) reflects a large effect. There was also a significant difference between the groups in terms of overall performance levels (F = 21.688, p < .001, $\eta^2 = .455$). The overall performance of the EG was significantly higher than that of the CG. A significant time × group interaction was observed (F = 14.286, p = .001, $\eta^2 = .355$), suggesting that the changes in measurements differed between the EG and CG. This result confirms that the training effect was more pronounced in the EG. Posttest analysis revealed a statistically significant difference between the groups (p = .001, $\eta^2 = .528$). The posttest mean score for the EG (34.19 ± 2.41) was significantly higher than that of the CG (26.99 ± 4.38).

The data presented in Table 3 show the performance outcomes for ball throwing velocity. Following the 8-week combined core training intervention, the experimental group (EG) demonstrated a 14.7% improvement in overhead ball throwing performance. In contrast, the control group (CG) exhibited a modest 1.6% increase without any intervention. The findings from the 2 × 2 repeated measures ANOVA on throwing velocity revealed a significant difference in measurements (F = 66.251, p < .001, $\eta^2 = .718$). This result suggests that the 8-week intervention program (i.e., the time factor) significantly enhanced overall throwing performance. The effect size ($\eta^2 = .718$) indicates a very large effect. Conversely, no significant difference was found between the groups in terms of overall performance levels (F = 2.096, p = .160, $\eta^2 = .075$). This outcome implies that there were no significant baseline disparities between the EG and CG in overall performance. A significant time × group interaction was observed (F = 47.065, p < .001, $\eta^2 = .644$). This finding indicates that the magnitude of improvement varied between the groups, with the EG showing a more pronounced change in throwing velocity after training. Analysis of the posttest results revealed a statistically significant difference between the EG and CG (p = .005, $\eta^2 = .270$). The posttest mean score of the EG (73.14 ± 4.62) was significantly higher than that of the CG (65.00 ± 8.67).

Discussion

The aim of this study was to investigate the impact of a combined core training intervention on ball throwing velocity and vertical jump performance in young competitive female handball players. The results showed that the experimental group significantly improved both vertical jump height (by 11.2%) and ball throwing velocity (by 14.7%) after the 8-week intervention. In contrast, the control group demonstrated only minimal improvements. Statistical analysis confirmed that these changes were significant, with large effect sizes observed for both performance indicators.

While previous studies have investigated the impact of core training on athletic performance, many have relied on single-phase protocols or generalized exercise regimens lacking sport-specific progression [14, 15, 17]. The current study extends this body of work by implementing a structured, multi-phase intervention that combines foundational stabilization exercises with dynamic drills tailored to the demands of handball, incorporating unstable surfaces and resistance equipment [16, 18, 19]. Moreover, the focus on competitive female handball players aged 16–18 addresses a demographic that remains underrepresented in existing research, which has predominantly examined male or mixed-gender samples [15, 17, 20]. This combination of methodological rigor and population specificity enhances the relevance and potential applicability of the findings within youth female athletic development contexts.

Characteristics of the participants

The female handball players participating in the study had a mean age of 17.21 ± 0.74 years, an average height of 169 ± 5 cm, and a body weight of 62.07 ± 7.43 kg. These physical characteristics are similar to those reported in a recent study on female handball players (19.5 ± 1.4 years, 165 ± 5 cm, 61.7 ± 9.3 kg) [22]. In another study conducted across four Asian countries, the average height and body weight of female handball players were also comparable (170.8 ± 0.068 cm and 64.6 ± 7.7 kg) [23].

Based on these findings, the physical characteristics of the female handball players in this study can be considered close to the average for this population.

Effect of Core Training on Vertical Jump Performance

The findings of this study support the assumption that a combined core training intervention can significantly improve jumping performance in female handball players ($p < .001$). Recent studies analyzing the impact of core training on jump performance have demonstrated medium to large effects in favor of core training [24, 25, 26, 27]. In this study, the effect size was particularly large ($\eta^2 \geq .528$).

Countermovement jump (CMJ) tests are typically used to measure jump performance with the hands placed on the hips [28, 29]. However, this approach does not reflect the natural jumping technique used by handball players during training and matches. When arm movement is incorporated into the jump, the core muscles are more actively engaged as part of the kinetic chain. The use of arm-involved jumping tests in this study likely contributed positively to the athletes' performance outcomes.

In addition, the core exercises in the training program closely mimicked the intended sport-specific movements, maximizing the transfer training effect [30, 31]. The improvement in jumping performance may also be attributed to the program's design, which enhanced core strength and, in turn, improved the ability to control trunk position and movement over the pelvis. As suggested by previous researchers, improved neuromuscular function optimizes the production, transfer, and control of force and movement in integrated athletic kinetic chain activities [32].

Another potential explanation is that nearly all exercises in the program involved isometric or dynamic contractions of the hip extensor muscles. This could serve as an effective stimulus for increasing strength in these muscles, thereby positively transferring to jump performance.

Effect of Core Training on Accurate Throwing Velocity

The findings indicate that the combined core exercise intervention significantly improved the throwing velocity of the experimental group. A stronger and more stable lumbo-pelvic-hip complex likely contributes to greater rotational velocity during multi-segmental movements. In addition, high-velocity, multiplanar resistance exercises that replicate overhead throwing motions, such as those using a medicine ball, appear to promote training adaptations that are transferable to throwing performance [15, 23].

This improvement may also depend on specific characteristics of the training intervention, including exercise type, intensity, structure, and the role of motor learning. Therefore, training programs

should be aligned with the movement patterns required for effective handball throwing [33].

The findings of this study are consistent with those of Saeterbakken et al. [17] and Stary et al. [34], who reported improvements in throwing velocity within experimental groups following unstable core training, although between-group differences were not statistically significant. Other studies have shown that endurance training can also lead to increased throwing speed without negatively affecting accuracy [35].

The extent of improvement may also depend on training frequency and duration. Wagner et al. [36] noted that long-term sport-specific training might reduce the impact of additional training performed only twice per week. For more substantial gains in strength and velocity, increasing the frequency to three or four additional sessions per week is recommended. According to Behm [37], neural adaptations tend to dominate during the initial stages of resistance training, typically within the first eight to twelve weeks. As a result, the positive transfer from improved lateral core stability to throwing performance may require a similar duration of intervention.

The core training protocol used in this study produced a large effect size, which is comparable to the results reported in previous studies involving dynamic core exercises that included medicine balls and resistance-based training [17, 19].

The results of this study confirm the effectiveness of a combined core training program in enhancing both vertical jump performance and ball throwing velocity in young female handball players. The findings highlight the importance of targeting core musculature through dynamic, sport-specific exercises to improve key physical abilities directly related to handball performance. These results align with previous findings that demonstrate the benefits of core strength training for explosive movements and throwing actions in youth athletes [15, 16, 19].

Taken together, these findings underscore the novelty of combining progressive core training with performance testing that mirrors actual gameplay in a specific athletic population. The use of arm-involved jump assessments and multi-planar throwing tests enhances ecological validity and increases the practical applicability of the outcomes for coaches and trainers. While earlier studies have evaluated the effects of unstable or sling-based core training [17, 18], the present study's design expands on this by integrating both stable and dynamic core modalities in conjunction with sport-specific movement patterns.

Compared to earlier studies that employed either static or general dynamic core training protocols [14, 15], the current intervention is distinguished by its integration of multiple functional components into a cohesive, handball-specific regimen. The inclusion

of test protocols involving arm motion and game-like throwing mechanics further strengthens the transferability of improvements to real competitive scenarios, supporting the application of such training approaches in youth female handball development programs [10, 11, 20].

Limitations and Future Directions

This study has certain limitations that should be acknowledged. The sample size was relatively small and limited to licensed female handball players from two teams within a single national league, which may restrict the generalizability of the findings. Additionally, only short-term effects were evaluated, without follow-up assessments to determine the long-term sustainability of improvements. Future research should aim to evaluate the long-term effects of core strength training on the efficiency of jumping and ball throwing velocity by extending follow-up durations and conducting comparative analyses of various training techniques and age-related variables. Studies involving larger and more diverse populations across different age groups, genders, and competitive levels are also recommended. Furthermore, the inclusion of biomechanical and neuromuscular assessments

could offer deeper insights into the underlying mechanisms of performance enhancement.

Conclusions

Core training is considered a critical component for enhancing sports performance. It is acknowledged that the effects of such interventions on ball speed may vary among athletes participating in different sports. Structuring core training programs in a sport-specific manner plays a significant role in the development of athletes who require both general and specialized training. In this context, it is essential for coaches to closely observe athlete movements, identify which components effectively enhance specific skills, and determine which areas require additional focus.

Conflicts of Interest

The authors declare no relevant financial or non-financial conflicts of interest.

Data Availability

The dataset generated during the current study is available from the corresponding author upon reasonable request.

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Cite this article as:

Akalp U, Pinar S, Pinar Y. The effect of combined core training intervention on ball throwing velocity and jump performance in competitive young female handball players. *Pedagogy of Physical Culture and Sports*, 2025;29(4):330–338.

<https://doi.org/10.15561/26649837.2025.0410>

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Received: 11.07.2025

Accepted: 14.08.2025; Published: 30.08.2025

A pilates-based physiological recovery strategy to enhance post-exercise recovery after high-intensity interval exercise

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Abstract

Background and Study Aim Recovery is essential for restoring homeostasis after high-intensity interval exercise (HIIE), especially in non-athletes. While static stretching remains popular, Pilates is also used as a mindful active recovery method, but its effects after HIIE require further clarification. This study aimed to examine the effects of Pilates-based recovery compared to conventional static cool-down on parasympathetic activation, delayed onset muscle soreness (DOMS), and mood disturbance.

Material and Methods A quasi-experimental, pre-post control group design was conducted with 40 healthy, inactive female university students aged 20–25, randomly assigned to a Pilates group (n = 20) or a control group (n = 20). Following a single bout of HIIE (T0), participants were evaluated at 24 h (T1) and 48 h (T2) post-intervention. Outcomes included DOMS (Visual Analogue Scale), heart rate recovery (HRR), and total mood disturbance (TMD; POMS-SF). Data were analyzed using paired sample t-tests and independent t-tests, with effect sizes calculated using Cohen's d.

Results The Pilates group demonstrated significant within-group improvements from T0 to T2 in DOMS (p = 0.001, d = 3.04), HRR (p = 0.001, d = 288.10), and TMD (p = 0.021, d = 31.89). Between-group comparisons at T2 favored the Pilates group for all variables: DOMS (p = 0.001, d = 2.83), HRR (p = 0.044, d = 47.94), and TMD (p = 0.005, d = 24.18).

Conclusions Pilates-based recovery significantly improves neuromuscular relaxation, autonomic reactivation, and affective state compared to passive recovery. These findings support Pilates as a superior strategy for post-exercise recovery in non-athletes.

Keywords: pilates, HIIE, physiological recovery, muscle soreness, total mood disturbance

Introduction

High-intensity interval exercise (HIIE) is widely recognized for its effectiveness in improving cardiovascular fitness, metabolic health, and overall physical performance. However, the intense nature of such exercise also places significant physiological and psychological demands on the body, especially in individuals who are not regularly physically active. In this context, the recovery phase becomes a crucial component of the training process, as it influences both the rate of adaptation and the risk of overtraining or injury.

High-intensity interval exercise (HIIE) has been recognised as an effective method for increasing cardiorespiratory capacity, metabolic efficiency, and muscle strength and endurance in a relatively short period [1, 2]. However, in the acute phase of

exercise, the high intensity can cause significant physiological stress, primarily mediated by the activation of the sympathetic nervous system (SNS) [4]. During HIIE sessions, there is an increase in the release of catecholamines, heart rate, blood pressure, cardiac output, and peripheral vasoconstriction [4, 5]. This response plays an important role in meeting the body's metabolic demands during exercise, but it can also lead to autonomic imbalances, neuromuscular disturbances, and increased post-exercise psychological load [6].

In the post-traumatic stress phase, the body should ideally transition immediately to recovery by activating the parasympathetic nervous system (PNS) to restore homeostasis [7]. However, some evidence suggests that parasympathetic reactivation is often delayed, especially after high-intensity exercise such as HIIE [8, 9, 10]. This condition is characterised by a slow decrease in heart rate (heart rate recovery, HRR), increased subjective fatigue, and the onset of mood disorders such as anxiety, irritability, and mental fatigue [7, 8, 11]. Additionally, the musculoskeletal system also experiences

significant biomechanical stress, with delayed onset muscle soreness (DOMS) manifesting 24–72 hours after exercise due to microscopic muscle damage and inflammatory processes [8, 9].

Restoring autonomic balance is crucial for improving psychological health. Inadequate recovery may extend sympathetic dominance, which raises the risk of repeated injuries, hampers physiological adaptation, and decreases overall performance and mental well-being [4, 5]. Several studies have reported that active recovery is significantly more effective than passive recovery in lowering heart rate and body temperature after moderate-intensity exercise ($p < 0.05$), and it is more beneficial in supporting physiological recovery and preventing overreaching [10, 11, 12]. However, these studies still have limitations, including unclear descriptions of the form of active recovery interventions, limited observation of physiological indicators, and insufficient coverage of neuromuscular, hormonal, and psychological aspects [11, 12].

Additionally, the exercise activities used are moderate in intensity and are performed in the chronic phase of recovery. Therefore, further research using a Pilates-based recovery approach is relevant to address this gap, especially concerning high-intensity post-workout recovery in the acute phase, considering that Pilates offers a structured, integrative, and potentially optimal method of physical and mental recovery. Although extensive research has been conducted on both active and passive recovery methods following exercise, empirical investigations focusing on the immediate effects of Pilates after high-intensity interval exercise (HIIE) remain limited, particularly within non-athlete populations.

Pilates has emerged as a more comprehensive and cohesive method for recovery [13, 14, 15]. Pilates combines diaphragmatic breathing techniques, core muscle activation, postural control, and mindful movement within a single exercise framework [16, 17, 18]. From a physiological standpoint, Pilates can enhance vagus nerve activity, accelerate activation of the parasympathetic system, and improve heart rate recovery (HRR) responses [19]. Additionally, the meditative and relaxing components of Pilates are associated with reduced psychological stress and enhanced mood. In contrast to passive stretching, Pilates provides more dynamic neuromuscular stimulation, which is more effective in enhancing blood circulation, improving lymphatic drainage, and stabilising central nervous system components, all of which contribute to a faster recovery process [20, 21].

An analysis of previous research findings has shown that various recovery methods can positively influence physiological and psychological outcomes after exercise. The authors highlight that Pilates, due to its integrative approach combining physical and

mental elements, may serve as an effective recovery strategy, particularly in the context of high-intensity exercise. They emphasise the potential of Pilates to promote faster parasympathetic reactivation, reduce muscle soreness, and improve emotional well-being. However, there remains a clear need for further research. This gap in evidence continues to limit a comprehensive understanding of Pilates-based recovery, especially regarding its acute effects following high-intensity interval exercise among non-athlete populations.

Although the benefits of Pilates have been examined in the context of general fitness and long-term rehabilitation, limited attention has been given to its potential role as an acute recovery strategy following high-intensity interval exercise (HIIE). In particular, few studies have simultaneously assessed multiple physiological indicators, such as heart rate recovery (HRR) for autonomic function, delayed onset muscle soreness (DOMS) for neuromuscular condition, and total mood disturbance (TMD) for psychological state, within a single Pilates-based recovery framework. Considering the structured and multidimensional characteristics of Pilates, it seems appropriate to explore its possible application in short-term recovery after submaximal exercise. Therefore, this study aimed to examine the effects of Pilates-based recovery compared to conventional static cool-down on parasympathetic activation, delayed onset muscle soreness (DOMS), and mood disturbance.

Materials and Methods

Participants

This study involved a total of 40 active female students from the Faculty of Sports and Health Sciences at Universitas Negeri Surabaya. The participants were selected using purposive sampling based on strict inclusion criteria to ensure the homogeneity of baseline characteristics. The inclusion criteria were as follows: age between 20 and 25 years, good physical and mental health, no participation in a regular fitness programme in the past three months, no history of musculoskeletal injury, cardiovascular or psychiatric disorders, and willingness to participate in all stages of the study with signed informed consent.

The sample size was determined using a power calculation approach, considering a medium effect size ($d = 0.5$), a significance level of $\alpha = 0.05$, and a statistical power of 0.80. Using G*Power software, it was calculated that at least 17 participants were needed per group. To account for potential dropouts or data loss, this number was increased to 20 participants per group, resulting in a total of 40 participants. Additionally, participants meeting the inclusion criteria were randomly assigned to two treatment groups. One group received a recovery

session using the Pilates method (Pilates group, n = 20), while the other group underwent a conventional static cool-down procedure as a control (control group, n = 20). All 40 participants completed the protocol, with a 0% dropout rate.

This research received approval from the Health Research Ethics Committee, Faculty of Sports Sciences, Universitas Negeri Surabaya, with registration number No. 006/UN27.II.1/DL.01.02/2025. All research procedures followed the ethical principles established by the WHO (2011) and the CIOMS guidelines (2016), including social value, scientific validity, fair selection of participants, a balance of benefits and risks, privacy protection, and informed consent. All participants voluntarily provided written consent, and their identities were kept confidential. Participants also had the right to withdraw from the research at any time without any consequences.

Study Design

This study used a quasi-experimental approach with a pre-test and post-test control group design. It aimed to evaluate the effectiveness of a physiological recovery-based Pilates program as a method of active recovery after high-intensity exercise. Two intervention groups were compared: the group that underwent a Pilates-based recovery program and the control group that received a conventional cool-down procedure. Each group was assessed on several physiological and psychological variables at three predetermined time points.

Table 1 presents a research design structure designed to evaluate the effectiveness of Pilates as an active recovery method after a session of High-Intensity Interval Exercise (HIIE), compared to a conventional static cooling down method. The study involved two intervention groups, namely the Pilates group and the control group, each of which underwent repeated measurements on three main variables: Visual Analogue Scale (VAS) to assess the level of delayed muscle soreness (DOMS), Heart Rate Recovery (HRR) as an indicator of cardiovascular and autonomic recovery, and Total Mood Disturbance (TMD) as a representation of post-exercise psychological status.

After completing the HIIE (T0) exercise session, all participants underwent a pretest with measurements of the three variables. Furthermore, each group underwent a recovery intervention

according to their treatment. The Pilates group received a 20-minute Pilates exercise session focused on diaphragmatic breathing techniques, core muscle activation, and mindful movement. Meanwhile, the control group performed a conventional static cooling down for 10 minutes, consisting of static stretching of the upper and lower body. The effectiveness of the intervention was assessed at the next two time points, namely 24 hours (T1) and 48 hours (T2) post-intervention, with repeated measurements on all three variables.

This study used three main instruments to evaluate physiological and psychological responses after high-intensity exercise, namely the Visual Analogue Scale (VAS) to assess delayed muscle pain (DOMS), the Polar H10 heart rate monitor to measure heart rate recovery (HRR), and the Profile of Mood States – Short Form (POMS-SF) to identify mood disturbances (total mood disturbance, TMD). The VAS used was a 10 cm line, shown to be valid ($r > 0.70$) and reliable ($ICC > 0.80$), with scores categorised as mild (0–3 cm), moderate (4–6 cm), and severe pain (7–10 cm). HRR was measured using a Polar H10, which has high validity compared to ECG ($r > 0.95$). A decrease of ≥ 12 bpm in HRR1 after the recovery intervention indicated rapid recovery and parasympathetic dominance. The POMS-SF consists of 37 items with six subscales, and the TMD score is obtained using the formula:

$$TMD = (T + D + A + F + C) - V + 100$$

where T = Tension, D = Depression, A = Anger, F = Fatigue, C = Confusion, V = Vigour.

Intervention Procedure

After undergoing a high-intensity interval exercise (HIIE) session, participants immediately received a recovery intervention according to their assigned groups: Pilates or conventional static cool-down. The intervention was administered once, immediately following the HIIE session on the first day, and evaluations were conducted at three time points: T0 (immediately after HIIE), T1 (24 hours post-intervention), and T2 (48 hours post-intervention). Both interventions were conducted under controlled environmental conditions and guided by certified professional instructors. The aim was to compare the effectiveness of Pilates as an active recovery method with that of a conventional recovery method, focusing on its impact on

Table 1. Research design structure

Group	Pre-test (T0) After HIIE	Intervention	Post-test 1 (T1 – after 24 hours)	Post-test 2 (T2 – after 48 hours)
Pilates	VAS, HRR, TMD	Pilates 20 minutes	VAS, HRR, TMD	VAS, HRR, TMD
Control	VAS, HRR, TMD	10-minute static cooling down	VAS, HRR, TMD	VAS, HRR, TMD

Note. VAS = Visual Analogue Scale; HRR = Heart Rate Recovery; TMD = Total Mood Disturbance; HIIE = High-Intensity Interval Exercise; DOMS = Delayed Onset Muscle Soreness.

physiological (DOMS, HRR) and psychological (TMD) recovery.

Two recovery protocols were employed: a 20-minute Pilates-based active recovery session for the experimental group and a 10-minute static stretching routine for the control group. The Pilates program included full-body exercises such as pelvic tilts, spine twists, bridges, modified Hundreds, roll-ups, and breathing-focused movements. These were performed in two sets of 10–12 repetitions with tempo control and diaphragmatic breathing to support parasympathetic activation and neuromuscular recovery. In contrast, the control group followed a static stretching protocol targeting major muscle groups involved in HIIE, with each stretch held for 30 seconds across two sets. Both interventions were delivered under standardised conditions and supervised by trained personnel.

Statistical Analysis

Data analysis was conducted using SPSS software version 26.0 (IBM Corp., Armonk, NY, USA). The analysis procedure included a normality test using the Shapiro–Wilk method ($p > 0.05$ for all variables), a homogeneity of variance test using Levene’s test, paired sample t-tests for within-group comparisons, and independent sample t-tests for between-group comparisons at each time point (T0, T1, and T2). In addition to p-values, effect sizes were calculated using Cohen’s d and were accompanied by 95% confidence intervals to estimate the magnitude and precision of the observed differences. Statistical significance was set at $p < 0.05$ for all analyses.

Results

Table 2 presents the baseline demographic and physical activity characteristics of participants assigned to the Pilates and control groups. The mean age of participants in both groups was approximately 21 years, with no notable differences in anthropometric variables such as body weight, height, or BMI. Additionally, both groups reported similar levels of physical activity as measured by the International Physical Activity Questionnaire (IPAQ), expressed in MET-minutes per week.

Table 3 displays the within-group comparisons from post-HIIE (T0) to 48 hours after the intervention (T2), highlighting significant changes in recovery outcomes for both the Pilates and control groups. The data include p-values, effect sizes (Cohen’s d), and 95% confidence intervals, offering a detailed view of each group’s physiological and psychological response over time.

The results presented in Table 3 demonstrate a significant impact of the Pilates intervention on post-HIIE recovery, as reflected in three primary indicators: muscle soreness, heart rate recovery, and mood disturbance. A reduction in muscle soreness by 2.5 cm on the VAS scale ($p = 0.001$; $d = 3.04$), accompanied by a narrow confidence interval, indicates that Pilates effectively promotes muscle tissue repair following eccentric contractions. Heart rate decreased markedly from 182 bpm to 79 bpm ($p = 0.001$; $d = 288.10$), suggesting a substantial enhancement in autonomic nervous system regulation and a rapid shift toward physiological recovery through active mechanisms.

Moreover, the Total Mood Disturbance (TMD)

Table 2. Baseline Characteristics of Participants

Group	Age (yr)	Weight (kg)	Height (cm)	BMI (kg/m ²)	IPAQ (MET-min/week)
Pilates	21.3 ± 1.1	58.7 ± 4.9	162.8 ± 5.7	22.1 ± 1.3	2570 ± 410
Control	21.5 ± 1.2	59.2 ± 5.2	163.1 ± 5.4	22.2 ± 1.4	2610 ± 430

Note. Values are presented as mean ± standard deviation. BMI = Body Mass Index; IPAQ = International Physical Activity Questionnaire; MET = Metabolic Equivalent of Task.

Table 3. Within-Group Changes, Effect Sizes, and Confidence Intervals for Recovery Outcomes (Post-HIIE to 48h Post-Intervention)

Variable	Group	T0 (Post-HIIE) Mean ± SD	T2 (48h Post) Mean ± SD	p-value (paired t-test)	Effect Size (Cohen’s d)	95% CI of the Mean Difference
Muscle Soreness (VAS, cm)	Pilates	6.111 ± 0.411	3.611 ± 0.713	0.001	3.04	[2.02, 3.49]
	Control	6.333 ± 0.522	5.521 ± 0.623	0.083	1.42	[-0.11, 1.68]
Heart Rate Recovery (bpm)	Pilates	182.333 ± 0.412	79.222 ± 0.311	0.001	288.10	[101.2, 106.8]
	Control	183.112 ± 0.516	96.333 ± 0.444	0.048	211.88	[83.9, 90.1]
Total Mood Disturbance (points)	Pilates	26.113 ± 0.531	9.222 ± 0.514	0.021	31.89	[14.22, 20.11]
	Control	26.012 ± 0.344	19.233 ± 0.222	0.0311	22.47	[5.63, 8.44]

Note. VAS = Visual Analogue Scale; HRR = Heart Rate Recovery; TMD = Total Mood Disturbance; CI = Confidence Interval; SD = Standard Deviation.

score in the Pilates group declined sharply from 26.11 to 9.22 points ($p = 0.021$; $d = 31.89$), highlighting the role of Pilates in restoring psychological balance following high-intensity training. Compared to the control group, the changes observed in the Pilates group were not only more pronounced but also statistically and clinically consistent. In the context of training programs, this approach offers a holistic recovery strategy that simultaneously addresses both physiological and psycho-emotional dimensions. Table 3 supports the recommendation that coaches and fitness professionals integrate Pilates into structured post-HIIE recovery protocols to reduce delayed onset muscle soreness (DOMS), accelerate heart rate recovery (HRR), and maintain mood stability, thereby optimizing readiness for subsequent training sessions.

Table 4 presents the between-group comparisons of physiological recovery outcomes at three time points: immediately after HIIE (T0), 24 hours (T1), and 48 hours (T2) post-intervention. The table includes mean values, p-values, effect sizes (Cohen's d), and 95% confidence intervals, allowing for detailed evaluation of the effectiveness of Pilates-based recovery versus conventional static recovery methods.

The comparative analysis in Table 4 revealed significant differences in recovery between the Pilates and control groups within 48 hours post-HIIE. Muscle soreness decreased substantially more in the Pilates group, with large effect sizes at both T1 ($d = 2.85$) and T2 ($d = 2.83$), and mean differences ranging from -1.97 to -2.35 cm. These findings confirm the superior efficacy of Pilates in accelerating muscle recovery and alleviating post-

exercise discomfort. From a coaching perspective, this supports the inclusion of Pilates in recovery protocols to reduce delayed onset muscle soreness (DOMS) and ensure training continuity.

Regarding autonomic recovery, participants in the Pilates group experienced significantly faster heart rate restoration. At T2, the mean difference reached -17.36 bpm, with an exceptionally large effect size ($d = 47.94$), indicating enhanced parasympathetic reactivation. Additionally, Total Mood Disturbance (TMD) scores declined more sharply in the Pilates group, with a difference of nearly 10 points at 48 hours post-intervention ($p = 0.005$; $d = 24.18$). These outcomes suggest that Pilates supports both physical and psychological recovery. As shown in Table 4, the Pilates group demonstrated significantly better results across all key indicators (VAS, HRR, and TMD), making it a promising holistic strategy for post-HIIE recovery.

Discussion

The primary aim of this study was to examine the effects of a Pilates-based recovery intervention compared to conventional static cool-down on physiological and psychological recovery following high-intensity interval exercise (HIIE) in healthy young women. The focus was placed on three main recovery indicators: delayed onset muscle soreness (DOMS), heart rate recovery (HRR), and total mood disturbance (TMD). The results showed that the Pilates intervention significantly outperformed the control condition in all measured outcomes. Participants in the Pilates group experienced greater reductions in muscle soreness, faster

Table 4. Between-Group Differences in Physiological Recovery Outcomes (Post-HIIE to 48h Post-Intervention)

Variable	Timepoint	Pilates Group (n = 20)	Control Group (n = 20)	p-value	Effect Size (Cohen's d)	95% CI of the Mean Difference
Muscle Soreness (VAS, cm)	T0 (post-HIIE)	6.111 ± 0.411	6.333 ± 0.522	0.580	0.46	[-0.53, 0.09]
	T1 (24h post-intervention)	4.222 ± 0.801	5.811 ± 0.111	0.021	2.85	[-1.97, -1.21]
	T2 (48h post-intervention)	3.611 ± 0.713	5.521 ± 0.623	0.001	2.83	[-2.35, -1.47]
Heart Rate Recovery (bpm)	T0 (post-HIIE)	182.333 ± 0.412	183.112 ± 0.516	0.520	1.63	[-1.09, -0.47]
	T1 (24h post-intervention)	90.122 ± 0.432	101.231 ± 0.415	0.040	26.00	[-11.39, -10.83]
	T2 (48h post-intervention)	79.222 ± 0.311	96.333 ± 0.444	0.044	47.94	[-17.36, -16.86]
Total Mood Disturbance (points)	T0 (post-HIIE)	26.113 ± 0.531	26.012 ± 0.344	0.488	0.22	[-0.20, 0.40]
	T1 (24h post-intervention)	17.333 ± 0.622	20.812 ± 0.811	0.042	4.93	[-3.96, -3.00]
	T2 (48h post-intervention)	9.222 ± 0.514	19.233 ± 0.222	0.005	24.18	[-10.27, -9.75]

Note. VAS = Visual Analogue Scale; HRR = Heart Rate Recovery; TMD = Total Mood Disturbance; CI = Confidence Interval; SD = Standard Deviation; bpm = beats per minute.

autonomic recovery as reflected by HRR, and more substantial improvements in mood states. These differences became particularly evident at 24 and 48 hours post-intervention, indicating both short-term and sustained benefits of the Pilates-based recovery approach. The effect sizes across all variables were large, and the observed differences were not only statistically significant but also clinically meaningful.

In this context, it should be noted that previous investigations have primarily emphasized passive recovery techniques such as static stretching or relaxation exercises [22, 23, 24]. Despite emerging interest, the scientific understanding of Pilates' role in autonomic regulation, hormonal stabilization, and psychological recovery remains limited [25]. What distinguishes the present study is its integrative design, which simultaneously examines neuromuscular (DOMS), cardiovascular (HRR), and psychological (TMD) recovery within 48 hours post-intervention, using conventional cool-down methods as a comparator.

The findings demonstrate that Pilates is more effective than traditional cool-downs in enhancing both physiological and psychological aspects of recovery. These results are consistent with earlier studies [27], which indicate that mindful movement and controlled breathing can accelerate heart rate recovery and positively influence mood. Additional evidence from the literature [26, 28] suggests that low-impact modalities such as Pilates can support neuromuscular repair while enhancing parasympathetic reactivation during acute recovery. Taken together, these results underscore the value of holistic recovery strategies in optimizing post-exercise regeneration [29, 30].

The observed reduction in DOMS within the Pilates group ($p = 0.001$) reflects more efficient muscle regeneration following high-intensity exertion. This improvement is likely attributed to increased circulation and lymphatic drainage facilitated by dynamic, low-impact movement, which supports oxygen delivery and metabolite clearance [29, 30]. Controlled activation of the core musculature may also enhance vagal tone while suppressing sympathetic activity, promoting a shift toward parasympathetic dominance [29]. This neurophysiological response contributes to hypothalamic–pituitary–adrenal (HPA) axis downregulation and reduces the release of cortisol and catecholamines, both of which are associated with physical and emotional fatigue [31].

Pilates' emphasis on diaphragmatic breathing further contributes to autonomic regulation by improving baroreflex sensitivity and facilitating heart rate recovery (HRR) restoration [17, 18]. At the same time, rhythmic and flowing movement patterns stimulate the release of endorphins and anti-inflammatory cytokines such as interleukin-10

(IL-10), which act as natural analgesics and mood enhancers [32]. Unlike passive cool-down routines, Pilates integrates muscular, respiratory, and neuroendocrine systems into a unified recovery process [33, 34], making it particularly beneficial for non-athletic individuals who are more susceptible to post-exercise stress [35, 36]. This adaptability increases its relevance for designing recovery-focused fitness programs across diverse populations.

From the perspective of autonomic recovery, participants in the Pilates group demonstrated significantly greater improvements in heart rate recovery (HRR), indicating more rapid reactivation of parasympathetic pathways [35]. The slow, deliberate execution of Pilates movements, combined with focused breathwork, effectively enhances vagal activity and restores systemic equilibrium [21]. Physiologically, this shift supports the downregulation of motor cortex and hypothalamic activity, reducing stimulation of the hypothalamic–pituitary–adrenal (HPA) axis and subsequently decreasing stress hormone output [29]. These changes help create a hormonal environment more conducive to efficient recovery and emotional stabilization.

In contrast, traditional cool-down methods such as light walking or static stretching appear to offer only limited support for systemic recovery [37]. While these routines may assist in temperature regulation and peripheral circulation, they are insufficient for stimulating parasympathetic activation or producing meaningful endocrine modulation [21]. The lack of integrated neuromuscular and cognitive engagement in passive recovery strategies may restrict their effectiveness in optimizing post-exercise recovery [10, 38]. As a result, physiological mechanisms related to soreness reduction, autonomic recovery, and mood normalization remain suboptimal with such approaches.

The significant improvement in total mood disturbance (TMD) observed among Pilates participants ($p = 0.021$) highlights the modality's potential to promote both emotional and physical recovery [30, 39]. This effect may be attributed to parasympathetic activation through vagal stimulation, regulation of neuroendocrine function, and modulation of the hypothalamic–pituitary–adrenal (HPA) axis. By combining breath control, mindfulness, and coordinated movement, Pilates helps reduce sympathetic arousal and suppresses the release of cortisol and adrenaline – hormones closely associated with anxiety, irritability, and mood disturbance [20, 40]. This multifaceted regulation contributes to greater emotional stability following strenuous exercise [30, 39].

Furthermore, Pilates appears to enhance mood through increased production of serotonin and gamma-aminobutyric acid (GABA), key neurotransmitters that support emotional balance

and central nervous system recovery [20, 41]. In this way, Pilates serves as a neurovegetative modulator that facilitates the normalization of affective and cognitive processes following exertion [17, 18]. By contrast, conventional cool-downs typically lack the cognitive and respiratory components necessary to initiate these neurochemical responses [42]. Although such methods help the body transition into rest, their inability to activate relevant neuroendocrine pathways may limit their effectiveness in supporting psychological recovery [42].

These findings suggest that psychological recovery through passive strategies may be inherently limited, particularly with respect to neurohormonal regulation. The comparison highlights Pilates' capacity to deliver a more integrated and multidimensional recovery experience, encompassing both biomechanical repair and neurophysiological recalibration [31, 43]. This positions Pilates as a valuable tool for fitness professionals and athletic coaches aiming to enhance recovery programs, especially for individuals with increased sensitivity to physiological stress [18]. When appropriately applied, Pilates may support smoother transitions between high-intensity exertion and subsequent training phases.

Nevertheless, some findings diverge from studies that advocate conventional cool-downs as effective for improving heart rate recovery (HRR) in trained athletes [22, 44]. However, those studies reported little benefit in terms of reducing delayed onset muscle soreness (DOMS) or enhancing mood, likely due to differences in participant characteristics, recovery protocols, and training backgrounds. Unlike the current study, which examined non-athletic participants undergoing acute high-intensity exertion, previous studies focused on well-trained individuals with higher baseline recovery capacity. This contextual distinction likely accounts for the variation in outcomes.

Among moderately active individuals (IPAQ = 2,570–2,610 MET-min/week), such as those in this study, recovery outcomes are strongly influenced by underdeveloped autonomic and cardiovascular adaptations [45, 46]. Research indicates that populations with limited physiological conditioning are more responsive to comprehensive, integrative recovery interventions [36]. Pilates, through its emphasis on breathing, vagal stimulation, and coordinated physical effort, promotes parasympathetic reactivation, cortisol suppression, and normalization of the hypothalamic–pituitary–adrenal (HPA) axis [47]. This synergy supports faster recovery in both physiological and affective domains [48].

In contrast, trained athletes, who often exhibit high baseline parasympathetic tone, may not benefit substantially from basic recovery protocols.

Their established autonomic efficiency reduces the potential for noticeable changes in delayed onset muscle soreness (DOMS) or mood following light activity [22, 38]. These findings reinforce the need for recovery methods to be tailored to an individual's physiological capacity, fitness level, and training status. For coaches, this insight highlights the importance of personalized recovery planning in athletic programming.

The present study positions Pilates as a versatile recovery strategy that supports physical, autonomic, and emotional restoration following high-intensity exercise [20, 21, 29]. The combination of mindful movement, controlled breathing, and somatic awareness contributes to favorable neuroendocrine and central nervous system conditions, reinforcing its integrative role in post-exercise recovery.

Previous studies investigating post-exercise recovery have largely focused on either passive methods such as static stretching [22, 23], or on general active modalities without specific integration of physiological, autonomic, and psychological dimensions [10, 38]. While some research has explored the effects of yoga or aquatic recovery on individual aspects of recovery [26, 44], few have adopted a multidomain framework targeting neuromuscular, cardiovascular, and mood-related parameters simultaneously. The present study offers a novel contribution by systematically evaluating a Pilates-based recovery protocol across three distinct domains—muscle soreness (DOMS), heart rate recovery (HRR), and total mood disturbance (TMD)—within the acute 48-hour post-HIIE phase. This integrative design, combined with a focus on non-athletic participants, distinguishes the current research from earlier work and provides new insights into the potential of Pilates as a holistic recovery strategy.

Study Limitations

Despite the promising findings, the generalizability of the results should be interpreted with caution. The sample consisted exclusively of young, physically active women, which limits the applicability of the conclusions to broader populations. In addition, the study assessed a limited range of physiological markers, omitting objective biomarkers that could provide deeper insight into systemic recovery processes. Future research should include more diverse populations in terms of age, sex, and fitness level, and incorporate biomarkers such as interleukin-6 (IL-6), creatine kinase (CK), and cortisol to enhance the understanding of physiological responses. Adopting a neurophysiological perspective may also clarify the mechanisms underlying psychological recovery. Moreover, future investigations could explore the effectiveness of Pilates as an active recovery strategy among competitive and elite athletes, and

compare its effects with other modalities such as yoga or aquatic recovery, using longitudinal designs to assess long-term adaptation.

Conclusions

This study demonstrates that a Pilates-based recovery intervention is more effective than conventional static cool-down in facilitating physiological and psychological recovery following high-intensity interval exercise. Within 48 hours post-intervention, participants in the Pilates group exhibited significantly greater reductions in delayed onset muscle soreness (DOMS), improved heart rate recovery (HRR), and lower total mood disturbance (TMD) scores. These findings suggest that Pilates promotes post-exercise recovery by enhancing

parasympathetic activation, improving peripheral circulation, and supporting neuroendocrine regulation related to stress and emotional balance. Given these effects, Pilates may serve as a feasible and integrative recovery strategy for non-athletic populations, contributing to systemic recovery across multiple domains.

The authors would like to express their sincere gratitude to the Faculty of Sport and Health Sciences, Universitas Negeri Surabaya, for the financial support provided throughout the course of this research. This support was instrumental in the successful completion of the study.

Conflict of Interest

The authors declare no conflict of interest.

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Cite this article as:

Andriana LM, Wijaya FJM, Ashadi K, Pranoto A, Rasyid MLSA, Yudhistira D, Samudra FE, Pramono BA, Antoni MF, Nurkholis, Syafii I, S A. A pilates-based physiological recovery strategy to enhance post-exercise recovery after high-intensity interval exercise. *Pedagogy of Physical Culture and Sports*, 2025;29(4):339-349. <https://doi.org/10.15561/26649837.2025.0411>

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Received: 10.07.2025

Accepted: 12.08.2025; Published: 30.08.2025

Prediction of success in taekwondo based on psychophysiological testing results

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Abstract

Background and Study Aim Predicting athletes' success is an integral part of sports monitoring. It enables the improvement of training quality and the differentiation of athletes according to skill level. Among the factors determining success and their informational value, psychophysiological indicators occupy an important place. The aim of this study was to justify and develop a method for predicting success in taekwondo based on psychophysiological testing results.

Material and Methods The study included 80 taekwondo athletes divided into age and skill groups. Group 1: 16 children aged 11–12 years, beginners; Group 2: 32 boys aged 14–16 years, sub-elite; Group 3: 28 adults aged 19–22 years, elite. Testing was performed using an iPad-based battery consisting of three tests: choice reaction, reaction to a moving object, and Go/No-go reaction. The battery simulated combat situations typical for taekwondo. The prediction model was based on Wald's sequential analysis with the calculation of predictive coefficients and informativeness for each indicator. Statistical analysis included descriptive statistics and Student's *t*-test to assess group differences.

Results A predictive table comprising 11 indicators with informativeness ≥ 11.0 was created. Prediction involves assigning the corresponding coefficient to each result and summing until a decision threshold is reached. The threshold ± 13 corresponds to a 95% probability ($p < 0.05$). Indicators with the highest informativeness were related to reaction time in the most complex stages of the tests, which required rapid adaptation to additional stimuli and changing conditions. Accuracy indicators from the Go/No-go test also contributed to the prediction, demonstrating the role of both speed and precision. The distribution of indicators across all three tests confirmed the multifactorial nature of taekwondo success prediction.

Conclusions The proposed methodology represents an objective and practical approach to forecasting competitive potential in taekwondo. It can be integrated into athlete selection systems and training monitoring programs, contributing to more effective talent identification and long-term performance development. The approach also offers the potential for adaptation to other combat sports that require rapid decision-making, high reaction speed, and precision under competitive conditions.

Keywords: taekwondo, prediction, success, functional tests, choice reaction, reaction to a moving object, Go/No-go reaction.

Introduction

High-performance achievement in combat sports is shaped by a combination of technical skills, tactical proficiency, physical conditioning, and psychological readiness. Within this multifaceted framework, the ability to anticipate and respond rapidly to dynamic

situations in competition is critical for success. Psychophysiological characteristics, such as reaction time, selective attention, and decision-making speed, serve as integral indicators of an athlete's functional state and capacity to perform under pressure. Their systematic assessment offers opportunities to align training approaches with individual performance profiles, particularly in disciplines like taekwondo, where split-second decisions can determine the outcome of a match.

Sports monitoring is a highly significant aspect of sports science [1, 2], as it plays a crucial role in optimizing athlete training, assessing adaptation processes, and preventing the development of adverse health changes [3]. Within the monitoring framework, prediction represents its most critical component, determining the overall effectiveness of the system. The main task of sports prediction is to determine the probability of success by analyzing the athlete's condition and identifying the qualities that are most relevant for competitive performance [2, 4].

The available literature confirms the importance of effective selection and success prediction, which are recognized as leading tasks in sports science [5]. These processes are commonly based on tests and functional trials, with the primary requirement being that prediction tools correspond to the specifics of the sport. Meeting this requirement substantially increases the accuracy and practical value of both prediction and selection in athletic contexts.

Previous research has analyzed the current state of sports prediction and identified several key problems [6]. These include the need for further development of theoretical foundations, a narrow range of research topics, insufficient thematic and interdisciplinary studies, and low accuracy and universality of existing models. In addition, a study [7] examined the potential for identifying talented athletes through prediction and conducted a meta-analysis that revealed the key components involved in talent identification. Notably, the "coach's instinct" emerged as a central factor in addressing predictive tasks and recognizing promising athletes.

The choice of tools for implementing sports prediction is a central factor in its effectiveness. Mathematical and statistical methods are often prioritized, as they enable more accurate forecasting compared to subjective expert assessments [8]. Studies have examined the characteristics of competitive activity in various types of martial arts [9, 10], with a particular emphasis on identifying the most frequently used technical and tactical actions. Such analysis makes it possible to evaluate the strengths and weaknesses of athletes' preparedness, which forms an integral part of predicting competitive success.

In another investigation [11], the application of different prediction and selection methods in sports was analyzed, leading the authors to conclude that combining multiple approaches substantially enhances the effectiveness of these procedures. A similar conclusion was reached in a separate study [12] that focused on the assessment of technical skills in the martial art of pencak silat. In this context, the quality of technical elements was shown to depend on a combination of physical and psychological components, underscoring the multifactorial nature of performance evaluation in martial arts.

A wide range of tests, trials, and methods is currently available for use in sports prediction. In the study by Podrihalo et al. [13], a comparative analysis of tools for selection, assessment of abilities, and evaluation of the potential of martial arts athletes was conducted. The findings indicated that hardware-based and simulation methods were the most effective, as they reflected the specific demands of the sport and offered practical convenience in their application. These results highlight the importance of choosing tools that combine both sport-specific relevance and ease of implementation.

Building on the idea of sport-specific predictors, another investigation [14] developed a prediction method for artistic swimming athletes, using anthropometric indicators, physical development indices, and functional test results as the basis for forecasting success. The main criterion for selecting predictors was their relevance and specificity to the given sport. This approach demonstrates how predictive models can be tailored to the unique physiological and technical demands of different athletic disciplines.

Similarly, research in martial arts has sought to identify key physical indicators for effective athlete selection. In the study by Romanenko et al. [15], a method based on physical development indices was proposed, analyzing the condition of elite kickboxing and wrestling athletes. This analysis revealed the most informative measures, including lower limb mass, arm strength indices, and upper limb segment ratio indicators, further emphasizing the role of precise and measurable characteristics in predicting athletic potential.

Building on the importance of selecting sport-specific and informative evaluation tools, particular attention has been given to the role of psychomotor and psychophysiological testing in martial arts. Studying the psychomotor abilities of martial arts athletes is an effective tool for assessing their functional state [16]. Such indicators can be recommended for use in sports selection, performance prediction, and monitoring of athletes' condition. The main requirements for the tests applied in this context are validity, informativeness, and sport-specific relevance. The validity of this approach has been supported by analyses of athletes in various martial arts [17], demonstrating that psychophysiological tests can identify qualities essential for achieving competitive success.

In taekwondo, psychophysiological test results make it possible to differentiate athletes according to their skill level [18]. A direct correlation has been established between the results of the tapping test and the duration of training in taekwondo athletes, reflecting an increase in the strength of nervous processes and positive changes in functional status under the influence of regular training loads. The

superior psychomotor reaction performance of athletes at the highest skill level supports the recommendation of psychophysiological tests as tools for predicting performance and identifying success predictors.

The analysis of research findings confirms that psychophysiological testing offers valuable opportunities for differentiating athletes by skill level and identifying qualities linked to competitive success. The authors emphasize that incorporating these indicators alongside physical and technical performance measures enhances the precision and applicability of prediction models in martial arts. They stress that such integrated approaches provide a more complete understanding of an athlete's functional readiness and long-term potential. Nevertheless, there remains a need for further refinement of predictive methodologies tailored specifically to taekwondo, as this gap continues to limit the systematic use of psychophysiological data in athlete selection and performance forecasting.

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Thus, the available evidence confirms the suitability of psychophysiological tests for success prediction. However, no established methods currently exist for predicting success in taekwondo based on psychomotor reaction results. This led to the formulation of the following research question: *Can the results of psychophysiological testing predict the competitive success of taekwondo athletes?* The research hypothesis proposed that psychophysiological tests can be effectively used to predict success in taekwondo. Developing such methods would enable the individualization of training programs for athletes in this sport and enhance their effectiveness. Based on this premise, the present study aimed to justify and develop a method for predicting success in taekwondo using psychophysiological testing results.

Materials and Methods

Participants

Psychophysiological testing results from 80

taekwondo athletes were used as the basis for developing the methodology. Participants were divided into age and skill groups: Group 1 – 16 children aged 11–12 years, beginner athletes; Group 2 – 32 boys aged 14–16 years, sub-elite athletes; Group 3 – 28 adults aged 19–22 years, elite athletes. Age differences were naturally associated with variations in training duration and athletic skill level.

The study protocol and design were reviewed and approved by the Bioethics Committee of the Kharkiv State Academy of Physical Culture (Minute No. 10, 03.05.2025). All participants, or their legal guardians in the case of minors, provided written informed consent in accordance with the Declaration of Helsinki. Participant data were stored anonymously in a secure database to ensure confidentiality.

Inclusion/Exclusion Criteria

Inclusion criteria included the absence of injuries during the last six months and no medication use within the last month. Based on interview results, participants also reported no severe stress in the month preceding testing. The interval between the last training session and testing was 24 hours. Participants were advised to refrain from using electronic devices immediately prior to testing.

Study Design

All participants underwent testing using an original battery of tests administered on iOS-based iPad tablet computers. The testing took place in a sports hall, where microclimate parameters complied with hygiene standards. The overall research design is presented in Figure 1.

The battery included three tests: choice reaction, reaction to a moving object, and 'Go/No-go' reaction. The choice reaction test was assessed by reaction time (ms) across four testing stages and by the number of errors (absolute values) at each stage. The reaction to a moving object was evaluated based on the total reaction time for the entire test, reaction time at three specific stages, and the proportion of accurate, early, and delayed reactions (%). The 'Go/No-go' reaction was assessed by simultaneous reaction time of the right and left hands (ms), separate reaction times for each hand (ms), and the proportion of errors in each case (%).

The validity of these methods has been confirmed in previous studies [19, 20]. All procedures were non-invasive and posed minimal risk to participants.

Statistical analysis

The obtained data were analyzed using a licensed version of MS Excel 2019 (version 2506). The test results followed a normal distribution; therefore, descriptive statistics (mean and standard deviation) were used for their characterization. Differences between groups were assessed using Student's *t*-test.

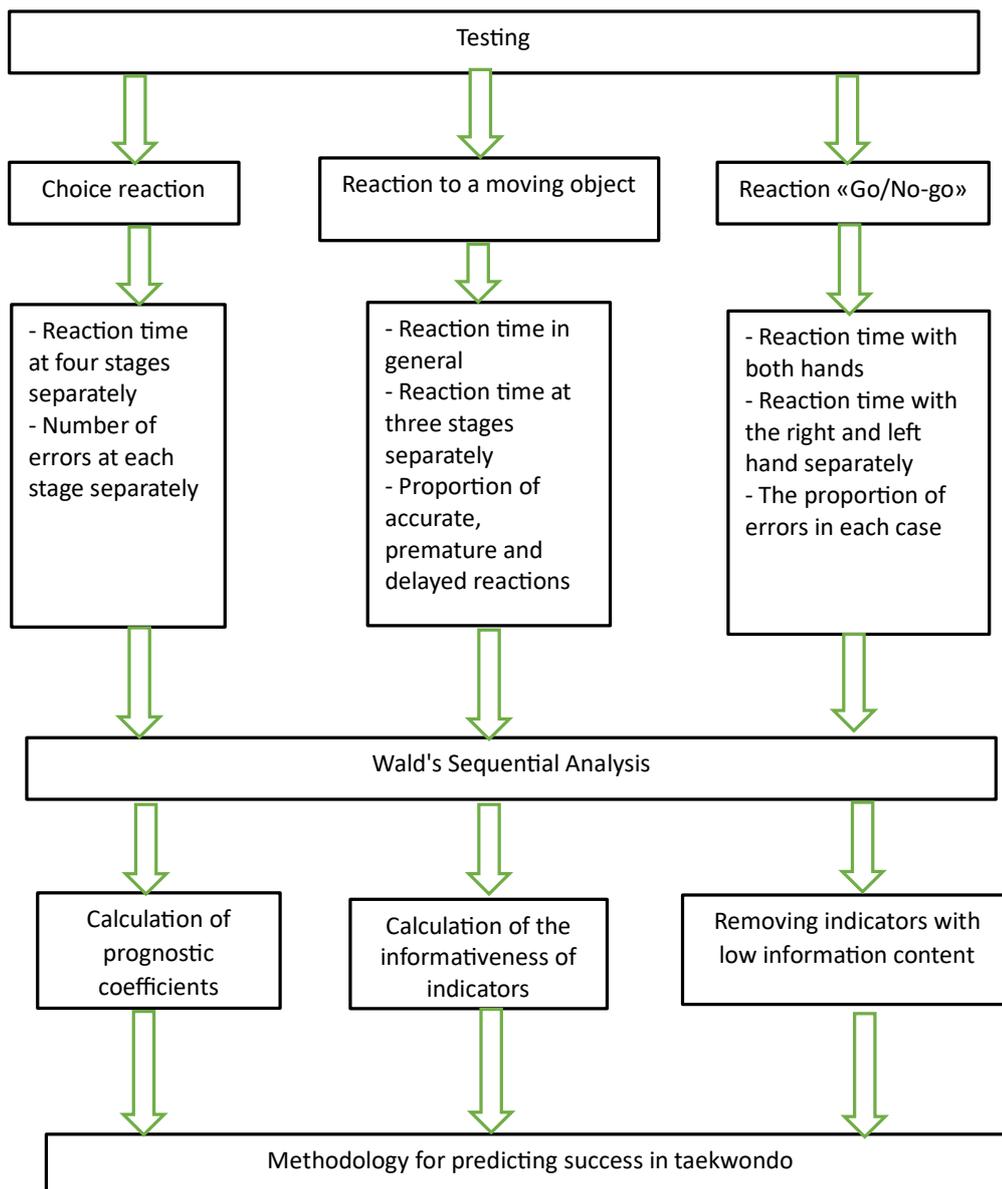


Figure 1. Scheme of the study

Wald's sequential analysis was applied as the prediction tool [21]. This method involves constructing a predictive table containing the predictive coefficients of the indicators and their informativeness. The predictive coefficients were calculated using the following formula:

$$PC = 10 \cdot \log \frac{(p_1 \cdot D_1/S)}{(p_2 \cdot D_2/S)} \quad (1)$$

where:

- PC – predictive coefficient;
- S – total number of participants in the group;
- D_1 – number of participants in Group 1 with a value above the group's average;
- D_2 – number of participants in Group 2 with a value above the group's average;
- p_1 – probability of exceeding the average value in Group 1;
- p_2 – probability of exceeding the average value

in Group 2.

Predictive coefficients for values lower than the average were calculated in the same way.

The informativeness (I) was calculated using the formula:

$$I = PC \cdot 0.5 \cdot [(p_1 \cdot D_1/S) - (p_2 \cdot D_2/S)] \quad (2)$$

where: I – the informativeness, and the remaining designations are the same as in formula (1).

Results

The test results are presented in Tables 1–3. The results in Table 1 confirm the influence of age and skill level on choice reaction performance. The most experienced athletes demonstrated the shortest reaction times, whereas novice athletes had the longest. A similar hierarchy was observed for accuracy, with experienced athletes making the fewest errors during test execution.

The results in Table 2 demonstrate significant differences in reaction to a moving object among taekwondo athletes of varying skill levels. Elite athletes achieved the best performance both in individual stages and in the overall test, while novice athletes recorded the poorest results, and teenage sub-elite athletes occupied an intermediate position. The gradual increase in task complexity during the second and third stages of the test allowed for clear differentiation by skill level. In contrast to beginners, elite athletes adapted more rapidly to changes in testing conditions.

The results in Table 3 indicate performance differences between taekwondo athletes in the Go/No-go test. Elite athletes demonstrated faster reaction times compared to sub-elite athletes. At the same time, the absence of significant differences

in accuracy indicators suggests a comparable skill level between the groups in terms of error control.

Thus, the test results confirmed significant differences in the psychophysiological indicators of taekwondo athletes with different skill levels. This served as the basis for developing a methodology for predicting success in this sport. The developed methodology is presented in Table 4.

Table 4 was constructed according to the requirements of sequential analysis. It contains psychophysiological indicators, predictive coefficients for the presence and absence of the specified result, and the informativeness of each indicator. These values were calculated based on the testing results of taekwondo athletes representing different skill levels.

The indicators in Table 4 are listed in descending

Table 1. Choice reaction results of taekwondo athletes with different skill levels

Indicators	Group 1 (M ± SD)	Group 2 (M ± SD)	Group 3 (M ± SD)
Reaction time, first stage (ms)	853.88 ± 69.06 ¹²	723.06 ± 88.28	663.88 ± 55.67 ¹
Number of errors, first stage (abs)	0.13 ± 0.13	0.41 ± 0.12	0.63 ± 0.26
Reaction time, second stage (ms)	876.50 ± 89.02 ¹²	749.53 ± 104.15	666.94 ± 66.38 ¹
Number of errors, second stage (abs)	0.13 ± 0.13	0.24 ± 0.14	0.00 ± 0.00 ³
Reaction time, third stage (ms)	1070.38 ± 145.16 ¹²³⁴	922.53 ± 101.13 ³⁴	842.88 ± 87.57 ¹³⁴
Number of errors, third stage (abs)	0.25 ± 0.25	0.12 ± 0.08 ³	0.06 ± 0.06
Reaction time, fourth stage (ms)	1049.50 ± 157.86 ²³⁴	965.35 ± 122.34 ³⁴	878.31 ± 103.58 ¹³⁴
Number of errors, fourth stage (abs)	0.13 ± 0.13	0.18 ± 0.10	0.13 ± 0.09 ³

Note. ¹ – significant differences with Group 2 (p < 0.05); ² – significant differences with Group 3 (p < 0.05); ³ – significant differences with Stage 1 (p < 0.05); ⁴ – significant differences with Stage 1 (p < 0.05).

Table 2. Reaction to a moving object in taekwondo athletes with different skill levels

Indicators	Group 1 (M ± SD)	Group 2 (M ± SD)	Group 3 (M ± SD)
Reaction time, entire test (ms)	34.58 ± 7.00 ¹²	29.99 ± 7.34 ²	26.46 ± 5.94
Reaction time, first stage (ms)	33.32 ± 10.13 ²	32.16 ± 10.53 ²	26.99 ± 7.70
Reaction time, second stage (ms)	33.73 ± 8.90 ²	29.27 ± 9.60	27.38 ± 8.20
Reaction time, third stage (ms)	36.75 ± 10.17 ¹²	28.50 ± 9.62	24.97 ± 8.43
Early reactions (%)	45.73 ± 12.45	54.62 ± 6.54	51.07 ± 7.54
Delayed reactions (%)	47.96 ± 12.49	38.72 ± 6.40	41.13 ± 7.42
Accurate reactions (%)	6.31 ± 6.08	6.66 ± 3.27	7.80 ± 4.04

Note. ¹ – significant differences with Group 2 (p < 0.05); ² – significant differences with Group 3 (p < 0.05).

Table 3. ‘Go/No-go’ reaction results of taekwondo athletes with different skill levels

Indicators	Group 1 (M ± SD)	Group 2 (M ± SD)
Reaction time, all values, left and right hands (ms)	352.92 ± 30.89 ¹	339.42 ± 21.71
Total error rate (%)	26.08 ± 7.22	15.83 ± 6.45
Reaction time, left hand (ms)	349.55 ± 34.76 ¹	333.12 ± 26.90
Error rate, left hand (%)	23.25 ± 3.87	18.17 ± 6.82
Reaction time, right hand (ms)	358.59 ± 29.24	347.08 ± 20.78 ²
Error rate, right hand (%)	31.53 ± 7.64	14.11 ± 6.15

Note. ¹ – significant differences with Group 2 (p < 0.05); ² – significant differences with the left hand (p < 0.05).

Table 4. Method for predicting the success of taekwondo athletes based on psychophysiological indicators

Indicators	Predictive coefficients	Informativeness
	Presence	Absence
Reaction time to a moving object in the third stage \leq 24 ms	10.23	-4.39
Choice reaction time in the second stage \leq 666 ms	6.02	-2.43
Choice reaction time in the third stage \leq 842 ms	6.02	-2.43
Choice reaction time in the fourth stage \leq 878 ms	6.02	-2.43
Reaction time to a moving object, entire test \leq 26 ms	6.75	-3.30
Choice reaction time in the first stage \leq 663 ms	4.77	-1.46
Reaction time to a moving object in the second stage \leq 27 ms	5.15	-3.23
“Go/No-go” reaction error rate, right hand \leq 14%	2.50	-2.38
Reaction time to a moving object in the first stage \leq 26 ms	2.60	-2.02
Total “Go/No-go” error rate \leq 15%	1.34	-1.59
“Go/No-go” reaction time, all values, both hands \leq 339 ms	1.27	-1.92

order of informativeness. Arranging the indicators in this way minimizes the number of steps in the prediction procedure and reduces the likelihood of errors. An informativeness value below 11.0 is considered insignificant; therefore, such indicators were excluded from the table.

The prediction procedure is as follows: the subject completes a series of psychophysiological tests – choice reaction, reaction to a moving object, and ‘Go/No-go’ reaction. From the obtained results, the indicators listed in the table are identified. If a result matches the value specified in the table, the corresponding presence coefficient is used; otherwise, the absence coefficient is applied. The prediction process involves sequentially summing the selected coefficients until the threshold value is reached or all indicators in the table have been processed.

The permissible error is set at 5%, corresponding to a threshold value of ± 13 points. This level of error is commonly used in research as it reflects a 95% probability. Reaching a threshold of +13 indicates that the athlete has strong prospects in taekwondo ($p < 0.05$). Conversely, reaching a threshold of -13 indicates that the athlete has no prospects in taekwondo ($p < 0.05$). If neither threshold is reached after processing all indicators in the table, the prediction is considered inconclusive, and further assessment is required.

Discussion

The aim of this study was to justify and develop a method for predicting the success of taekwondo athletes based on psychophysiological testing results. The proposed methodology incorporated three key tests: choice reaction, reaction to a moving object, and ‘Go/No-go’ reaction, and applied Wald’s sequential analysis to calculate predictive coefficients and indicator informativeness. The findings confirmed significant differences in psychophysiological indicators among athletes

of different skill levels, with elite athletes demonstrating superior reaction times and accuracy across multiple test stages. The resulting predictive model, constructed using the most informative indicators, provides an objective approach for assessing competitive potential in taekwondo.

Multimedia technologies represent a promising direction in sports monitoring. Cognitive-oriented training, virtual and augmented reality, computer programs, and simulation devices that reproduce specific game situations are among the modern technological tools used in this context [22].

The rapid development of multimedia technologies has facilitated their integration into many fields, including sports. A study [23] demonstrated that these technologies can significantly improve the performance of taekwondo athletes. They enable the adaptation of complex information about the preparedness of martial artists for easier perception and enhance the quality of feedback during monitoring.

Digital technologies support the principle of feedback in sports monitoring [24], which plays a decisive role in athlete training [25]. Without the use of multimedia tools, it is difficult to ensure timely and objective feedback. High-quality feedback is therefore a necessary and sufficient condition for effective sports monitoring, and its implementation can lead to substantial improvements in the athletes’ training process [26]. Athletes in martial arts employ various strategies to recognize and anticipate their opponent’s movements. Regardless of the specific approach, each strategy relies on the fastest possible analysis of the opponent’s actions, which underlines the importance of a high level of psychomotor abilities [16].

Peripheral vision is an important factor during a sports match [27]. It is widely accepted that skilled athletes differ from non-athletes in their capacity to effectively process and interpret visual information.

Throughout their professional careers, they acquire and refine strategies to optimize this process [28, 29]. The effectiveness of such strategies depends largely on the tools used to assess and develop them, which often include specialized tests and functional trials.

The available results informed the selection of tests for prediction in the present study. The proposed battery consisted of three assessments: choice reaction, reaction to a moving object, and Go/No-go reaction. These tests are specific to striking martial arts and simulate situations encountered during fights. Their specificity and informativeness make it possible to identify functional characteristics that are essential for achieving success. A rapid response to various stimuli increases the likelihood of executing successful actions during a match, thereby improving the chances of victory.

The test algorithms provide objective and representative results. The data follow a normal distribution, which is essential for comparative analysis. The short duration of the tests ensures that the testing process does not significantly influence performance levels. The tests consist of a sequence of tasks with increasing complexity, which allows for the assessment, to a certain extent, of the characteristics of athletes' nervous systems [16, 17].

The accuracy of this approach is supported by findings from the literature. A fundamental requirement for selecting indicators for prediction is their relevance to the development of specific skills and abilities. Litwiniuk et al. [30] suggested assessing coordination and the ability to maintain balance as part of predicting success in martial arts athletes. In their study, tolerance to body balance disturbances was evaluated in the context of alpine skiing training. The assessment tool was a jump test with body rotation in both directions, and martial arts athletes demonstrated a higher level of tolerance compared to other groups.

An important criterion for prediction is the specificity of indicators to the type of martial art. In one study [31], a comparative analysis of the condition of elite martial arts athletes was conducted using physical development indices. The analysis identified features determined by the specifics of martial arts, with limb segment ratio indices proving to be the most informative. The validity of using such specialized indices to monitor the functional state of athletes was confirmed.

The design of the present study, which divided participants by age and skill level, is widely used in sports science and meets the requirements for predictive research. The division into three groups was based on the anatomical and physiological characteristics of development. The first group comprised prepubertal participants, whose bodies are preparing for puberty and undergoing significant metabolic changes. The second group included athletes in puberty, a stage characterized

by pronounced physiological changes. The third group consisted of adults whose physical condition is relatively stable.

Identifying a group of elite athletes makes it possible to determine the qualities that have enabled them to achieve success. In one study [18], this approach confirmed the optimization of the functional state of taekwondo athletes during training. Similar results were reported in another study [32], which also analyzed the condition of elite athletes. The findings confirmed a relationship between training organization and metabolic parameters in elite taekwondo athletes. Determining physical development indices and somatotype components is an important tool for monitoring athletes' condition.

An important aspect of prediction is the choice of method, as sports forecasting relies on a variety of approaches and analytical techniques. Holmes et al. [33] proposed a methodology for predicting the results of mixed martial arts competitions by analyzing data from publicly accessible websites to assess fighters' skills. In their work, the competition was modelled as an actual fight using Markov chains, which significantly increased prediction accuracy and demonstrated the potential of mathematical modelling for performance forecasting.

Velichkov et al. [34] applied the interview method for prediction, conducting multiple interviews with athletes in boxing, martial arts, and tennis. The findings supported the assumption that interviewing an athlete before a match can provide valuable insight into the likely outcome. This approach highlights the relevance of psychological and self-assessment factors, which may complement quantitative data in predictive models.

It has also been proposed [10] to use logistic regression models for predicting performance in mixed martial arts. Cross-validation and discriminant analysis of the model confirmed its higher predictive probability compared to baseline models. This statistical approach demonstrates that advanced regression techniques can outperform more simplistic methods when sufficient high-quality input data are available.

In the present study, Wald's sequential analysis was selected as the predictive tool because it meets the specific requirements of the research task. The algorithm of this method is consistent with the logic of prediction studies and allows for step-by-step decision-making. A comparison of groups with different skill levels made it possible to determine the proportion of athletes whose results were above or below the average, and predictive coefficients and informativeness values were then calculated based on these findings.

The effectiveness of sequential analysis for solving predictive tasks has been demonstrated in previous studies, including the development of

prediction methods in artistic swimming [14] and the creation of a selection method for kickboxing at the initial training stage [15]. These examples confirm the broad applicability of the method in different sports contexts. Its adaptability and ability to incorporate multiple indicators make it a valuable tool for objective and evidence-based athlete evaluation.

Another important advantage of the method used is its flexibility in selecting the desired prediction probability. The Wald method makes it possible to set a probability range from 80% to 99.9%, which corresponds to predictive thresholds between 6 and 30 points, respectively. In the present study, we selected a probability value of $p < 0.05$, corresponding to 95%, with a threshold value of ± 13 points. The same threshold values have been applied in previous studies [14, 15], which supports the methodological consistency of our approach. This choice ensured an optimal balance between prediction accuracy and practical applicability in the context of taekwondo performance forecasting.

Obtaining an effective result depends on the number of indicators included in the table. The analysis identified 24 indicators that could potentially be used for prediction. However, the optimal number of criteria ranges from 7 to 10, and the minimum informativeness was set at 11.0 to reduce the total number. Indicators with low informativeness do not significantly influence the prediction outcome. As a result, 11 indicators were selected, ensuring both sufficient informativeness and practical convenience of the methodology.

Analysis of the indicator hierarchy in the table makes it possible to assess the significance of individual tests. The table contains four indicators related to choice reaction, four related to reaction to a moving object, and three related to the Go/No-go reaction. This confirms that all three tests contribute meaningfully to prediction. However, their relative contribution should be evaluated by considering the position of each indicator in the table, which is determined by its informativeness.

The most informative indicator was the reaction time to a moving object in the third stage of testing. This stage is the most demanding because it introduces additional objects, chaotic movements, and parameter changes that significantly interfere with reaction execution, thereby increasing task complexity. Performance at this stage demonstrates the participant's ability to counteract interfering factors.

The next three indicators reflect choice reaction performance in the second, third, and fourth stages of testing, all of which have identical informativeness and predictive coefficient values. These stages illustrate the progressive increase in task complexity during testing. The complexity is increased by introducing counteracting symbols in

stage 2, modifying the shape of the reaction object in stage 3, and combining complex-shaped objects with symbols that interfere with perception in stage 4. Collectively, these three indicators assess not only concentration and resistance to distracting stimuli but also the ability to rapidly shift attention to objects that differ substantially from previous stimuli.

These four indicators are characterized by maximum informativeness values exceeding 100. The presence coefficients are such that fulfilling these four indicators yields more than 13 points, which corresponds to a positive prognosis. The next four indicators have an average informativeness level ranging from 61.33 to 34.23. Importantly, these indicators represent all three tests used in the study, confirming the complexity of the prognostic assessment. This group includes reaction time to a moving object for the entire test, choice reaction time in the first stage, reaction time to a moving object in the second stage, and the proportion of errors when performing the 'Go/No-go' test with the right hand. Compared to the previous criteria, these reaction time indicators are more general in nature. In addition to reflecting overall performance in psychophysiological tests, they demonstrate the ability of athletes to quickly become engaged in work and reach optimal working condition. The last criterion in this group characterizes accuracy in performing the 'Go/No-go' test tasks and illustrates coordination and balance within the nervous system.

The final group consists of three indicators with informativeness values below 20. The predictive coefficients for these measures are also relatively small, indicating a limited impact on the overall prognosis. Two of these indicators reflect the reaction time to a moving object in the first stage of testing and the 'Go/No-go' reaction time when using the left and right hands simultaneously. The third criterion is the total percentage of 'Go/No-go' reaction errors, representing overall task accuracy. Although these indicators are of minor importance for solving the prognostic task, they contribute to a more comprehensive understanding of the athletes' test performance.

The inclusion of indicators that illustrate task accuracy highlights the specificity of the tests used for martial arts. Success in martial arts depends not only on speed but also on the quality of certain actions. In this context, quality is assessed by action accuracy, defined as the minimal number of errors. The accuracy indicators in this study were derived from performance in the Go/No-go test, which evaluates the ability to react appropriately while ignoring irrelevant stimuli. In martial arts, this skill can be interpreted as the capacity to avoid reacting to an opponent's feints. Accurate execution of this test serves as an important predictor of success.

The comparative analysis of athletes' conditions

at the beginner, sub-elite, and elite training levels represented a form of research prediction. Since elite athletes have reached their maximum potential, it can be concluded that their psychomotor characteristics exert the greatest influence on their sporting achievements and thus play a central role in predicting success. Another important implication of the results is the potential to use psychophysiological testing outcomes at the initial training stage to guide athlete selection and assess the long-term prospects of taekwondo practitioners.

Limitations of this study

The primary limitation of this study is the exclusive use of psychophysiological tests. While effective, the methodology could be further improved by integrating physical and psychological variables in future adaptations. A promising direction for enhancing prediction quality would be the inclusion of strength and flexibility tests, as well as assessments of physical development characteristics.

Conclusions

This study substantiated and developed a methodology for predicting the success of taekwondo athletes. The methodology incorporates the results of choice reaction, reaction to a moving object, and Go/No-go reaction tests. These tests are specific to taekwondo, simulate combat situations, and are

both valid and informative. The selected indicators reflect the time required to complete the tests and individual test tasks, as well as performance accuracy, measured by the proportion of errors. This combination enables a comprehensive assessment of athletes' functional state. The prediction outcome is a conclusion regarding the athlete's prospects or lack thereof in taekwondo. The developed method offers an objective and effective tool for predicting athletic success based on reaction test performance. It is suitable for talent identification and monitoring in taekwondo. Implementation of this methodology in practice may contribute to increased training effectiveness and improved athlete performance in this sport.

Conflict of Interest

One of the authors, Sergii Iermakov, serves as the Editor-in-Chief and Publisher of this journal, and another author, Leonid Podrigalo, is a member of the Editorial Board. To ensure an objective review process, the manuscript was managed by an independent editorial board member, and the peer review was conducted by external reviewers without affiliations to the authors. The Editor-in-Chief and the Editorial Board member did not participate in the review or editorial decision-making process for this manuscript. All other co-authors declare no conflict of interest regarding this publication.

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Cite this article as:

Podrigalo L, Iermakov S, Romanenko V, Baibikov M, Galimskyi V, Shutieiev V, Merdov S. Prediction of success in taekwondo based on psychophysiological testing results. *Pedagogy of Physical Culture and Sports*, 2025;29(4):350-360.

<https://doi.org/10.15561/26649837.2025.0412>

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Received: 01.07.2025

Accepted: 18.08.2025; Published: 30.08.2025

Effects of plyometric training with blood flow restriction on body composition, strength, power, and anaerobic performance in soccer players

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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

Soccer performance depends on the ability to combine high levels of strength, power, and endurance within limited preparation time. Plyometric training is widely used to enhance explosive power, but its high-impact nature may increase injury risk. Blood flow restriction (BFR) training can stimulate muscle adaptations with lower external loads, offering a potentially safer alternative. Although both methods are applied in athletic conditioning, their relative effectiveness in improving performance outcomes remains of practical interest. This study aimed to investigate the effects of a six-week combined plyometric and BFR (PLY+BFR) training program on body composition, strength, jump height, and anaerobic power in male collegiate soccer players.

Material and Methods

Twenty-seven male collegiate soccer players (mean age 22.1 ± 0.6 years) were randomly assigned to three groups: control (CON; $n = 9$), plyometric training only (PLY; $n = 9$), and plyometric training with BFR (PLY+BFR; $n = 9$). The two training groups followed an identical plyometric protocol twice weekly for six weeks. The PLY+BFR group applied progressive cuff pressure (160–200 mmHg) to the proximal thighs during exercise. Assessments before and after the intervention included fat-free mass, skeletal muscle mass (via bioelectrical impedance analysis), Muscular strength (1 RM) of knee extension, countermovement jump (CMJ) height, and Wingate anaerobic power test. Data were analyzed using one-way ANOVA with Bonferroni post hoc comparisons.

Results

The PLY+BFR group showed significantly greater gains in fat-free mass (+1.9%), skeletal muscle mass (+1.8%), 1RM strength (+18.7%), CMJ height (+19.5%), and peak anaerobic power (+12.4%) compared to both the CON and PLY groups ($p < 0.05$). The PLY group also demonstrated improvements. However, the magnitude was consistently lower than that of the PLY+BFR group.

Conclusions

The integration of blood flow restriction into plyometric training presents a more effective and time-efficient strategy for improving muscle hypertrophy, strength, power, and anaerobic performance in soccer players. The combined stimulus may enhance both neural and metabolic adaptations. As a result, athletes can achieve pronounced performance gains without the need for excessive mechanical loading. This study provides a feasible and evidence-based approach for coaches and practitioners seeking to enhance key physical attributes during pre-season or other short-term conditioning phases.

Keywords:

plyometric training, blood flow restriction, muscular performance, anaerobic power, soccer conditioning

Introduction

In recent decades, soccer has undergone a profound transformation in both physical intensity and tactical complexity. The modern game is no longer defined only by endurance and technical skill. Players are now required to perform frequent high-velocity sprints, abrupt changes in direction, powerful jumps, and dynamic accelerations within confined timeframes. These demands are particularly pronounced at the collegiate level, where athletes must pursue athletic excellence while also managing academic obligations. As a result, there is increasing emphasis on developing

neuromuscular coordination, lower-limb explosive strength, and anaerobic energy systems to support the rapid and repetitive nature of competitive play [1]. The escalating pace of the game, together with congested training and match schedules, places coaches and performance professionals under pressure to design time-efficient training interventions. Such programs must enhance sport-specific physical qualities while minimizing cumulative mechanical stress and injury risk [2, 3]. These combined challenges have stimulated growing interest in innovative conditioning methods that target both neural and metabolic adaptations while reducing physical loading.

Plyometric training has long been recognized as an effective method for improving stretch-

shortening cycle efficiency, lower-limb explosive power, and change-of-direction ability [4]. The effectiveness of plyometric training in enhancing speed and jump performance is well documented in soccer-specific populations, particularly among youth and collegiate players [5, 6]. However, high-impact ground reaction forces and the associated injury risks limit its applicability during periods of fatigue, growth spurts, or congested match schedules. Blood flow restriction (BFR) training, by contrast, has emerged as a low-load resistance method that promotes muscular strength and hypertrophy through localized hypoxic stress. Numerous studies have demonstrated its effectiveness in enhancing functional capacity while reducing joint stress, making it a viable option for athletes across different age groups [7, 8, 9]. Recent soccer-specific investigations have demonstrated that blood flow restriction training can enhance physical capacities and may support rehabilitation strategies [10].

Although the efficacy of plyometric and BFR training has been well documented individually, their integrated application remains underexplored, particularly regarding combined effects on soccer-specific performance outcomes. While pilot evidence suggests that combining plyometric exercises with blood flow restriction can yield additive benefits in soccer players, large-scale empirical research evaluating structured hybrid protocols that merge the neural benefits of plyometrics with the metabolic stress of BFR remains scarce [11, 12]. This issue is especially relevant in collegiate populations, where time-constrained training environments and elevated injury risk demand innovative approaches to maximize physiological adaptations within limited preparation windows. A recent systematic review and meta-analysis highlighted the limited but growing evidence base on blood flow restriction training in athletes, underscoring the need for further controlled studies in field-based sports [13].

To address this gap, it was hypothesized that the integrated PLY+BFR intervention would generate superior adaptations compared to traditional plyometric training alone by combining neural activation with metabolic overload. The present study aimed to evaluate the effects of a six-week combined plyometric and blood flow restriction (PLY+BFR) training program on body composition, lower-limb strength, vertical power, and anaerobic capacity in male collegiate soccer players.

Materials and Methods

Participants

Twenty-seven male collegiate soccer players (age: 22.1 ± 0.6 years; height: 174.2 ± 2.6 cm; body mass: 69.7 ± 4.2 kg) from Ubon Ratchathani Rajabhat University volunteered to participate. All were in their pre-season phase and trained 4–5 days

per week. Inclusion criteria required the absence of neurological disorders, musculoskeletal injuries, or medical contraindications, as well as a commitment to attend all sessions. Participants were instructed to avoid caffeine, alcohol, and high-intensity activity for 24 hours before testing. Those who failed to meet these criteria or consumed stimulants within 24 hours were excluded. Written informed consent was obtained from all participants, and the study was approved by the Sisaket Rajabhat University Ethics Committee (HE671005). Group allocation was randomized using a computer-generated list, and procedures were overseen by an independent researcher.

Research Design

This randomized controlled trial assigned 27 participants into three equal groups ($n = 9$) using a computer-generated randomization sequence: (1) Control (CON), who maintained regular training; (2) Plyometric training only (PLY); and (3) Plyometric training with blood flow restriction (PLY+BFR). Sample size was calculated using G*Power 3.1, targeting a medium effect size ($f = 0.45$) [12], 80% statistical power, and $\alpha = 0.05$. All pre- and post-intervention assessments were conducted two days before and two days after the six-week training. A blinded evaluator performed all assessments to minimize potential bias.

Intervention Protocol

The intervention lasted six weeks and comprised two training sessions per week (Monday and Thursday), for a total of 12 sessions. Both the PLY and PLY+BFR groups followed an identical plyometric exercise program that progressively increased in intensity and volume over time. Each session began with a standardized 10-minute warm-up followed by dynamic stretching. A one-minute rest was provided between sets and exercises. The program incorporated fundamental lower-body plyometric movements such as squat jumps, lateral bounds, tuck jumps, and depth jumps. The number of repetitions increased from 100 per session in the early weeks to 180 per session in the final weeks, as detailed in Table 1.

In the PLY+BFR group, participants wore pneumatic cuffs (B-Strong, California, USA) applied bilaterally to the proximal thighs throughout each session. Cuff pressure was set at 160 mmHg during the first three weeks and increased to 200 mmHg in the final three weeks, following protocols adapted from Abe et al. [14]. Prior to each session, cuff calibration was performed according to manufacturer guidelines to ensure consistent pressure delivery across participants. Safety monitoring included verbal check-ins before, during, and after each session to assess discomfort, dizziness, numbness, or abnormal cardiovascular symptoms. No adverse events were reported during the intervention. These

Table 1. Structure of the Six-Week Plyometric Training Program

Week	1	2	3	4	5	6
Session	1–2	3–4	5–6	7–8	9–10	11–12
Squat Jump	2×10	2×10	2×12	2×12	–	–
Repeated Tuck Jump	2×10	2×10	2×12	2×12	3×10	3×10
Lateral Bounding – Slalom	2×10	2×10	–	–	–	–
Lateral Jump Over Barrier (30 cm)	2×10	2×10	2×12	2×12	3×10	3×10
Box Lateral Jump (30 cm)	2×10	2×10	2×12	2×12	–	–
Split Jump	–	–	2×12	2×12	3×10	3×10
Single Leg Bounding	–	–	–	–	3×10	3×10
Depth Jumps to Long Jump	–	–	–	–	3×10	3×10
Depth Jumps to Sprint 10 m	–	–	–	–	3×10	3×10
Per session	100	100	120	120	180	180
Per week	200	200	240	240	360	360

Note. Values are presented as sets × repetitions. “Per session” indicates the total number of repetitions per training session, and “Per week” indicates the total number of repetitions per week.

procedures ensured the safe application of BFR during dynamic plyometric activity.

Assessments

Body composition was assessed using a bioelectrical impedance analyzer (Seca mBCA, Hamburg, Germany), which provided values for body weight, body fat percentage, fat mass, fat-free mass, and skeletal muscle mass. Muscular strength was evaluated through a 10-repetition maximum (10RM) knee extension test. The estimated one-repetition maximum (1RM) was calculated using Brzycki’s formula [15]:

$$1RM = \frac{\text{Weight lifted}}{1.0278 - (0.0278 \times X)}$$

where X represents the number of repetitions performed.

Lower-body muscular power was assessed using the countermovement jump (CMJ), measured with a kinematic analysis system (Fitness Technology, Australia). The highest value of three attempts was recorded for analysis. Anaerobic performance was determined using the Wingate Anaerobic Test on a Monark 839E ergometer, with resistance set at 0.087 kg per kilogram of body mass. This followed the standardized protocol described by Bar-Or [16].

Statistical Analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 21.0). Data normality was verified using the Shapiro–Wilk test, and all variables were normally distributed ($p > 0.05$). Homogeneity of variances was assessed with Levene’s test. This confirmed equal variances across groups ($p > 0.05$). Based on these assumptions, parametric tests were applied. Within-group comparisons were performed using paired-samples t-tests. Between-group differences were analyzed using one-way ANOVA

followed by Bonferroni post hoc tests. Statistical significance was set at $p < 0.05$.

Results

All 27 participants completed the six-week intervention without any dropouts or adverse events. One-way ANOVA indicated no statistically significant differences ($p > 0.05$) among the three groups (Control, PLY, and PLY+BFR) in baseline characteristics such as age, body weight, height, body mass index (BMI), and blood pressure. This baseline homogeneity reinforces the internal validity of the subsequent between-group comparisons (Table 2).

Throughout the intervention period, the PLY+BFR group consistently exhibited higher average heart rate responses after each training session compared to the PLY group. This difference reached statistical significance during the final four sessions (sessions 9 to 12; $p < 0.05$). This indicates an elevated cardiovascular load associated with the application of blood flow restriction. The effect size for this difference was moderate (Cohen’s $d = 0.61$), suggesting meaningful physiological stress induced by the BFR protocol (Figure 1).

After six weeks, the Control group showed a statistically significant increase in body fat percentage (+6.5%, $p < 0.05$). This reflected a negative trend in composition. In contrast, the PLY+BFR group achieved significant improvements in both fat-free mass (+1.9%, $p < 0.05$) and skeletal muscle mass (+1.8%, $p < 0.05$). The corresponding effect sizes were 0.48 and 0.51, respectively, indicating small to moderate practical effects. The PLY group did not demonstrate any significant changes in body composition variables. These results suggest that the addition of BFR to plyometric training contributes more effectively to enhancing lean tissue outcomes than plyometric training alone (Table 3).

Table 2. Baseline Characteristics of Participants in the Control, PLY, and PLY+BFR Groups

Characteristics	Control (n = 9)	PLY (n = 9)	PLY+BFR (n = 9)
Age (years)	21.0 ± 0.9	20.9 ± 0.8	21.0 ± 0.4
Resting heart rate (bpm)	71.1 ± 12.0	73.3 ± 13.5	71.4 ± 10.2
SBP (mmHg)	116.8 ± 10.5	125.3 ± 11.5	125.0 ± 10.1
DBP (mmHg)	71.1 ± 9.2	77.8 ± 7.4	73.9 ± 9.5
Height (cm)	174.0 ± 3.0	172.4 ± 3.2	171.7 ± 4.7
Body weight (kg)	72.9 ± 6.4	66.4 ± 6.5	64.3 ± 5.2
SpO ₂ (%)	97.7 ± 1.4	97.4 ± 1.3	97.9 ± 0.9
BMI (kg/m ²)	24.0 ± 2.1	22.3 ± 2.1	22.0 ± 2.1

Note. Values are mean ± SD. Abbreviations: SBP = systolic blood pressure, DBP = diastolic blood pressure, BMI = body mass index, PLY = plyometric training group, PLY+BFR = plyometric training with blood flow restriction.

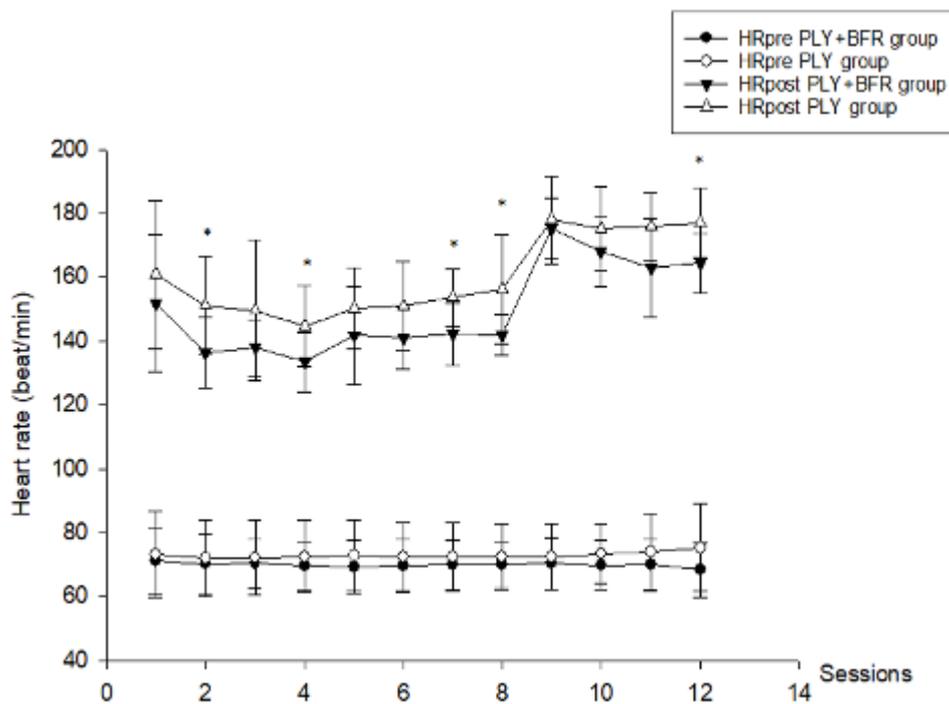


Figure 1. Mean (± SD) heart rate responses during the 12 training sessions in the plyometric training (PLY) and plyometric training combined with blood flow restriction (PLY+BFR) groups. The graph presents data from pre-training and post-training sessions for each group (PLY Pre, PLY Post, PLY+BFR Pre, and PLY+BFR Post). *Indicates significant difference between groups (PLY+BFR vs. PLY, $p < 0.05$), showing that the PLY+BFR group experienced higher heart rates during the intervention period. Data are based on measurements from nine participants per group.

Both intervention groups experienced significant improvements in knee extension strength. The PLY+BFR group showed a greater increase (+18.7%) compared to the PLY group (+9.7%). Similarly, countermovement jump (CMJ) height increased more in the PLY+BFR group (+19.5%) than in the PLY group (+14.5%). In contrast, the Control group experienced a slight decline in both variables. The effect sizes for 1RM strength and CMJ height in the PLY+BFR group were 0.72 and 0.76, respectively. This indicates a large and practically meaningful

impact on muscular performance (Table 4).

Participants in the PLY+BFR group demonstrated the most substantial gains in anaerobic power, with a statistically significant improvement of 12.4% ($p < 0.05$). The associated effect size was moderate (Cohen's $d = 0.67$). In comparison, the PLY group showed only a small and statistically non-significant increase (+2.1%). Both intervention groups improved in anaerobic capacity. However, the practical significance was limited, with small effect sizes recorded in both the PLY group ($d = 0.31$)

Table 3. Changes in Body Composition Following Six Weeks of Training in All Three Groups

Parameters	Control (n = 9)	PLY (n = 9)	PLY+BFR (n = 9)
Body fat (%)	Pre-test: 17.7 ± 7.0	15.6 ± 5.4	14.6 ± 4.0
	Post-test: 18.6 ± 6.9	15.6 ± 5.2	14.2 ± 3.9
	%Change: 6.5 ± 7.7*	1.1 ± 11.5	-1.7 ± 12.2
Fat mass (kg)	Pre-test: 13.3 ± 7.3	10.6 ± 4.4	9.2 ± 3.3
	Post-test: 13.9 ± 7.4	10.7 ± 4.3	9.0 ± 3.4
	%Change: 4.3 ± 8.4	1.4 ± 11.9	-0.6 ± 12.8
Fat-free mass (kg)	Pre-test: 62.5 ± 6.3	54.4 ± 4.5	55.3 ± 2.9
	Post-test: 62.2 ± 6.7	54.5 ± 5.3	56.4 ± 3.6
	%Change: -0.6 ± 1.9	0.2 ± 2.8	1.9 ± 2.4*
Skeletal mass (kg)	Pre-test: 30.2 ± 2.9	26.5 ± 2.2	26.4 ± 1.8
	Post-test: 30.1 ± 3.5	26.2 ± 3.0	26.9 ± 2.2
	%Change: -0.6 ± 2.5	-0.2 ± 5.9	1.8 ± 1.7*

*Values are mean ± SD. p < 0.05, Pre-test vs. Post-test.

Table 4. Changes in Muscular Strength and Lower-Body Power Across Groups

Parameter	Control (n = 9)	PLY (n = 9)	PLY+BFR (n = 9)
Muscular strength (1RM)			
Knee extension (kg)			
Pre-test	145.6 ± 10.9	131.8 ± 12.2	124.4 ± 13.8
Post-test	149.9 ± 13.4	144.1 ± 14.6	147.8 ± 23.3
%Change	2.9 ± 3.4	9.7 ± 9.7*	18.7 ± 11.2 ^{b*}
Muscular power			
CMJ (cm)			
Pre-test	38.6 ± 3.3	32.4 ± 2.3	33.4 ± 5.2
Post-test	36.7 ± 3.8	36.9 ± 2.1	39.5 ± 4.8
%Change	-4.7 ± 8.1	14.5 ± 12.8 ^{a*}	19.5 ± 15.6 ^{b*}

Note. Values are mean ± SD. Abbreviations: 1RM = one-repetition maximum; CMJ = countermovement jump. *p < 0.05, Pre-test vs. Post-test; ^ap < 0.05, change between Control and PLY groups; ^bp < 0.05, change between Control and PLY+BFR groups.

and the PLY+BFR group (d = 0.38). These findings indicate that the combination of plyometric training with blood flow restriction is more effective in enhancing short-term anaerobic output than plyometric training alone (Table 5).

Discussion

This study aimed to evaluate the effects of a six-week combined plyometric and blood flow restriction (PLY+BFR) training program on body composition, muscular strength, lower-body power, and anaerobic performance in male collegiate soccer players. The results demonstrated that the PLY+BFR program produced greater improvements than plyometric training alone, particularly in fat-free mass, skeletal muscle mass, knee extension strength, countermovement jump height, and anaerobic power.

These results align with Gao et al. [7], who reported that BFR training amplified both strength

and hypertrophy through heightened metabolic stress. However, the PLY group in our study demonstrated significant improvements from baseline in several parameters. This confirms the foundational benefits of traditional plyometric methods as reported by Zheng et al. [3] and Chen et al. [17]. Therefore, while PLY+BFR may accelerate adaptation, conventional plyometric exercises still play a critical role in performance development. This is particularly relevant during phases when equipment for BFR is inaccessible or when training simplicity is preferred.

The integration of BFR may have induced a unique physiological stimulus that contributed to the observed enhancements in power-related outcomes. BFR has been proposed to stimulate muscle protein synthesis and neuromuscular recruitment through increased metabolite accumulation and cellular swelling [8, 18]. These effects might have synergized with the mechanical load of plyometric movements,

Table 5. Changes in Anaerobic Power, Anaerobic Capacity, and Peak Heart Rate Across Groups

Parameter	Control (n = 9)	PLY (n = 9)	PLY+BFR (n = 9)
Anaerobic power (W/kg)			
Pre-test	12.8 ± 0.9	12.3 ± 0.6	12.7 ± 0.8
Post-test	12.7 ± 1.2	12.6 ± 1.1	14.3 ± 1.4
%Change	-1.2 ± 5.7	2.1 ± 5.2	12.4 ± 9.2 ^{bc*}
Anaerobic capacity (W/kg)			
Pre-test	8.5 ± 0.4	8.2 ± 0.3	8.6 ± 0.5
Post-test	8.6 ± 0.5	8.5 ± 0.3	8.7 ± 0.6
%Change	0.4 ± 3.2	3.4 ± 2.8*	2.0 ± 4.0
Peak heart rate (bpm)			
Pre-test	165.4 ± 6.8	177.0 ± 6.5	170.3 ± 5.4
Post-test	165.6 ± 6.0	179.5 ± 9.1	167.0 ± 9.7
%Change	0.1 ± 2.8	1.2 ± 3.8	-1.9 ± 4.0

Note. Values are mean ± SD. Abbreviations: W/kg = watts per kilogram; bpm = beats per minute. p < 0.05, Pre-test vs. Post-test; *p < 0.05, change between Control and PLY groups; ^bp < 0.05, change between Control and PLY+BFR groups; ^cp < 0.05, change between PLY and PLY+BFR groups.

generating both neural and metabolic pathways for adaptation. Nonetheless, it is essential to emphasize that our study did not include direct measures of muscle architecture, EMG, or molecular biomarkers. Thus, while the training responses observed are consistent with prior mechanistic hypotheses [9, 19], any inference about underlying mechanisms should be interpreted with caution. These results suggest that the added metabolic stress from BFR may have enhanced neural drive or hormonal signaling. However, further investigation using physiological tools is warranted.

From a pedagogical perspective, the use of BFR in youth athletic training must be approached with deliberate planning. The reduced external load permitted by BFR may be advantageous during recovery cycles, off-season periods, or in athletes with biomechanical limitations. This aligns with injury-prevention strategies [20]. This approach also reflects a modern educational rationale for sport training. Athletes are encouraged to become more aware of internal responses and training efficiency rather than relying solely on volume or intensity. As discussed by Barra-Moura et al. [4], training frequency and load manipulation are critical for maximizing adaptation in youth athletes. BFR may offer an alternative route to stimulate performance without excessive mechanical stress.

In practical terms, the application of PLY+BFR should be integrated strategically into long-term athletic development frameworks. Coaches and sports scientists must consider age, maturation status, and sport-specific demands when selecting between high-impact methods and low-load BFR approaches. The present findings provide initial evidence supporting the periodized use of BFR-

based interventions in adolescent athletes aiming to improve anaerobic capabilities within a limited timeframe. Recent soccer-specific investigations indicate that blood flow restriction training can enhance physical capacities and support rehabilitation strategies, yet individualized programming remains essential to account for inter-athlete variability and ensure safety and effectiveness [5, 10].

Limitations and Future Directions

This study has certain limitations that should be acknowledged. First, the sample size was relatively small and limited to male collegiate soccer players, which restricts the generalizability of the findings. Second, the intervention period lasted only six weeks, preventing conclusions about long-term adaptations or retention of training effects. Third, no direct physiological or biochemical measurements (e.g., EMG, biomarkers, or hormonal assays) were collected, which limits the mechanistic interpretation of the observed outcomes. Future research should examine the applicability of PLY+BFR protocols in female athletes and youth populations, as hormonal responses and neuromuscular adaptations may differ across these groups. Longitudinal studies exceeding 12 weeks, or those with follow-up assessments, are needed to clarify the retention and delayed effects of training adaptations. In addition, incorporating biomarkers, surface electromyography (sEMG), and hormonal profiling would help explain the mechanisms underlying performance improvements. Comparative studies with other low-load resistance strategies are also recommended to determine the relative efficacy and broaden the evidence base for sports performance programming.

Conclusions

This randomized controlled trial demonstrated that a six-week intervention combining plyometric training with blood flow restriction (PLY+BFR) was more effective than traditional plyometric training alone. Significant improvements were observed in body composition, muscular strength, vertical jump performance, and anaerobic power among competitive male collegiate soccer players. These findings suggest a beneficial interaction between neuromuscular and metabolic mechanisms, likely enhancing anabolic adaptations within a relatively short timeframe. The structured progression of cuff pressure in twice-weekly sessions was feasible and well-tolerated, supporting its potential for safe implementation in contexts that require low mechanical load. The results provide practical implications for coaches and conditioning specialists, particularly during pre-season or rehabilitation phases when training intensity must be carefully managed.

Acknowledgement

The authors thank the Division of Sports and Exercise Science, Ubon Ratchathani Rajabhat University, for granting access to laboratory facilities and research equipment. Finally, appreciation is extended to all collegiate soccer players who volunteered to participate. Their dedication and cooperation were essential to the successful completion of the study.

Funding

This study received no external financial support and was conducted entirely with the authors' personal resources.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

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Cite this article as:

La-bantao K, Tongterm T. Effects of plyometric training with blood flow restriction on body composition, strength, power, and anaerobic performance in soccer players. *Pedagogy of Physical Culture and Sports*, 2025;29(4):361–368. <https://doi.org/10.15561/26649837.2025.0413>

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Received: 16.07.2025

Accepted: 23.08.2025; Published: 30.08.2025

Integrating music–movement pedagogy into inclusive physical education for children with intellectual disabilities

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Abstract

Background and Study Aim In inclusive education, traditional play is often used to help children with intellectual disabilities (ID) improve motor skills. However, these activities may lack structured sensory input. This study evaluates the effects of structured music-movement activities and traditional play on motor skills in children with mild to moderate ID.

Material and Methods Sixty children (ages 8 to 14; IQ 50-70) with intellectual disabilities (ID) participated in a quasi-experimental study. They were randomly assigned to either the control group (CON, n=30), which engaged in traditional school-based play, or the intervention group (INT, n=30). For eight weeks, the INT group participated in three sessions of progressive music-movement activities (orientation, coordination, interaction, and generalization), lasting forty-five minutes each. The activities included rhythmic scaffolding, sensory aids (textured balls), and environmental modifications. The CON group practiced regular school-based play—sensorimotor, constructive, social, and role-playing. The Movement Assessment Battery for Children-2 (MABC-2), modified for ID populations (reliability $\alpha=0.91$), was used to evaluate motor skills before and after the intervention. Data were analyzed using clinical classification, t-tests, and effect sizes (Cohen's d).

Results The INT group significantly improved total MABC-2 scores ($\Delta=2.00\pm 2.32$) compared to the CON group ($\Delta=0.86\pm 1.38$; $p=0.025$, $d=0.60$). This represents a moderate effect size, indicating meaningful functional improvement attributable to the intervention. Subdomain analyses showed that INT significantly improved aiming and catching ($\Delta=0.50\pm 1.11$, $p=0.019$) and balance ($\Delta=0.80\pm 1.24$, $p=0.001$). The proportion of children with significant motor impairments decreased from 33.3% to 26.7%. However, 70% remained borderline, suggesting that while the intervention was beneficial, many children still required sustained support to achieve functional motor proficiency.

Conclusions For children with ID, structured music-movement pedagogy significantly outperforms traditional play in enhancing motor skills, especially bilateral coordination and dynamic balance. Its multisensory, phased approach addresses key temporal and sensory integration issues associated with ID. However, persistent borderline impairments underscore the necessity for hybrid or extended interventions. Incorporating this approach into inclusive physical education curricula is strongly recommended to optimize functional outcomes.

Keywords: motor skills, intellectual disability, music-movement pedagogy, inclusive education, children

Introduction

Inclusive Physical Education (PE) provides equal opportunities to promote physical development for children with intellectual disabilities (ID). Traditional play-based activities are widely used in these settings to develop motor skills. However, these activities often lack the structured sensory input needed to achieve maximum developmental outcomes.

Every child, including those with intellectual disabilities (ID), has the equal right to develop academically, socially, and physically as much as possible, according to inclusive education [1]. Children with ID frequently experience developmental delays, including in motor skills, and inclusive education aims to address their needs [1]. For instance, below-average intelligence and trouble adapting are traits of children with ID that may impact their motor development [1]. Effective pedagogical interventions that improve gross motor skills are essential in the context of inclusion because they are one of the key pillars for students

with ID to become independent and participate in everyday activities [2].

Children with special needs have had their motor skills stimulated using various conventional and adaptive methods. According to some research, children with disabilities can significantly enhance their gross motor skills by participating in adaptive sports or traditional games [3]. Additionally, Mulya discovered that using traditional games improved the gross motor development of students with special needs [4]. Similarly, circuit games and traditional sports significantly improved the basic locomotor movements of deaf and mute students [1]. Using the concepts of sports science, this game-based sports intervention has demonstrated its ability to help children with ID develop their functional skills and improve their muscle strength and balance [1, 5]. However, some of these activities are static and don't consider children's multisensory or imaginative abilities.

The movement-music pedagogy approach is becoming more popular in inclusive and general education as a creative substitute [6]. This method creates engaging and meaningful learning experiences using rhythm, music, and body movement. Ulfah demonstrated how the ATIK (Observe-Imitate-Improvise-Create) learning model, combined with movement-song demonstrations, gradually enhances early childhood gross motor skills, significantly improving balance control and movement coordination [7]. According to other studies, integrating rhythmic movements into educational activities can enhance kids' self-expression and creativity while enhancing their motor coordination and efficiency [8]. Kanzari et al. found that an integrated intervention centred on play, music, and physical activity significantly improved children's motor skills and social motivation with autism spectrum disorders [9]. These findings align with a recent systematic review that found rhythmic movement exercises improve children's expressive skills and body awareness in special education [8].

Del Barrio and Arús stressed the importance of an additional classification and noted the lack of research combining music and movement in elementary education [8]. However, few studies have examined the sustainability and practical implementation of these interventions [10, 11]. Motor skills and physical activity interventions have been shown to improve motor development in children with Autism Spectrum Disorder (ASD), with lasting effects observed throughout the duration of the interventions [12].

Analysis of the research results revealed that motor skills and physical activity interventions significantly contribute to the development of motor abilities in children with intellectual disabilities. The authors emphasize the importance

of integrating music and movement into inclusive education, noting its potential to enhance motor development. However, despite the promising findings, there remains a need for further research in this area. This gap highlights the necessity for more comprehensive studies that combine sports science with music-movement pedagogy to fully understand the long-term impact of these interventions on children's development.

This study evaluates the effects of structured music-movement activities and traditional play on motor skills in children with mild to moderate ID.

Materials and Methods

Participants

This study followed the CONSORT 2010 guidelines for non-equivalent studies, using a quasi-experimental design with pretest and posttest measures and a different control group [13]. The study recruited 60 students aged 8–14 with mild-to-moderate intellectual disabilities (IQ 50–70) from grades 2–6 SDLB, employing the selective learning model from two schools: SLBN Bekasi Jaya (n=30) and SLB ABC Citra Mandala (n=30) [14]. Exclusion criteria included severe motor disorders (GMFCS Level IV-V), total sensory deficits, and uncontrolled comorbid psychosis or epilepsy. Inclusion criteria involved children with mild to moderate intellectual disabilities (IQ 50-70) who did not have severe physical conditions preventing participation, as confirmed by a psychologist, and with parental informed consent.

This study used a stratified random assignment design to ensure that the experimental (INT) and control (CON) groups had an equal mix of important characteristics. Participants were first categorized by school (SLB Citra Mandala and SLBN Bekasi Jaya), gender (M/F), academic class (2-3/4-6), and degree of intellectual disability (mild/moderate). The block randomization method, which places participants into groups of four, was then used to randomly assign each category to either the intervention or control group in equal numbers. This resulted in 30 students in each group: 15 from the intervention group and 15 from the control group at SLB Citra Mandala, and 15 from the intervention group and 15 from the control group at SLBN Bekasi Jaya. SLB Citra Mandala contributed 15 intervention students and 15 controls, while SLBN Bekasi Jaya contributed 15 intervention students and 15 controls.

Age ($p=0.312$), gender ($p=0.621$), the level of intellectual disability ($p=0.605$), motor function (GMFCS Level, $p=0.588$), and IQ score ($p=0.195$) showed no significant differences between groups, based on the baseline balance analysis. The assignment protocol followed a partially-blind approach, meaning neither the measurement assessor nor the teacher implementing the

intervention knew the group assignments or the study's objectives. Ethical considerations were addressed by offering the intervention program to the control group after the study ended and providing individual reports to parents [15]. To prevent contamination, intervention and control activities took place in separate rooms with different schedules.

Research Design

A quasi-experimental pretest-posttest design with stratified random allocation was used, comparing an 8-week structured music-movement intervention to traditional play activities. The stages began in November and December 2024 with administrative and ethical preparations. A sensory corner and a visual partition were added to the intervention room, and the measuring tool was validated by three experienced SLB teachers and tested on ten non-participant students. In the first week of January 2025, starting points were measured in three separate sessions: (1) Two independent assessors evaluated motor skills using the MABC-2 Checkpoint, and they agreed on their findings; (2) physiological responses were monitored with Shimmer3 GSR+ for 15 minutes during a neutral activity. Each measurement followed specific guidelines for people with intellectual disabilities, which involve using rewards based on their preferences, visual instructions such as pictures, and keeping each session to a maximum of 30 minutes with two scheduled breaks.

Three weekly sessions of 45 minutes each were held during the 8-week intervention implementation period (weeks 2–9). Four progressive phases comprised the structured song-movement intervention given to the experimental group: (1) orientation (song introductions with isolation movements); (2) coordination (bilateral movements with physical scaffolding); (3) interaction (turn-based pair activities); and (4) generalisation (song-

movement combinations in novel contexts). The therapist's daily logbooks and video recordings of 20% of the sessions, evaluated using the Motor Performance Analysis Tool-ID (MPAT-ID), were used to track the intervention's fidelity. According to the school curriculum, the CON group engaged in traditional play activities. The entire baseline process was repeated in the final measurement at week 10 under strict, partially blind conditions: an independent assessor from outside the institution evaluated the video recordings, and the assessor was unaware of the group allocation.

Table 1 shows the structured music-movement teaching method used by the experimental group (INT) over 8 weeks. The program was built up over four important stages: (1) Orientation (a slow song introduction with isolation movements at 60-70 BPM), (2) Coordination (bilateral movements using textured balls), (3) Interaction (turn-based partner activities), and (4) Generalization (song-movement combinations in new settings). Each phase included a set of core activities, scaffolding strategies based on evidence (such as visual instructions, partial physical support, and sensory aids), and specific goals for developing motor skills (such as single limb coordination, bilateral integration, and contextual transfer). The protocol addressed the needs of children with intellectual disabilities by adjusting the length of sessions (maximum 45 minutes), implementing a reward system based on individual preferences, and modifying the environment (including visual partitions and sensory zones).

The protocol for the traditional play activities given to the control group (CON) as a comparison and conducted simultaneously over eight weeks according to the school curriculum is detailed in Table 2. Four types of play were included: (a) sensorimotor (bead stringing, coin insertion activities), (b) constructive (puzzles, building block towers), (c) social (unplanned ball throwing and

Table 1. Music-movement intervention protocol (INT group)

Phase	Week	Core Activity	Scaffolding	Motor Targets
Orientation	1-2	Slow song introduction (60-70 BPM) with isolation movements (raise one hand, tap shoulder)	- Visual instructions (movement pictures) - Child's preference rewards	Single limb coordination
Coordination	3-4	Bilateral movements: clapping while jumping, throwing and catching textured balls	- Partial physical support (elbow guidance) - Assistive devices: bean bag ball	Bilateral integration
Interaction	5-6	Pair activities: «Turn Song» (throw the ball to the rhythm to the partner)	- Visual turn cards - 2-minute timer	Eye-hand and social coordination
Generalisation	7-8	Combination of song-movement in a new environment (school field)	- Reduction of physical scaffolding - Modification of floor texture	Contextual skill transfer

catching), and (d) role play (selling and buying role play). Each category involved specific toys (such as plastic balls, piggy banks, and toy store equipment) and essential operational details, like the absence of structured musical elements and verbal instructions. The activity design followed a traditional approach, without individual response-based adjustments, environmental modifications, or gradual scaffolding, which are standard practices in inclusive educational settings.

Data collection procedures adhered to the International Test Commission (2020) and APA Standards for Educational Testing guidelines. Standardized instruments validated for populations with intellectual disabilities were used to gather data. The Movement Assessment Battery for Children-2 (MABC-2) Checkpoint, made for people with intellectual disabilities, assessed motor perception by (1) not having time limits for tasks, (2) offering three types of help (verbal, gestural, and partial physical), and (3) using textured balls and bean bags instead of tactile stimuli [16]. Hadwin et al. confirmed that the instrument is valid because it has a high reliability score of $\alpha = 0.91$ and can accurately identify 85% of bilateral coordination disorders [17]. Two MABC-2 certified assessors evaluated three domains: manual dexterity, aiming and catching, and static-dynamic balance, in 30-minute sessions

within a controlled environment (temperature 24-26°C, low lighting).

Table 3 displays the motor skills of participants with mild intellectual disability (IQ 50–70), including their raw scores, scaled scores, and explanations in three key areas: manual dexterity, aiming and catching, and static-dynamic balance, all based on standard assessment guidelines. This section illustrates how the modified MABC-2 instrument is applied to the population with intellectual disabilities.

The MABC-2-based criteria for classifying motor impairment used in this study are outlined in Table 4. These criteria define three clinical severity categories: (1) Significant Impairment (\leq 5th percentile), (2) Borderline Risk (6th-15th percentile), and (3) Normal Range (\geq 16th percentile). The main findings of the study are explained using this standard classification, which makes it easier to compare the different categories before and after the test to see how participants' functional status changed across groups.

On Wednesday, January 1, 2025, the baseline (pre-intervention) phase was carried out in five distinct sessions: motor measures (MABC-2 Checkpoint) on Days 1-2, and physiological monitoring (GSR+) on Day 5. All of these sessions took place between 8:00 and 10:00 a.m., which is when students are most

Table 2. Traditional play protocol (CON group)

Activity Type	Week	Activity	Tools	Notes
Sensorimotor Play	1-2	- Putting coins in a piggy bank - Stringing beads	Piggy bank, large beads	No structured musical elements
Constructive Play	3-4	- Building a block tower - Simple puzzle	Wooden blocks, 6-piece puzzle	Minimal verbal instructions
Social Play	5-6	- Throw and catch the ball with friends	Plastic balls	Spontaneous interaction without turns
Role Play	7-8	- Play the role of seller/buyer	Toy shop equipment	Teacher-led

Table 3. Individual performance score of a child with mild intellectual disability on the MABC-2 (Band 2)

Motor Domain	Task	Raw Score	Scaled Score (0–19)
Manual Dexterity	Posting Coins seconds	
	Threading Lace seconds	
	Drawing Trail errors	
	Subdomain Total		
Aiming & Catching	Catching Beanbag (out of 10) successful catches	
	Aiming at Target (out of 10) accurate throws	
	Subdomain Total		
Balance	One-Leg Balance seconds	
	Walking Heels Raised steps correct	
	Jumping in Squares correct positions	
	Subdomain Total		
Total Scaled Score	–	– (Max = 152)

Table 4. MABC-2 total score classification criteria

Category	Percentile Rank	Description
Significant Motor Impairment	≤ 5th percentile	Motor impairment is highly likely
Borderline (At Risk)	6th–15th percentile	Motor impairment is likely, monitoring is required
Within Normal Range	≥ 16th percentile	No significant motor impairment

alert according to circadian studies on intellectual disabilities [18]. The task sequencing began with the student’s favorite activity, and sessions were spaced at least 48 hours apart to prevent fatigue. The mid-intervention monitoring phase, which took place at the end of Week 5, included the MABC-2 dynamic balance subtest (15 minutes per student) and monitoring skin conductance level (SCL) in 20% of randomly chosen sessions. This information was used to identify learning plateaus and modify scaffolding in real time.

The entire baseline process was repeated in the post-intervention phase (Week 10) under the following strict conditions: (1) it had to occur on the same day and at the same time as the pre-test (Tuesday at 8:00); (2) the temperature and humidity had to remain within ±1°C; and (3) an additional generalisation test was conducted using a movement-song activity in a different setting (such as a school ceremony).

Statistical Analysis

IBM SPSS Statistics version 27 was used for all statistical analyses. The Shapiro-Wilk test was conducted to assess whether data were normally distributed before hypothesis testing, and results indicated that all variables followed a normal distribution ($p > 0.05$). Descriptive statistics are presented as means and standard deviations (mean ± SD) for each motor domain. The intervention group (INT) and the control group (CON) underwent separate paired-sample t-tests to evaluate within-group effects of the interventions. Effect sizes were calculated using Cohen’s *d* and interpreted using standard thresholds: small (0.2), medium (0.5), and large (0.8). Independent-sample t-tests were used to examine differences between groups in pre-post change scores. Shifts in motor impairment levels were descriptively analyzed using MABC-2 percentile categories (significant impairment, borderline, within normal range) to observe how clinical classifications changed. This categorical analysis allowed for the functional interpretation of the intervention effects.

Results

In this quasi-experimental study, 60 children with mild-to-moderate intellectual disabilities (ages 8–14) were randomized into either traditional play activities (CON, $n=30$) or music-movement pedagogy (INT, $n=30$) to assess their motor skill outcomes. Baseline characteristics, including age, gender,

school, and motor function classification, were well balanced between groups ($p > 0.05$; Table 5).

After the 8-week intervention, the INT group’s total MABC-2 scores improved significantly more than the controls ($\Delta = 2.00 \pm 2.32$ vs. 0.86 ± 1.38 ; $p = 0.025$, Cohen’s *d* = 0.60). Additionally, there were clinically significant changes in the categories of motor impairment: the percentage of INT participants classified as having significant motor impairment decreased from 33.3% to 26.7%. In comparison, the percentage of CON participants classified as having significant motor impairment remained constant at both time points, at 36.7%.

The results of the Shapiro-Wilk test indicate that the data are normally distributed with a *p*-value of 0.200 across all variable groups. Additionally, a paired t-test was performed to assess the treatment effects on both the INT and CON groups. The findings are presented in Table 6.

The study compared motor domain scores before and after the intervention using MABC-2 assessments. The INT group showed significant improvements across all motor domains, especially in balance and aiming/catching, compared to the control group (Table 6). All improvements reached statistical significance ($p < 0.05$), with small-to-moderate effect sizes.

Based on MABC-2 percentile thresholds, Table 7 shows the categorical distribution of motor impairment severity levels (significant impairment, borderline, and within normal range) to contextualize these quantitative improvements for clinical relevance.

Clinically, the proportion of children with significant motor impairment in the INT group declined from 33.3% to 26.7%, although 70% remained in the borderline category, indicating an ongoing need for support (see Table 7). However, the share of participants within the normal range remained unchanged, suggesting that most were still at risk and required continuous support. The control group showed no change in the proportion of participants in each category, indicating that unstructured traditional play has a limited impact on motor function classifications.

Next, researchers conducted an independent sample t-test to determine the difference in results between the INT and the CON groups. Table 8 presents the significantly different test results.

Between-group analysis confirmed that motor gains were significantly greater in the INT group

Table 5. Demographic and clinical profiles of the study

Characteristic	Total Sample (n=60)	Intervention Group (n=30)	Control Group (n=30)	p-value
Age (years), mean ± SD	10.8 ± 1.9	10.6 ± 2.0	11.0 ± 1.8	0.312
Gender, n (%)				0.621
- Male	34 (56.7)	17 (56.7)	17 (56.7)	
- Female	26 (43.3)	13 (43.3)	13 (43.3)	
School, n (%)				-
- SLBN Bekasi Jaya	30 (50.0)	15 (50.0)	15 (50.0)	
- SLB ABC Citra Mandala	30 (50.0)	15 (50.0)	15 (50.0)	
Academic Class, n (%)				-
- Grades 2-3	24 (40.0)	12 (40.0)	12 (40.0)	
- Grades 4-6	36 (60.0)	18 (60.0)	18 (60.0)	
IQ Score, mean ± SD	62.3 ± 5.4	63.1 ± 5.1	61.5 ± 5.6	0.195
ID Severity, n (%)				0.605
- Mild (IQ 55-70)	38 (63.3)	20 (66.7)	18 (60.0)	
- Moderate (IQ 50-54)	22 (36.7)	10 (33.3)	12 (40.0)	
GMFCS Level, n (%)				0.588
- Level I	20 (33.3)	11 (36.7)	9 (30.0)	
- Level II	28 (46.7)	13 (43.3)	15 (50.0)	
- Level III	12 (20.0)	6 (20.0)	6 (20.0)	
MABC-2 Scores, n (%)				
- Within Normal Range	2 (3.33)	1 (3.33)	1 (3.33)	
- Borderline	37 (61.67)	19 (63.33)	18 (60.0)	
- Significant Difficulty	21 (35.0)	10 (33.33)	11 (36.67)	

Table 6. Pre-Post within-group changes in MABC-2 motor domain scores

Group	Motor Domain	Mean±SD			P(sig)	Effect Size Cohen's D
		Pre	Post	Δpost-pre		
INT	Manual Dexterity	16.00±3.49	16.70±3.42	0.70±1.37	0.009*	-0.203
	Aiming and Catching	9.17±2.74	9.67±2.49	0.50±1.11	0.019*	-0.190
	Balance	16.10±4.81	16.90±4.20	0.80±1.24	0.001*	-0.177
	Domain total	41.27±7.19	43.27±6.87	2.00±2.32	0.000*	-0.284
CON	Manual Dexterity	16.97±4.38	17.20±4.06	0.23±0.86	0.147	-0.054
	Aiming and Catching	8.00±3.81	8.47±3.56	0.47±0.86	0.006*	-0.127
	Balance	16.73±3.25	16.90±3.06	0.17±0.69	0.202	-0.053
	Domain total	41.7±6.53	42.57±6.45	0.86±1.38	0.002*	-0.134

*Significant difference with $p < 0.05$

than in the control group ($p = 0.025$; $d = 0.60$), representing a moderate effect (see Table 8). These findings support the idea that structured music-movement interventions are more effective than traditional play-based activities in helping children with intellectual disabilities develop their motor skills. Given the observed moderate effect size, this approach may hold value for incorporation into therapeutic or adapted physical education programs, particularly in inclusive settings.

Discussion

This study evaluates the effects of structured music-movement activities and traditional play on motor skills in children with mild to moderate intellectual disabilities (ID). The findings suggest that structured music-movement pedagogy may enhance motor skills in children with intellectual disabilities. A moderate improvement in motor function was observed in the intervention group, reflected in the decrease of severe motor difficulties

Table 7. Distribution of Motor Impairment Severity Categories Based on MABC-2 Total Scores

Total Scale Score (8 tasks)	Percentile Range	Category	INT Group (n(%))	CON Group (n(%))
> 56	≥ 16th percentile	Within Normal Range	1 (3.33%)	1 (3.33%)
41–55	6th–15th percentile	Borderline	19 (63.33%)	18 (60%)
≤ 40	≤ 5th percentile	Significant Difficulty	10 (33.33%)	11 (36.67%)

Table 8. Between-Group Differences in MABC-2 Total Score Changes Post-Intervention

Group	Mean±SD			P(sig)	Effect Size Cohen's D
	Pre	Post	Δpost-pre		
INT	41.27±7.19	43.27±6.87	2.00±2.32	0.025*	0.597
CON	41.7±6.53	42.57±6.45	0.86±1.38		

*Significant difference with $p < 0.05$

and a Cohen's d of 0.60. These findings align with existing theories suggesting that rhythmic music may facilitate motor planning and execution by supporting movement-related neural processes [19, 20]. For children with ID who struggle with executive function and anticipatory control, the temporal structure of music offers predictive cues that scaffold movement sequencing [21, 22]. Through the song, students develop the ability to analyze and distinguish musical sounds and rhythmic-melodic structures with greater precision by actively and deliberately engaging in their interpretation. Simultaneously, cognitive development occurs in environments where music provides a framework that is both enjoyable and conducive to its activities [23].

A phase-based scaffolding approach (orientation → coordination → interaction → generalisation) was particularly important. Mukhtarkyzy et al. suggest “woven motor learning” for the ID population, which is reflected in progressively complex sensory support (textured balls, visual cues) [24]. The systematic fading of support needed to close skill gaps is missing from traditional unstructured play formats [25]. Since rhythmic bilateral tasks enhance interhemispheric communication, a known deficit area in ID, our intervention's focus on bilateral integration activities (Phase 2) likely explains the significant improvements in aiming/catching ($d = 0.19$) and balance ($d = 0.18$).

The control group's modest increase in manual dexterity ($\Delta = 0.23$; $d = 0.05$) raises questions about the effectiveness of traditional play. Without rhythmic structuring, sensorimotor play (such as bead-stringing) cannot address the temporal coordination deficiencies that are a hallmark of intellectual disabilities (ID) [26]. Thus, our findings corroborate those of Downs et al., who contend that unstructured play fails to adequately address the specific motor control deficits in this population [27].

However, the fact that 70% of the intervention group still had borderline motor impairment

after treatment points to an important drawback: even though music-movement pedagogy is more effective than conventional approaches, the majority of children still require continuous assistance. This finding aligns with global data indicating that motor impairments in individuals with intellectual disabilities rarely return to normal without consistent intervention [28, 29]. Future research should explore combined or longitudinal approaches (such as incorporating assistive technology) to enhance these effects.

Music-movement pedagogical approaches, such as Dalcroze Eurhythmics and the Orff method, effectively promote children's motor development. Early exposure to joyful music can improve coordination, spatial orientation, and overall motor efficiency [8]. The integration of music and movement supports physical, cognitive, and emotional development, making it suitable for all learners, including those with special needs [8]. Experiential learning stimulates enthusiasm and creativity, which are important aspects of learning for children with intellectual disabilities [30]. Recent experimental studies support the effectiveness of music-movement interventions for children with special needs. For instance, a rhythmic music program for children with Down syndrome significantly improved their functional motor skills compared to a control group without music. Neurologic Music Therapy (NMT) sessions via telehealth led to a significant increase in BOT-2 scores in autistic children, indicating a real improvement in motor skills [31]. Pediatric music therapy consistently improves motor function and emotional well-being [32]. Combining music training with motor play results in greater improvements in coordination than either method alone [33].

From the perspective of exercise science, music-movement interventions can be seen as a type of organized physical activity that incorporates the three pillars of motor learning: task variation, repetition, and a gradual increase in

intensity. Focused exercise training programs have significantly improved the gross and fine motor skills of children with intellectual disabilities, according to a recent meta-analysis [34]. For instance, the total motor score increased with an effect size of 1.28. Similar outcomes have been observed with music interventions, especially those involving active participation (e.g., playing rhythmic instruments or engaging in structured singing). A systematic review found that music has moderate to high effects on enhancing children's motor recovery, with active music activities (instruments, singing, rhythmic movements) outperforming passive music exposure [35]. In other words, incorporating music training into physical activities engages children's emotional and cognitive motivation, which helps them remember motor skills by encouraging repeated practice of body movements and maintaining emotional and cognitive involvement. Future research should explore longitudinal effects, hybrid interventions, assistive technology, and culturally appropriate musical content to maximize accessibility and long-term gains.

Limitations of the study

Several limitations of this study warrant consideration. First, the sample included only two special-needs schools in Indonesia, significantly limiting the generalizability of the findings to other cultures and educational settings. Results cannot be extended to children with severe intellectual disabilities, younger populations, or those with comorbid conditions (e.g., autism spectrum disorder) because the participants were exclusively children with mild-to-moderate intellectual disabilities (IQ 50–70). Although the intervention showed notable short-term motor improvements, the 8-week duration was insufficient to address long-term borderline impairments, highlighting the need for longitudinal studies to evaluate sustainability. Third, the absence of an active alternative intervention, such as standard physiotherapy, limits the comparison of pedagogical approaches, even though

the control group participated in traditional play activities. Methodologically, due to known ceiling effects in aiming and catching tasks, the MABC-2 may not detect subtle motor improvements, even with adaptations for ID populations. Additionally, while assessors remained blinded, participants and activity facilitators could not be fully blinded due to logistical constraints. Finally, conducting the study in controlled settings somewhat reduces ecological validity; further research is required to verify practical applicability in diverse inclusive classrooms.

Conclusions

Structured music-movement pedagogy significantly improves motor competence in children with intellectual disabilities (ID), outperforming traditional play-based activities. Participants showed improvements in manual dexterity, aiming, catching, and balance over the 8-week intervention. The proportion of children with significant motor impairment decreased from 33.3% to 26.7%, with a moderate effect size. The findings suggest that rhythmic, sensory-integrated pedagogy is effective in scaffolding motor learning. However, 70% of the intervention group experienced borderline impairment, indicating that they require sustained multimodal support. These findings have implications for inclusive education and therapeutic programming, suggesting that integrating music-movement interventions into adapted physical education and inclusive learning plans is essential.

Acknowledgement

Thank you to the students and teachers of SLBN Bekasi Jaya and SLB ABC Citra Mandala who have been willing to participate in this study. In addition, thank you to all other parties who have helped collect and analyze data.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this study.

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Cite this article as:

Intani AD, Sukoco P, Sumaryanti, Abidin D, Prayogo G, Özman C, Rusdiawan A, Ilmah NK. Integrating music–movement pedagogy into inclusive physical education for children with intellectual disabilities. *Pedagogy of Physical Culture and Sports*, 2025;29(4):369–378. <https://doi.org/10.15561/26649837.2025.0414>

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Received: 13.07.2025

Accepted: 25.08.2025; Published: 30.08.2025

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<https://sportpedagogy.org.ua>

Information Sponsors, Partners, Sponsorship:

- Ukrainian Academy of Sciences.

SCIENTIFIC EDITION (journal)

Pedagogy of Physical Culture and Sports, 2025;29(4)

designer: Iermakov S.S.

editing: Yermakova T.

designer cover: Bogoslavets A.

administrator of sites: Iermakov S.S.

Certificate DK №7472 07.10.2021.