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ORIGINAL ARTICLE

Strength training versus high-intensity aerobic exercise: which is more effective in increasing il-10 production as an anti-inflammatory?

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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 Physical exercise is widely recognized as an effective strategy for improving health and quality of life. The purpose of this study was to analyze the effects of high-intensity and low-intensity strength training, as well as high-intensity aerobic exercise, on serum Interleukin-10 (IL-10) production.

Material and Methods Thirty college students were recruited to undergo different training programs in each group. The study employed an experimental design with three exercise groups: high-intensity strength training (STH), low-intensity strength training (STR), and high-intensity aerobic exercise (AH). Each group included 10 participants, and serum IL-10 levels were measured before exercise and 24 hours post-exercise. To assess long-term effects, participants trained three times per week for four weeks under carefully monitored conditions.

Results The results showed that all types of exercise significantly increased serum IL-10 levels. The AH group exhibited the highest increase, followed by the STR and STH groups. These findings align with previous studies demonstrating an increase in IL-10 following high-intensity aerobic exercise. The elevated IL-10 levels in the AH group can be attributed to improved cardiovascular capacity and the body's inflammatory response. Strength training, despite not increasing VO2max, also led to an IL-10 increase, though the effect was smaller compared to aerobic exercise.

Conclusions High-intensity aerobic exercise is more effective at increasing IL-10 production compared to strength training. This study suggests combining both types of exercise to maximize immunological benefits. Such an approach can also enhance post-exercise recovery. It is important to consider the duration and recovery intervals, as these factors influence the immune response.

Keywords: aerobic exercise, anti-inflammatory, high-intensity, strength training

Introduction

Physical exercise has long been recognized as one of the most effective strategies for improving health and quality of life [1]. Various training methods are currently available, including weight training and aerobic training. Previous studies have identified that both weight training and aerobic training offer significant benefits for enhancing physical abilities and metabolic functions [2, 3, 4, 5, 6]. However, despite these positive effects, repeated high-intensity exercise can lead to muscle inflammation [7, 8, 9]. A key indicator often used to measure and assess the resolution of inflammatory responses caused by muscle contractions is Interleukin-10 (IL-10), also known as human cytokine synthesis inhibitory factor (CSIF) [10, 11, 12].

IL-10 is produced to suppress the production of pro-inflammatory cytokines resulting from muscle contractions, which, if continuously produced, can cause tissue damage and delay the recovery process [13, 14]. The production of IL-10 aids in recovery during and after physical exercise [10]. However, to date, no research has specifically analyzed the effects of high- and low-intensity strength training and high-intensity aerobic training on IL-10 production. Each of these methods involves different mechanisms that stimulate the body to adapt to the training process. Strength training relies on muscle strength indicators through the

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use of maximum loads, focusing on maximizing the body's physical capacity for specific movements [15]. In contrast, aerobic exercise emphasizes improving cardiovascular and respiratory function, aiming to increase endurance for sustained physical activity [16, 17]. These differences in mechanisms suggest variations in IL-10 production, which require further analysis through research.

Some previous studies have primarily focused on the differences between exercise types, such as aerobic exercise and strength training, without considering the role of intensity in each type of exercise [18, 19]. However, incorporating intensity has significant potential to influence the physiological and immunological outcomes of exercise.

The urgency of this research is underscored by the critical role of IL-10 in regulating inflammation linked to various health conditions, including heart disease, diabetes, and autoimmune disorders [20, 21, 22, 23]. As more individuals engage in exercise programs to improve health, understanding how exercise intensity and type affect IL-10 production will contribute to designing more effective programs. Such programs could enhance immunity, accelerate recovery, and reduce the risk of chronic inflammatory diseases [24, 25, 26].

This study aims to examine the effects of different exercise types combined with varying intensities on IL-10 biomarker production. It is expected to contribute to a better understanding of how exercise variations influence the body's immune response, particularly in managing post-exercise inflammation.

Materials and Methods

Participants

College students were recruited to participate in different training programs assigned to each group. The students were first matched based on age, resting heart rate (RHr), SpO2, blood pressure, glucose level, hemoglobin, weight, height, BMI, fat percentage, muscle mass, visceral fat, and bone mass. Thirty students, who had a history of engaging in physical exercise three times a week, were randomly assigned to the high-intensity strength training group (STH; age = 18.1 ± 0.31 years, n = 10), low-intensity strength training group (STR; age = 19.6 ± 2.36 years, n = 10), and high-intensity aerobic training group (AH; age = 18.7 ± 1.25 years, n = 10).

The body composition measurement procedure, blood sampling process, and physical exercise protocols were explained to all participants. Each participant read and signed a consent form before joining the study. The experimental procedure was approved by the Ethics Committee (107/EC/KEPK-FKUC/III/2024).

Research Design

This study investigated the effects of four weeks of physical training using different methods on IL-10 production. All participants completed a personal and medical history questionnaire and a lifestyle assessment, which served as a screening tool. Participants were familiarized with the testing procedures before starting the study.

To assess the long-term effects, participants underwent training three times per week for four weeks under carefully monitored conditions. Blood samples were collected at the beginning and end of the training period to measure serum IL-10 concentrations.

The VO2peak test, maximal strength assessment (for the STH and STR groups), body composition measurements, and IL-10 level evaluations were performed at the start and end of the training period. All measurements were conducted by the researcher at the same time each day. The study took place from August to September 2024.

Body Composition Measurement and Health

Body composition measurements were conducted using Tanita BC-545N series scales to collect data on body weight, BMI, body fat, muscle mass, visceral fat, and bone mass. Glucose levels were measured using the Accutrend Plus, hemoglobin (HB) levels using Easytouch, SpO2 levels using the Beurer PO40, and blood pressure using the Omron Blood Pressure Monitor Hem-8712. Each participant's pulse was measured using the Polar H-10 device [27].

The physical exercise program was designed to optimize participants' training outcomes and ensure adherence to the study protocol. Details of the program are illustrated in Figure 1, which outlines the exercise methods and regimens used during the four-week intervention.

Before testing, athletes were given 2 × 24 hours of rest to ensure optimal condition for the 1 RM bench press and leg extension tests. The implementation and procedures for the bench press and leg extension followed the guidelines of the NSCA [28]. Repetitions were performed in a controlled rhythm, with concentric contractions lasting approximately 1 second and eccentric actions lasting about 2 seconds. A 90-second rest period was provided between sets.

Statistical Analysis

Data analysis was performed using SPSS version 29 software. The Shapiro-Wilk test was used to assess the normality of the data, while the Levene test evaluated the homogeneity of variance. Data with a normal distribution and homogeneous variance were analyzed using paired t-tests and one-way ANOVA. Results are presented as mean ± SD. GraphPad Prism 10 software was used to create visual graphs.

Results

Based on the descriptive analysis, no significant differences were observed in the sample profiles across the three groups, as indicated by the results of the one-way ANOVA analysis shown in Table 1. The analysis results of the IL-10 biomarker for each group are presented in Table 2. Additionally, differences in serum IL-10 levels within each group and the corresponding delta values are displayed in Figure 2.

Table 2 shows the serum IL-10 levels for each group. The Pre serum IL-10 value was measured 24 hours before the exercise, while the Post value was measured 24 hours after the physical exercise.

Figure 2 illustrates that serum IL-10 levels before and after exercise differed significantly in each group ($p < 0.05$). Serum IL-10 levels increased after exercise in all groups.

Figure 3 presents the results of the one-way ANOVA test, followed by Tukey HSD post-hoc analysis across the three groups. IL-10 values were not significant (ns) in the pre-exercise data. However, significant differences (*) were observed between STH vs. AH and STR vs. AH in the post-exercise IL-10 values ($p < 0.05$). Similar significant differences were found in the delta calculations for STH vs. AH and STR vs. AH.

Discussion

The results of this study demonstrate that physical exercise interventions, regardless of the model and intensity applied, can increase serum IL-10 levels as an anti-inflammatory marker. These findings align with several previous studies, which also concluded that physical exercise elevates serum IL-10 levels 24 hours after activity [29, 30, 31]. The increase in anti-inflammatory serum serves as a counterbalance to the pro-inflammatory effects induced by exercise.

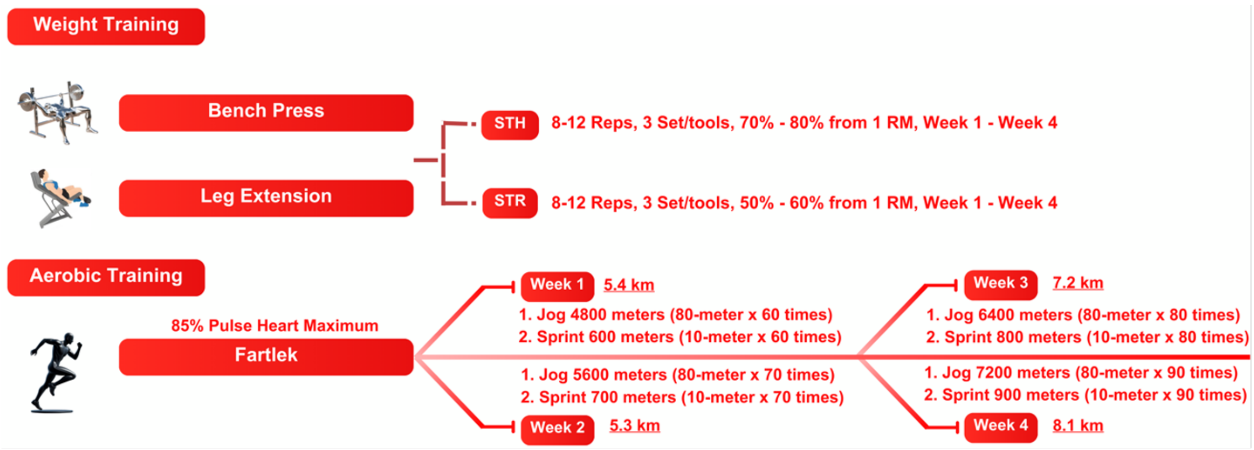

Figure 1. Physical exercise program

Table 1. Sample Profile Characteristics

Variable	STH	STR	AH	p-value
Age (years)	18.1 ± 0.31	19.6 ± 2.36	18.7 ± 1.25	0.114
RHR (bpm)	67 ± 6.84	70.6 ± 5.98	69.3 ± 4.39	0.389
SpO2 (%)	97.6 ± 1.26	97.6 ± 1.07	97.1 ± 1.10	0.540
Systole (mmHg)	114.9 ± 3.47	119.1 ± 2.96	118.3 ± 3.49	0.200
Diastole (mmHg)	74.7 ± 5.73	74.4 ± 4.92	73.9 ± 6.90	0.954
Glucose (mg/dL)	96.7 ± 8.08	101.8 ± 10.61	102.2 ± 9.23	0.357
HB (g/dL)	14.54 ± 1.13	14.23 ± 1.57	13.86 ± 1.30	0.538
Body Weight (kg)	62 ± 7.94	61.5 ± 6.20	64 ± 10.36	0.780
Height (m)	1.68 ± 0.05	1.69 ± 0.07	1.68 ± 0.06	0.910
BMI (kg/m^2)	21.73 ± 2.23	21.44 ± 1.39	22.59 ± 2.70	0.476
Body Fat (%)	15.14 ± 3.89	18.15 ± 3.26	18.01 ± 4.13	0.152
Muscle Mass (kg)	48.86 ± 5.40	48.61 ± 4.43	50.29 ± 6.15	0.755
Visceral Fat (level)	5 ± 1.33	4.55 ± 1.93	4.1 ± 1.39	0.453
Bone Mass (kg)	5.8 ± 0.49	5.86 ± 0.49	5.92 ± 0.64	0.887

Description: STH (strength training with high intensity), STR (strength training with low intensity), AH (aerobic training with high intensity).

Table 2. IL-10 Level in each group

Test	Group	N	Mean ± St.dev	Minimum	Maximum
Pre	STH	10	84.36 ± 19.46	63.52	124.79
	STR	10	82.10 ± 37.77	23.07	129.93
	AH	10	107.73 ± 20.73	81.10	157.00
Post	STH	10	136.33 ± 34.91	68.59	193.30
	STR	10	139.16 ± 29.26	82.59	173.82
	AH	10	199.76 ± 29.86	158.10	270.70
Delta	STH	10	51.96 ± 36.60	3.80	110.45
	STR	10	57.05 ± 32.49	10.29	127.47
	AH	10	92.02 ± 22.14	54.10	122.10

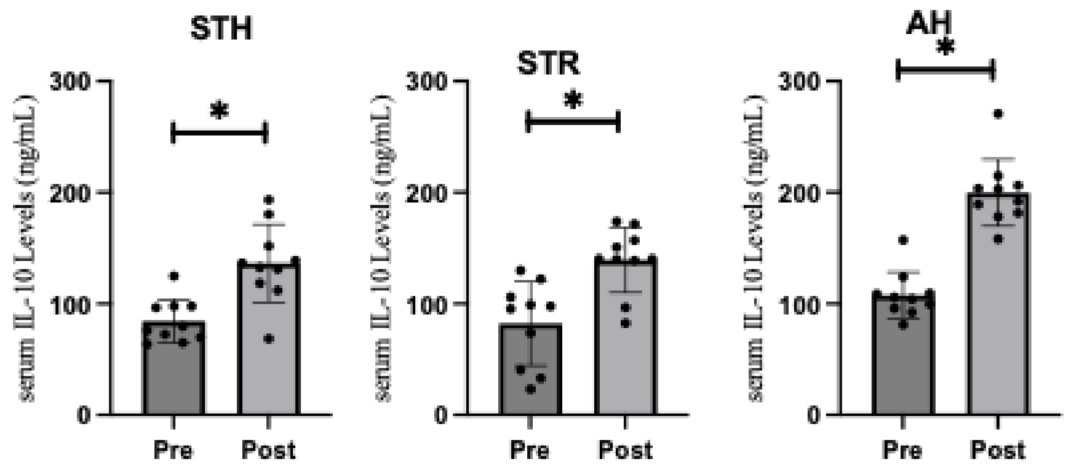

Figure 2. Differences in serum IL-10 Pre and Post for each group

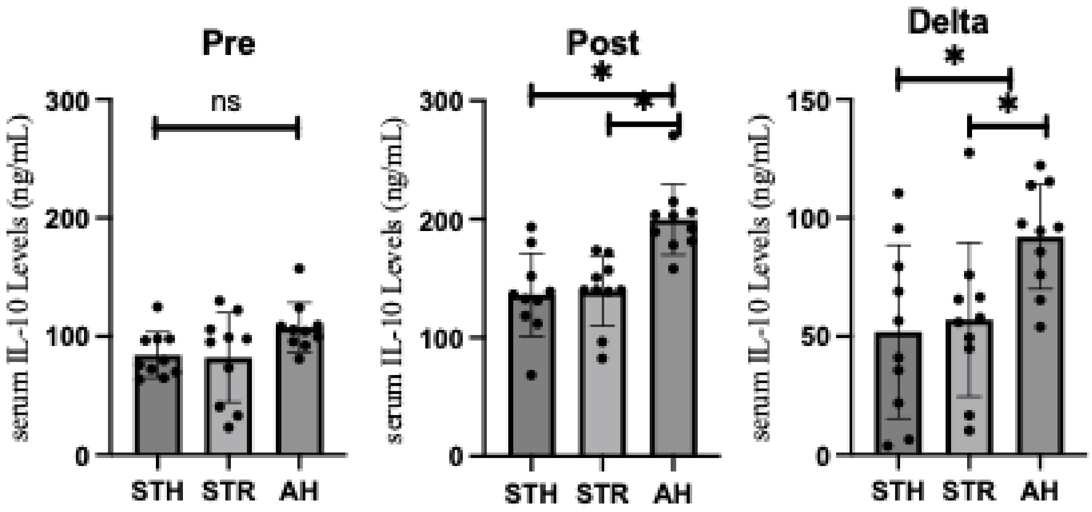

Figure 3. Differences in serum IL-10 in the three groups

Interestingly, this study found that the three training methods resulted in different changes in serum IL-10 levels. The high-intensity aerobic training group showed the greatest increase among the three groups. This finding is supported by previous research [32, 33, 34], which also reported an increase in serum IL-10 following high-intensity aerobic exercise. The increase in IL-10 occurs because high-intensity aerobic exercise induces inflammation, such as lipopolysaccharide-mediated activation of the Akt-STAT3 axis [35]. This activation triggers an anti-inflammatory response by increasing IL-10 production as a mechanism to reduce inflammation.

The increase in serum IL-10 observed in the weight training group contrasts with previous studies [36, 37], which reported no change in serum IL-10 levels following weight training. However, this finding aligns with other research [38, 39], which also concluded that strength training with weights leads to an increase in IL-10 levels.

The mechanism by which aerobic exercise over four weeks increases IL-10 production is not only linked to the high levels of inflammation experienced by athletes during training but also to improvements in VO2max. This aligns with findings from previous research [34], which demonstrated a relationship between increased VO2max and IL-10 production. In contrast, weight training in this study did not increase VO2max, as it primarily focused on changes in muscle size [40, 41, 42]. Differences in IL-10 production are also influenced by factors such as the type of exercise, intensity, duration, recovery between sessions, and variations in exercise regimens [43, 44, 45].

This study yielded interesting results, showing an increase in IL-10 production across all groups, with aerobic exercise producing a greater increase compared to strength training. These findings suggest that combining aerobic and strength training in the exercise process may provide greater benefits by improving both cardiovascular function and muscle strength. For older adults, enhanced cardiovascular and muscular capabilities can contribute to better health and fitness.

Study Limitations

This study is limited by its small sample size and short training duration, which may affect the generalizability of the findings. Additionally, the research focused solely on IL-10 production without exploring other related biomarkers or long-term health outcomes. Future studies should involve larger and more diverse populations, extend the training period, and investigate additional indicators such as oxidative stress markers, inflammatory cytokines, and mental health parameters to provide a more comprehensive understanding of the effects of combined exercise regimens.

Conclusions

This study concluded that all three exercise models (STH, STR, AH) were effective in increasing the production of the anti-inflammatory biomarker IL-10. High-intensity aerobic exercise had a greater impact on IL-10 production after four weeks of training. The primary advantage of high-intensity aerobic exercise lies in its significant effect on cardiovascular capacity and the inflammatory response. In contrast, strength training did not directly enhance cardiovascular capacity. Therefore, combining strength training with aerobic exercise is likely to provide greater benefits for the body's immune response and the acceleration of recovery processes.

Conflict of interests

The authors declare that there is no conflict of interests.

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ORIGINAL ARTICLE

Enhancing health-related physical fitness through Arnis: effects of a martial arts training program on collegiate students

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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 Arnis, a Filipino martial art, is recognized for its potential to enhance physical fitness, yet its comprehensive impact on health-related fitness remains underexplored. Therefore, this study investigated the effect of the Arnis Training program (ATG) on Health-related Physical fitness of untrained Collegiate Students.

Material and Methods The study randomly selected 192 college students, divided into two groups: Arnis Training (n=96) and Random Physical Activity (n=96). The ATG participated in a 10-week program with sparring and Anyo sessions, three times a week for 60–90 minutes, led by a certified instructor. The Random Physical Activity Group (RPAG) engaged in self-selected physical activities, following the same schedule. Pretesting and post-testing measured endurance, strength, and body composition using five tests: one-minute push-up, planking, three-minute step, 1 Repetition Max Bench Press (1RMBP), Back Squat (1RMBS), and a Skin Caliper test for lean body mass (LBM) and fat mass (FM). Post-testing occurred three days after the training to minimize fatigue. Paired t-tests were used for within-group comparisons, and independent t-tests for between-group comparisons.

Results Results indicated that Arnis training improved overall health-related fitness for all, especially females. Males did not gain in cardiovascular endurance or fat mass. The RPAG achieved better squatting strength and LBM for all, with males showing gains in cardiovascular fitness and fat mass. Moreover, the ATG outperformed in most areas except squatting strength, with females displaying notably higher fitness components than those in RPAG. The findings suggest Arnis effectively enhances fitness, particularly for females, though sex-specific requirements necessitate tailored programs emphasizing cardio or fat-reduction.

Conclusions The findings emphasize that ATG and RPAG training programs led to notable fitness improvements, but the ATG program showed more consistent gains across various fitness components. This suggests incorporating Arnis training into fitness programs could be highly beneficial, particularly for enhancing cardiovascular endurance, strength, and body composition. With its emphasis on agility, coordination, and strength, Arnis may offer a holistic approach to improving overall fitness. Its potential as a comprehensive training tool highlights the value of integrating martial arts-based programs into physical education and sports regimens to promote better health outcomes. This study underscores the importance of exploring diverse training methods like Arnis to optimize fitness and physical performance.

Keywords: Arnis, martial art, physical fitness, untrained collegiate students

Introduction

With the virtue of Republic Act no. 9850, Arnis is the National Martial art and Sport of the Philippines. This is commonly referred to as Eskrima or Kali. It focuses on combat with weapons such as sticks, knives, and other bladed instruments, as well as techniques using only the hands. The art of Filipino culture has a rich historical background, dating back to the pre-colonial era. It initially developed as a practical means of self-defense and then evolved into a form of artistic expression in resistance to colonial forces [1]. Arnis embodies the core principles of bravery and resourcefulness that define the Philippine society. Despite the efforts of colonizers to stifle its existence, this martial art has been discreetly safeguarded and transmitted over centuries. Today, Arnis is not only cherished as a sport but also as a fundamental aspect of Filipino cultural identity. It has been officially acknowledged as the national martial art and sport of the Philippines under the Republic Act 9850 [1]. Research emphasizes the societal and academic advantages of engaging in Arnis, demonstrating its contribution to enhancing physical well-being, self-control, and a sense of cultural identity among participants [2]. From a way of fighting for survival, martial arts, and sports, Arnis was widely practiced in the country of Philippines.

Physical fitness can be categorized into two aspects: health-related fitness components and skill-related fitness components. The first part pertains to the constituents of fitness that are

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crucial for maintaining a good physical appearance. Cardiovascular endurance, strength, and maintaining a good body composition, characterized by increased lean body mass and decreased fat mass, are crucial elements of physical fitness that provide multiple health advantages. Cardiovascular endurance improves cardiac health and promotes the effectiveness of the respiratory and circulatory systems, resulting in greater delivery of oxygen to tissues and enhanced elimination of metabolic waste products [3]. Strength and muscular endurance have a crucial role in total physical performance, metabolic rate, and injury prevention, especially as persons get older [4]. Increased lean body mass is correlated with enhanced muscle function, higher metabolic rate, and decreased vulnerability to frailty. Conversely, decreased fat mass is associated with reduced risks of cardiovascular diseases and comorbidities such as type 2 diabetes [5, 6]. Consistent participation in both aerobic and resistance training has been proven to promote these aspects of physical fitness. This, in turn, improves the quality of life and increases lifespan by reducing the risk factors for diseases and preserving functional independence [7]. For untrained individuals, their physical fitness components are essential as they are requirements for a healthy body, and also a prerequisite for sports participation

Moreover, previous studies have explored the usage of martial arts as a way to improve physical fitness among various populations. Martial arts instruction greatly improves physical and technical skills among different groups of people. Research suggests that tailored martial arts training boosts stability, strength, and endurance in college students, leading to notable improvements in fitness and technical proficiency [8]. Furthermore, research has demonstrated that implementing organized physical training programs can enhance both general physical fitness and the level of sports performance among martial arts athletes [9]. Studies examining the practice of intense martial arts among adults have found that it leads to enhancements in balance, cognitive abilities, and psychological well-being. These findings suggest that there are possible health advantages that can extend into old age [10]. In addition, balancing training specifically improves the functional performance of martial arts athletes by enhancing the execution of complicated movements [11]. Engaging in rigorous martial arts training has been found to have positive effects on physical fitness among senior individuals, indicating its potential as a healthy exercise for aging populations [12]. In addition, research has demonstrated notable enhancements in various aspects of physical fitness, including cardiorespiratory fitness, speed, agility, strength, flexibility, coordination, and balance, as a result of children participating in martial arts programs. This highlights the practical value of incorporating martial arts into physical education [13]. These studies highlight the importance of martial arts in enhancing physical well-being and technical skills in people of all age groups. With this, previous studies demonstrates that martial arts training significantly enhances physical fitness and technical skills in individuals of all ages, improving stability, strength, endurance, cognitive abilities, and overall well-being.

Furthermore, recent studies have investigated the potential of Arnis, the national martial art of the Philippines, as a form of training for improving physical fitness, specifically in terms of balance and functional strength among older individuals. A pilot study by Lipardo et al. [14] conducted a randomized controlled trial to evaluate the effects of a 12-week moderate-intensity Arnis-based program on balance control, fear of falling, and lower limb functional strength in older individuals living in the community. Another study by Barlis et al. [15] was conducted to assess the practicality and efficacy of a workout program based on Arnis, with a specific focus on enhancing static and dynamic balance control. The Delphi approach was employed to incorporate expert feedback into the design and evaluation of the program. This research plan [15] outlined a qualitative exploratory method for creating and customizing an exercise program centered around Arnis, with the explicit goal of diminishing the likelihood of falls and enhancing balance in older individuals.

Therefore, these studies indicate that exercise regimens based on Arnis might greatly enhance important physical health features, such as balance and functional strength, in the aged population. This can potentially decrease the likelihood of falls and increase overall quality of life. Incorporating cultural practices such as Arnis into fitness routines for older adults not only enhances physical well-being but also fosters the conservation of cultural heritage.

Despite existing studies on Arnis as a medium for improving physical fitness, several gaps remain. Current research primarily focuses on the effects of Arnis training on balance and functional strength in older adults, while other important aspects, such as cardiovascular health, agility, and mental health benefits, have not been thoroughly explored. Additionally, many studies lack robust control groups for comparative analysis, limiting the ability to isolate the specific benefits of Arnis training. Furthermore, the reliance on qualitative data and self-reports in existing studies introduces biases, and objective measurements are needed to provide insights into the effectiveness of Arnis [16]. Therefore, the present study examined the effects of Arnis training on key health-related physical fitness components among state university students. This research seeks to contribute to a more comprehensive understanding of the benefits of Arnis as a form of physical exercise.

Materials and Methods

Participants

The study involved 192 untrained collegiate students from a state university selected through random sampling. The participants were divided into two equal groups: the Arnis Training Group (ATG) and the Random Physical Activity Group (RPAG). The ATG received the Arnis training program, while the RPAG engaged in their preferred physical activities. Table 1 displays the sex distribution of the participants. Nearly half of the Arnis Training Group participants were female, with the rest being male. The Random Physical Activity Group had slightly fewer female participants than males. Both groups consisted of 96 participants, making up a total of 192 individuals in the study.

Table 1. Sex distribution of the Participants

Group	Female		Male		Total	
	n	%	n	%	n	%
Arnis Training Group (ATG)	49	25.52	47	24.48	96	50.00
Random Physical Activity Group (RPAG)	45	23.44	51	26.56	96	50.00
Total	94	48.96	98	51.04	192	100.00

Table 2 presents the participants' demographic profiles, including height, weight, and Body Mass Index (BMI). The ATG had a higher mean height than the RPAG. Regarding weight, the ATG also had a higher mean than the RPAG. Lastly, the ATG had a lower mean BMI than the RPAG.

Table 2. Demographic profile of the participants

Group	Height (cm)	Weight (kg)	BMI (kg/m²)
Arnis Training Group (ATG)	176.23±5.21	68.32±8.21	26.32±2.31
Random Physical Activity Group (RPAG)	172.89±3.23	65.55±6.32	27.31±1.68
Total	174.56±2.11	66.96±7.23	26.82±3.21

Ethical considerations

Participants were given a comprehensive briefing on the study, which included an explanation of their rights and the study's purpose. They were then asked to provide consent by signing a consent form. Following this, a Physical Readiness Questionnaire (PAR-Q) was administered to identify any underlying medical conditions that could affect participation. All data collected were treated with the utmost confidentiality.

Procedures

The pretesting involved collecting data on the health-related physical fitness components of the participants, which included Cardiovascular Endurance, Strength, Muscular Endurance, and Body Composition. The field tests used were the three-minute step test, 1-repetition max of bench press and squat, one-minute push-up test, plank test, lean body mass, and fat mass measurements. The data collection spanned two days to minimize the fatigue effect of the tests on subsequent assessments. Furthermore, the implementation phase involved applying the training program or physical activity specifically intended for both groups. For the Arnis Training Group, a 10-week Arnis training program consisting of a combination of sparring and Anyo (forms) was implemented. This was conducted under the instruction of a certified Arnis instructor affiliated with the Philippine Eskrima Kali Arnis Federation, the National Sports Association for Arnis in the Philippines. Each week consisted of three sessions, each lasting 60-90 minutes. On the other hand, participants in the Random Physical Activity Group were asked to engage in their preferred physical activities and record them for an hour [17]. This was done with the same duration and frequency of sessions. Lastly, the post-testing was conducted three days after the implementation phase for both groups. The same protocol was used to administer the aforementioned field tests.

Instruments

In collecting data on the health-related physical fitness components, several component-specific field tests were utilized. For cardiovascular endurance, the Three-Minute Step Test was used. Strength was measured through the 1 Repetition Maximum Test of the bench press and back squat. Muscular endurance was assessed through the One-Minute Push-Up Test and the Plank Test. The use of two field tests per fitness component was employed to ensure specificity in body parts. Lastly, for body composition, the Skin Caliper Test was used to measure the lean body mass and fat mass of the participants.

Statistical Analysis

To assess the potential effects of the two training regimens, inferential statistics were employed. For within-group comparisons, the paired t-test was used. On the other hand, comparisons between the two groups or between-group comparisons were conducted using the independent sample t-test. The study adopted $p < .05$ as the standard level of significance.

Results

Table 3 presents within-group comparisons evaluating the effects of the two implementations. For the ATG, significant improvements were observed across most fitness components. Cardiovascular endurance improved, as three-minute step test (TMST) scores decreased by approximately 3.5 seconds (*p* <.05). Strength improvements were evident in both horizontal pushing (*p* <.05) and squatting movements (*p* <.05). Muscular endurance gains were particularly notable, with one-minute push-up test (OMPUT) scores rising by approximately 5 repetitions and planking test (PT) scores increasing by nearly 6 seconds (both *p* <.05). Additionally, lean body mass (LBM) rose, while fat mass (FM) decreased slightly (*p* <.05), highlighting the interventions' effectiveness. For the RPAG, results were mixed. Significant gains were observed in squatting strength (*p* <.05) and core muscular endurance (*p* <.05). However, changes in cardiovascular endurance, horizontal pushing strength, lean body mass, and fat mass were either insignificant or minimal, indicating limited effects on these variables.

The present study includes a sex-specific investigation of the within-group comparisons. Table 4 presents the data for female participants. For the ATG, significant improvements were observed across all fitness components. Cardiovascular endurance increased (*p* <.05), accompanied by notable enhancements in strength for both horizontal pushing (*p* <.05) and squatting movements (*p* <.05). Muscular endurance in horizontal pushing (*p* <.05) and core strength (*p* <.05) also showed substantial improvements. Additionally, lean body mass increased significantly (*p* <.05), while fat mass decreased significantly (*p* <.05), highlighting the intervention's effectiveness in this group. In contrast, the RPAG showed mixed results. Cardiovascular endurance (*p* <.05) and strength in squatting movements (*p* <.05) significantly improved, as did muscular endurance in horizontal pushing (*p* <.05) and core strength (*p* <.05). Lean body mass also exhibited a significant increase (*p* <.05). However, fat mass changes were insignificant (*p* =.13), and strength in horizontal pushing movements showed minimal improvement (*p*=.21), indicating a more modest impact of the intervention in this group.

For male participants, Table 5 shows that, for the ATG group, cardiovascular endurance exhibited an insignificant decrease, with TMST scores showing no significant change (*p* = .15). However, strength in horizontal pushing movements significantly increased, as indicated by the 1RMBP scores (*p* <.05). Strength in squatting movements also significantly improved, with 1RMBS scores showing a statistically significant rise (*p* <.05). Muscular endurance in horizontal pushing significantly enhanced, as reflected by the OMPUT scores (*p* <.05). Core muscular endurance saw significant improvement, with PT scores showing a significant increase (*p*

Table 3. Within-group comparison of ATG and RPAG of all participants

Test Variables	PRETEST	POST TEST	*t*-value	*p*-value
		ATG		
TMST	130.75 ± 5.94	127.23 ± 5.94	4.11	p<.05
1RMBP	56.17 ± 7.44	60.07 ± 7.44	-3.63	p<.05
1RMBS	76.03 ± 6.42	80.78 ± 6.42	-5.13	p<.05
OMPUT	33.27 ± 5.90	38.09 ± 5.90	-5.65	p<.05
PT	65.37 ± 4.81	71.23 ± 4.81	-8.44	p<.05
LBM	66.96 ± 6.81	70.73 ± 6.81	-3.84	p<.05
FM	24.9 ± 4.94	23.705 ± 4.94	1.68	p<.05
		RPAG		
TMST	135.11 ± 9.03	136.72 ± 9.03	-1.23	0.065
1RMBP	53.86 ± 9.67	53.02 ± 9.67	0.61	0.036
1RMBS	77.38 ± 4.45	81.15 ± 4.45	-5.86	p<.05
OMPUT	28.12 ± 8.13	26.37 ± 8.13	1.5	0.23
PT	61.62 ± 5.76	63.18 ± 5.76	-1.87	p<.05
LBM	60.21 ± 6.11	63.79 ± 6.11	-4.06	0.12
FM	32.4 ± 9.33	31.48 ± 9.33	0.6	0.64

Note: Mean and Standard deviation are presented as M±SD. Test of significance is at p <.05. Legend: ATG-Arnis training group, RPAG- Random physical activity group, TMST- Three minute step test, 1RMBP- 1 Repetition max of bench press, 1RMBS- Back squat, OMPUT- One-minute push up test, PT- Planking test, LBM- Lean body mass, FM- Fat mass.

Table 4. Within-group comparison of ATG and RPAG of female participants

Test Variables	PRETEST	POST TEST	*t*-value	*p*-value
		ATG		
TMST	136±6.12	130.35±4.23	7.44	<.05
1RMBP	53.12±5.62	56.12±5.45	-3.75	<.05
1RMBS	72.47±8.96	78.47±6.30	-5.37	<.05
OMPUT	32.12±1.32	35.55±1.89	-14.58	<.05
PT	62.87±4.68	67.47±1.99	-8.86	<.05
LBM	65.21±9.32	70.45±8.92	-3.98	<.05
FM	25±3.12	24.11±1.65	2.47	<.05
		RPAG		
TMST	140.22±1.12	138.23±2.12	8.13	<.05
1RMBP	50.82±10.62	52.23±3.2	-1.25	.21
1RMBS	69.81±5.91	71.14±3.21	-1.94	<.05
OMPUT	25.02±1.82	26.01±3.2	-2.63	<.05
PT	50.87±2.68	51.66±1.24	-2.62	<.05
LBM	55.21±2.35	56.87±6.7	-2.29	<.05
FM	30±6.23	31.65±8.45	-1.54	.13

Note: Mean and Standard deviation are presented as M±SD. Test of significance is at p <.05. Legend: ATG- Arnis training group, RPAG- Random physical activity group, TMST- Three minute step test, 1RMBP- 1 Repetition max of bench press, 1RMBS- Back squat, OMPUT- One-minute push up test, PT- Planking test, LBM- Lean body mass, FM- Fat mass.

Table 5. Within-group comparison of ATG and RPAG of male participants

Test Variables	PRETEST	POST TEST	*t*-value	*p*-value
		ATG		
TMST	125.5 ± 9.32	124.1 ± 1.82	1.44	.15
1RMBP	59.22 ± 5.62	64.02 ± 1.62	-8.04	<.05
1RMBS	79.59 ± 4.08	83.09 ± 9.28	-3.38	<.05
OMPUT	34.42 ± 5.82	40.62 ± 5.71	-7.45	<.05
PT	67.87 ± 6.98	74.99 ± 3.78	-8.79	<.05
LBM	68.71 ± 5.20	71.01 ± 2.94	-3.77	<.05
FM	24.8 ± 7.92	23.31 ± 3.62	1.68	.09
		RPAG		
TMST	130.0 ± 12.52	135.2 ± 17.02	-2.41	<.05
1RMBP	56.9 ± 20.62	53.8 ± 18.30	1.1	.27
1RMBS	84.95 ± 18.42	91.15 ± 24.42	-1.99	.06
OMPUT	31.22 ± 20.32	26.72 ± 15.68	1.72	.09
PT	72.37 ± 4.68	74.69 ± 8.78	-2.28	.06
LBM	65.21 ± 21.18	70.71 ± 24.58	-1.66	.10
FM	34.8 ± 12.72	31.3 ± 10.22	2.1	<.05

Note: Mean and Standard deviation are presented as M±SD. Test of significance is at p <.05. Legend: ATG- Arnis training group, RPAG- Random physical activity group, TMST- Three minute step test, 1RMBP- 1 Repetition max of bench press, 1RMBS- Back squat, OMPUT- One-minute push up test, PT- Planking test, LBM- Lean body mass, FM- Fat mass.

<.05). Lean body mass also significantly increased, with LBM scores reflecting a notable rise (*p* <.05). However, changes in fat mass were insignificant, as FM scores showed no significant difference (*p* = .09). For the RPAG group, cardiovascular endurance significantly decreased, with TMST scores indicating a significant change (*p* <.05). Strength in horizontal pushing movements showed an insignificant decrease, with 1RMBP scores not reflecting a statistically significant change (*p* = .27). Strength in squatting movements exhibited a small but insignificant increase, with 1RMBS scores approaching statistical significance (*p* <.06). Muscular endurance in horizontal pushing showed improvement, but the change was not statistically significant (*p* = .09). Core muscular endurance showed an insignificant increase, with PT scores approaching significance (*p* <.06). Lean body mass showed an insignificant increase, with LBM scores not reaching statistical significance (*p* =.10). Fat mass significantly decreased, with FM scores showing a significant reduction (*p* <.05).

The study also included a between-group comparison to determine the superior training regime in terms of improving health-related fitness. An independent sample t-test was used for data analysis. Table 6 presents the results for all participants. The ATG group demonstrated superior cardiovascular endurance, with TMST scores significantly higher than those of the comparison group (*p* <.05). Similarly, ATG exhibited greater strength in horizontal pushing, as measured by the 1RMBP, with a significant difference (*p* <.05). No significant difference was observed in squatting strength between ATG and the comparison group, as evaluated by the 1RMBS (*p* = .65). Additionally, ATG showed higher muscular endurance in horizontal pushing, as indicated by the OMPUT, and stronger core muscular endurance, measured by the PT, with significant differences for both (*p* <.05). ATG also had a higher lean body mass and a lower fat mass, both showing significant differences (*p* <.05), reflecting overall better physical composition.

Table 7 shows the data for female participants in between-group comparisons. Cardiovascular endurance, as measured by the TMST, revealed that the AT group had a significantly higher score compared to the RPA group (*p* <.05). Horizontal pushing strength, assessed through the 1RMBP, was also higher in the AT group, with a significant difference (*p* <.05). Similarly, squat movement strength, measured by the 1RMBS, demonstrated that the AT group had superior strength compared to the RPA group, with a significant p-value (*p* <.05). Muscular endurance in horizontal pushing, as measured by the OMPUT, showed that the AT group outperformed the RPA group, with a highly significant p-value (*p* <.05). Core muscular endurance, assessed by the PT, indicated that the AT group had superior performance compared to the RPA group, also with a significant p-value (*p* <.05). Lean body mass comparisons revealed that the AT group had a higher lean body mass than the RPA group, with a notable p-value difference (*p* <.05). Lastly, fat mass was lower in the AT group compared to the RPA group, signifying another significant difference (*p* <.05). These findings collectively highlight that the AT group demonstrated superior effects across selected health-related physical fitness components.

Lastly, Table 8 presents the data for male participants in the between-group comparison. Cardiovascular endurance, measured through the TMST, indicated that the ATG group had higher endurance than the RPAG group, with a statistically significant difference (*p* <.05). The ATG group also showed greater strength in horizontal pushing, as assessed by the 1RMBP, and superior muscular endurance in the same activity, as measured by the OMPUT, both with significant p-values (*p* <.05). However, the RPAG group outperformed ATG in squat movement strength, a significant finding (*p* <.05). Muscular endurance of the core, measured by PT, and lean body mass did not show significant

Table 6. Between-group comparison of ATG and RPAG of all participants

Test Variables	ATG	RPAG	*t*-value	*p*-value
TMST	127.225 ± 5.94	136.715 ± 9.03	-8.60	<.05
1RMBP	60.07 ± 7.44	53.015 ± 9.67	5.67	<.05
1RMBS	80.78 ± 6.42	81.145 ± 4.45	-0.46	.65
OMPUT	38.085 ± 5.90	26.365 ± 8.13	11.43	<.05
PT	71.23 ± 4.81	63.175 ± 5.76	10.52	<.05
LBM	70.73 ± 6.81	63.79 ± 6.11	7.43	<.05
FM	23.705 ± 4.94	31.475 ± 9.33	-7.21	<.05

Note: Mean and Standard deviation are presented as M±SD. Test of significance is at p <.05. Legend: ATG- Arnis training group, RPAG- Random physical activity group, TMST- Three minute step test, 1RMBP- 1 Repetition max of bench press, 1RMBS- Back squat, OMPUT- One-minute push up test, PT- Planking test, LBM- Lean body mass, FM- Fat mass.

Table 7. Between-group comparison of ATG and RPAG of female participants

Test Variables	ATG	RPAG	*t*-value	*p*-value
TMST	130.35±4.23	136±6.12	-7.44	<.05
1RMBP	56.12±5.45	53.12±5.62	3.75	<.05
1RMBS	78.47±6.30	72.47±8.96	5.37	<.05
OMPUT	35.55±1.89	32.12±1.32	14.58	<.05
PT	67.47±1.99	62.87±4.68	8.86	<.05
LBM	70.45±8.92	65.21±9.32	3.98	<.05
FM	24.11±1.65	25±3.12	-2.47	<.05

Note: Mean and Standard deviation are presented as M±SD. Test of significance is at p <.05. Legend: ATG- Arnis training group, RPAG- Random physical activity group, TMST- Three minute step test, 1RMBP- 1 Repetition max of bench press, 1RMBS- Back squat, OMPUT- One-minute push up test, PT- Planking test, LBM- Lean body mass, FM- Fat mass.

Table 8. Between-group comparison of ATG and RPAG of male participants

Test Variables	ATG	RPAG	*t*-value	*p*-value
TMST	124.1 ± 1.82	135.2 ± 17.02	-6.35	<.05
1RMBP	64.02 ± 1.62	53.8 ± 18.30	5.45	<.05
1RMBS	83.09 ± 9.28	91.15 ± 24.42	-3.02	<.05
OMPUT	40.62 ± 5.71	26.72 ± 15.68	8.16	<.05
PT	74.99 ± 3.78	74.69 ± 8.78	0.31	0.76
LBM	71.01 ± 2.94	70.71 ± 24.58	0.12	0.91
FM	23.31 ± 3.62	31.3 ± 10.22	-7.22	<.05

Note: Mean and Standard deviation are presented as M±SD. Test of significance is at p <.05. Legend: ATG- Arnis training group, RPAG- Random physical activity group, TMST- Three minute step test, 1RMBP- 1 Repetition max of bench press, 1RMBS- Back squat, OMPUT- One-minute push up test, PT- Planking test, LBM- Lean body mass, FM- Fat mass.

differences between the groups ($p = 0.76$ and $p = 0.91$, respectively). Lastly, ATG exhibited a significantly lower fat mass compared to RPAG, highlighting differences in body composition ($p < .05$).

Discussion

The present study used a group pretest-posttest design which included within-group and between-group comparisons to investigate the effect of the Arnis training program and random physical activity on health-related physical fitness components. Furthermore, the two groups were compared in terms of their effect on the said components.

ATG within-group comparison

For the Arnis Training Group, all of the health-related physical fitness components were improved by Arnis training. A set of previous studies was in support of this claim, suggesting that martial arts improve the physical fitness of an individual. Cardiovascular endurance or aerobic capacity was improved by martial arts training according to the present study. This is the same case for the previous studies by Soo Bahk Do based on the aerobic capacity among the sedentary population [17]. The same is true for MMA athletes [18]. Compared to traditional aerobic classes, martial arts are superior in improving aerobic capacity. Using the Harvard Step Test, martial arts training has been shown to increase aerobic capacity [19].

For strength, previous studies support the present study by suggesting that martial arts training improves the strength of individuals. Martial arts training significantly enhances strength, as demonstrated in a 12-week program that improved university athletes' strength by Peng [20]. Similarly, Wan [9] confirmed that the effectiveness of martial arts in boosting strength and sports performance. Balance training in martial arts not only enhances balance but also increases strength, thus improving athletic performance [11]. Additionally, core strength training has been shown to significantly boost core stability and strength [21]. These studies collectively highlight martial arts as a potent tool for developing strength among practitioners. In relation to muscular endurance, previous studies supported the claim that martial arts training like arnis improves muscular endurance. Increasing dynamic strength and endurance is crucial for executing combat movements repeatedly in combat sports, emphasizing the essential role of martial arts training for success in these disciplines [22]. Specific martial arts fitness training significantly enhances strength and endurance among university martial arts practitioners [23].

The present study aligns with existing literature that supports the notion that martial arts training can enhance body composition across various populations. For example, Kung Fu training has been demonstrated to maintain or improve central adiposity among overweight/obese adolescents, suggesting beneficial effects on body composition [24]. In overweight/obese premenopausal women, Chyu et al. [25] observed that 12 weeks of martial arts exercise led to significant changes in body composition, including reductions in fat-free and muscle mass. Furthermore, Tota et al. [26] found that conditioning training in elite mixed martial arts athletes resulted in decreases in body fat mass and improvements in both anaerobic and aerobic performance. Therefore, research on various martial arts disciplines shows they can positively affect body composition by reducing body fat percentage and increasing lean muscle mass [27]. However, the present study contradicts a systematic review and meta-analysis that found no significant benefits of martial arts interventions on body composition in overweight and obese subjects, highlighting the need for further high-quality research [28]. Lastly, the current study additionally examined the sex-specific impact of the ATG on physical fitness. ATG did not lead to improvements in cardiovascular endurance and fat mass for male participants. Exclusively for the female participants. The indicated training led to improvements in all of the components.

RPAG within-group comparison

In the present study, RPAG within-group comparison suggested that all participants experienced improvements in squatting strength and lean body mass. Additionally, random physical activity was found to enhance muscular endurance in horizontal pushing and the core, as well as flexibility in the hamstrings and cardiovascular endurance [16]. However, female participants did not show improvements in the strength of horizontal pushing or lean body mass. The same study also noted that random physical activity improves muscular endurance of horizontal pushing, flexibility of the hamstrings, and cardiovascular endurance [16]. Lastly, male participants showed improvements in cardiovascular fitness and fat mass. Contrary to these findings, the study suggests that there were insignificant changes in muscular endurance of horizontal pushing, flexibility of the hamstrings, and cardiovascular endurance for male participants [16].

Between-group comparison

For between group comparison, it was suggested that except of strength of squatting movement, all of the health-related fitness components were higher in ATG. Various comparative studies examine the contrast between martial arts training and non-martial arts physical activities, such as general physical fitness programs and sports. Previous research has proven that martial arts training is highly effective in enhancing physical fitness. Comparatively, martial arts training has demonstrated substantial advantages in enhancing physical fitness, as opposed to other fitness programs.

An empirical investigation discovered that the incorporation of martial arts fitness training into regular training significantly improves stability and strength in university practitioners. This makes it a powerful approach to develop fitness in this particular population [20]. A separate study emphasized the efficacy of balance training in martial arts, leading to notable enhancements in sports fitness measures such as balance and functional indices. This research underscores the usefulness of balance training in improving the fitness of martial artists [11]. Furthermore, a comparison analysis conducted on adolescents participating in martial arts, team sports, and non-sports activities revealed that martial arts have a greater positive impact on muscular endurance and flexibility compared to the other forms of physical activity [29]. Moreover, a study by Olaru [30] shown that functional training in martial arts has a substantial impact on enhancing endurance, flexibility, and shoulder girth. This highlights the advantages of integrating functional training methods.

Moreover, apart from squatting strength, all health-related fitness components were higher in the ATG compared to the RPAG. Sex specificity was targeted by the study by providing sex-specific results. Male participants showed no significant differences in muscular endurance of the core and lean body mass, whereas female participants exhibited higher fitness components than those in the ATG. However, overall, the RPAG had lower scores on health-related fitness components, with female participants notably experiencing lower scores across all measured components.

Conclusions

The strength of this study lies in its comprehensive evaluation of the Arnis Training Group (ATG), which showed significant improvements across various fitness components. The ATG demonstrated notable benefits in cardiovascular endurance, strength, muscular endurance, lean body mass, and fat mass. These findings suggest that Arnis training is an effective intervention for enhancing overall fitness, especially compared to the more limited effects observed in the control group. However, the study's limitations include the short duration of the intervention and the absence of a broader range of fitness assessments. Future research should explore the longer-term effects of Arnis training and its impact on psychological outcomes such as motivation and mental resilience. Additionally, studies could further investigate the benefits of Arnis training in different populations to validate its effectiveness in improving physical health and fitness.

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Conflict of interests

The author declare that there is no conflict of interests.

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ORIGINAL ARTICLE

Effects of 3x3 progressive cycling interval training on cardiovascular fitness and body composition in overweight undergraduates

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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 Obesity has become a global health concern and high-intensity interval training (HIIT) has emerged as an effective exercise modality for improving body composition, promoting weight loss, and increasing cardiovascular fitness. This study aimed to investigate the effects of progressive 3 by 3 cycling interval training on cardiovascular fitness and body composition in overweight individuals.

Material and Methods Fifteen overweight undergraduate students were recruited (age = 20.2 ± 0.7 years; body weight = 78.2 ± 16.2 kg; BMI = 27.2 ± 3.7 kg/m^2; height = 168.9 ± 8.0 cm). The participants engaged in an 8-week progressive 3 by 3 cycling interval training program, consisting of 3 sessions per week. Body composition was measured using bioelectrical impedance analysis, blood lipid profiles were tested, and maximum oxygen consumption (VO_2max) was assessed at baseline and after the intervention. A one-way ANOVA was conducted to evaluate changes between pre- and post-intervention measurements.

Results The findings demonstrated that there were no significant changes in body composition parameters, including body weight, BMI, body fat percentage, fat mass, and visceral fat (all $p > 0.05$, all ES = Trivial). Similarly, blood lipid profile parameters were also not significantly changed between pre-intervention and post-intervention (all $p > 0.05$, all ES = Trivial). However, VO_2max significantly increased after 8 weeks of training (95% CI = 1.27–8.25 ml·kg^{-1}·min^{-1}, ES = Moderate, $p = 0.011$).

Conclusions The progressive 3 by 3 cycling interval training was effective in enhancing cardiovascular fitness in overweight individuals and may help reduce cardiovascular risk associated with low VO_2max.

Keywords: high intensity interval training, cycling interval training, VO_2max, obesity, body composition

Introduction

Obesity has emerged as a significant global health concern, contributing to various chronic conditions and reduced quality of life. High-intensity interval training (HIIT) has gained attention as an effective approach for improving cardiovascular fitness and managing body composition. The problem of excess weight is increasingly affecting the student population, highlighting the need for more effective solutions.

In this context, obesity has become a global health concern, affecting individuals across all age groups and socioeconomic statuses [1]. Characterized by the excessive accumulation of body fat and a high body mass index (BMI), obesity significantly increases the risk of numerous health complications, including cardiovascular disease, type 2 diabetes, and certain cancers [2]. The condition also places a considerable economic burden on healthcare systems worldwide, contributing to increased medical costs and reduced productivity [3]. Obesity is not limited to middle-aged or older adults; it also affects younger individuals and is often driven by a combination of poor dietary habits and sedentary lifestyles [4]. Furthermore, the chronic low-grade inflammation associated with obesity exacerbates metabolic dysfunction, leading to insulin resistance and dyslipidemia [5]. Addressing obesity requires a multifaceted approach that incorporates lifestyle interventions, such as dietary modifications and regular physical exercise programs [6].

For exercising, high-intensity interval training (HIIT) has emerged as an effective exercise modality for improving body composition and promoting weight loss [7]. HIIT alternates short bursts of intense physical activity with recovery periods, making it time-efficient and adaptable for various populations [8]. It has been studied for its ability to increase cardiovascular fitness, enhance metabolic rate, improve fat oxidation, and preserve lean muscle mass [9, 10, 11]. Unlike traditional steady-state aerobic exercise, HIIT induces greater post-exercise oxygen consumption, further accelerating caloric expenditure [12]. These versatile benefits make HIIT a valuable tool in combating obesity and promoting sustainable weight management.

Maximal oxygen uptake (VO_2max) is a critical indicator of cardiovascular fitness [13]. It reflects

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the body's capacity to utilize oxygen during intense physical activity, closely linking it to aerobic fitness [14]. A higher VO_2max is associated with reduced risks of cardiometabolic disorders, including hypertension, dyslipidemia, and type 2 diabetes [15, 16, 17]. Conversely, low VO_2max levels are predictive of increased morbidity and mortality related to non-communicable diseases [16]. Enhancing VO_2max and improving body composition through structured exercise, such as HIIT, has garnered significant research interest.

The analysis of research findings has shown that obesity is a significant global health issue affecting all age groups, including students. High-intensity interval training (HIIT) has proven to be an effective and time-efficient method for improving cardiovascular fitness and managing body composition. HIIT enhances VO_2max, improves metabolic efficiency, and preserves lean muscle mass, making it a valuable tool for combating obesity and reducing associated health risks. Accordingly, this study aims to investigate the effects of progressive 3 by 3 cycling interval training on cardiovascular fitness and body composition in overweight undergraduates.

Materials and Methods

Participants

A priori power analysis for sample size estimation was performed using G*Power version 3.1.9.7, specifying a two-tailed t-test for dependent means (matched pairs) with an effect size of 0.80, an alpha level of 0.05, and a power of 0.80. This analysis determined a required sample size of 15 participants. Consequently, 15 overweight undergraduate students (9 males and 6 females) were recruited, with an average age of 20.2 ± 0.7 years, body weight of 78.2 ± 16.2 kg, BMI of 27.2 ± 3.7 kg/m^2, and height of 168.9 ± 8.0 cm. Eligibility criteria ensured that participants were free of functional limitations and had no history of medical conditions that would restrict high-intensity exercise. A registered physician conducted general health screenings, and informed written consent was obtained from all participants prior to the study.

All participants were provided with comprehensive information regarding the study procedures, potential benefits, and associated risks, and gave written informed consent prior to participation. The study protocol was approved by the Research and Innovation Administration of Burapha University Ethics Committee (Code: IRB1-107/2562) and adhered to the ethical principles outlined in the Declaration of Helsinki.

Research Design

This study utilized a single-group experimental design to evaluate the effects of cycling interval training on cardiovascular fitness and body composition in overweight undergraduate students. The participants consisted of young, overweight male and female undergraduates from the Faculty of Sport Science, with a body mass index (BMI) of $\geqslant$ 25 kg/m^2. Cardiovascular fitness was assessed using maximum oxygen consumption (VO_2max), and body composition was measured via bioelectrical impedance analysis, both pre-intervention and post-intervention. The participants underwent 8 weeks of cycling interval training, with a frequency of 3 sessions per week (Figure 1).

Body Composition Measurement

Body weight, body fat percentage, fat mass, and visceral fat were measured using bioelectrical impedance analysis (X-contact 356; Jawon Medical Co., Seoul, South Korea). To ensure consistency, participants were instructed to adhere to specific pre-assessment guidelines, including fasting from food and beverages (except water) for at least 6 hours prior to measurement, abstaining from alcohol and caffeine for 24 hours, and avoiding vigorous physical activity for 48 hours. Additionally, participants were required to obtain a minimum of 6 hours of sleep the night before the assessment to reduce variability caused by fatigue or dehydration. Measurements were conducted in the physiology laboratory at 8:00 a.m. to control for diurnal variations in body composition metrics. Assessments took place three days prior to the start of the experiment and three days after the final training session to ensure consistency in timing. Participants wore lightweight, comfortable

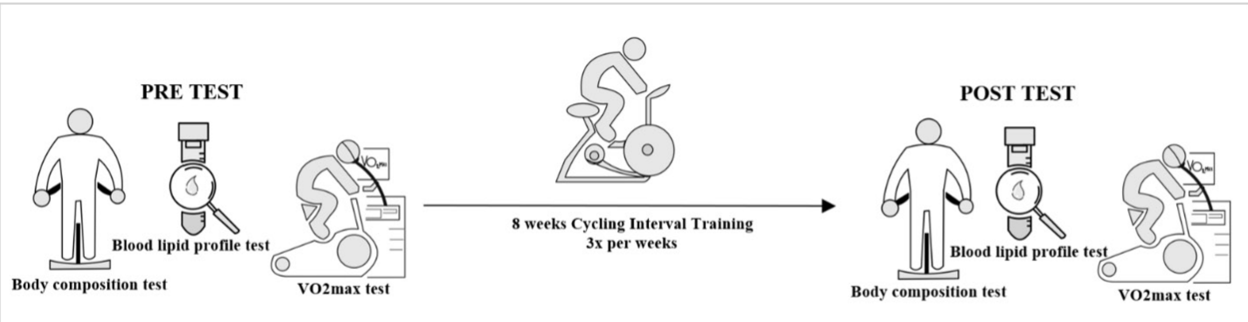

Figure 1. Study design.

clothing and removed all metal accessories during the measurement to prevent interference with the bioelectrical impedance device.

Blood lipid profile Test

A blood lipid profile test was conducted to evaluate participants' total cholesterol, high-density lipoprotein cholesterol (HDL-C), and low-density lipoprotein cholesterol (LDL-C) levels as indicators of health status. Blood samples were collected in the morning at approximately 9:00 a.m., following body composition measurements, in the university hospital's physiology laboratory. The assessments were performed three days prior to the start of the experiment and three days after the final training session. Participants were instructed to fast for at least six hours and refrain from exercise for 24 hours before testing. A 5 ml blood sample was drawn from each participant, and the analyses were conducted at the university hospital's pathology laboratory.

Maximum oxygen consumption assessment

On the same day, following the laboratory blood lipid profile test, maximum oxygen consumption (VO_2max) was assessed at approximately 11:00 a.m. using an incremental exercise protocol on a manually adjustable bicycle ergometer (Monark 828E, Sweden). The VO_2max test began with a 3-minute warm-up at a workload of 25 watts, followed by an increase in resistance by 25 watts each minute. Participants continued the test until they reached voluntary exhaustion due to fatigue. Oxygen consumption was continuously monitored using a breath-by-breath portable system (Oxycon Mobile, Hoechberg, Germany), and data were recorded every 30 seconds. The highest recorded 30-second oxygen consumption value was documented as the VO_2max. This VO_2max testing protocol adhered to the methodology described in a previously published study [18].

Cycling Interval Training

The cycling interval training was conducted on a stationary sprint bike (IC7 Indoor Cycle, Life Fitness, USA) and followed a protocol alternating between high-intensity intervals at 80–85% of heart rate reserve (HRR) and recovery periods at 50% HRR. HRR for each participant was calculated using Karvonen's formula (HRR = HRmax - HRrest). Heart rate was continuously monitored during each session with a heart rate monitor (H10, Polar, Finland). Participants trained in the morning three times per week over eight weeks, with session duration increasing progressively. In weeks 1–2, participants completed five sets of 3-minute intervals, totaling 30 minutes per session. This duration increased to six sets (36 minutes) in weeks 3–4, seven sets (42 minutes) in weeks 5–6, and eight sets (48 minutes) in weeks 7–8 (Table 1).

Table 1. Cycling Interval Training

Intensity	**Interval: 80 – 85%HRR** **Recovery: 50% HRR**
Frequency	3 sessions per week
Cycling Interval Training Protocol High intensity cycling : Recovery time x Numbers of sets (Total duration)	Week 1-2: 3:3 min x 5 sets (30minutes) Week 3-4: 3:3 min x 6 sets (36minutes) Week 5-6: 3:3 min x 7 sets (42minutes) Week 7-8: 3:3 min x 8 sets (48minutes)

Statistical analysis

The Shapiro-Wilk test was applied to assess data normality, and descriptive statistics were calculated to determine the mean and standard deviation of participants' baseline characteristics. A one-way ANOVA was used to compare participants' VO_2max, body composition metrics (body weight, body fat percentage, fat mass, and visceral fat), and blood test variables (LDL-C, HDL-C, and total cholesterol) between pre-intervention and post-intervention. Results were reported with changes and 95% confidence intervals (95% CI). Additionally, Cohen's effect sizes were calculated using the formula: mean change/pooled standard deviation. Effect sizes were interpreted as follows: 0.00–0.19 (Trivial), 0.20–0.49 (Small), 0.50–0.79 (Moderate), and ⩾0.80 (Large), in accordance with Cohen's criteria [19]. All statistical analyses were conducted using IBM SPSS Statistics version 21, with the significance level set at $\alpha = 0.05$.

Results

There was no significant difference in body composition parameters (all $p > 0.05$, all ES = Trivial) or blood lipid profile measurements (all $p > 0.05$, all ES = Trivial) between pre-intervention and post-intervention (Table 2). In contrast, VO_2max demonstrated a significant improvement following the 8-week intervention, with a mean increase of 4.76 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (Δ16.24%, 95% CI = 1.27–8.25 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, ES = Moderate, $p = 0.011$) (Figure 2).

The effect sizes of the changes observed in each parameter are illustrated in Figure 3, providing a visual representation of the magnitude of these effects and facilitating clearer interpretation of the intervention's impact.

Table 2. Changes in measurements between Pre- and Post-intervention

Measurement	Participants (n = 15)		Change (CI95%)
	Pre-intervention (Mean ± SD)	Post-intervention (Mean ± SD)	
Body weight (kg)	78.17 ± 4.18	77.81 ± 4.33	-0.37 (1.21; 0.47)
BMI (kg/m^2)	27.15 ± 0.96	27.02 ± 1.04	-0.13 (-0.44; 0.18)
Body fat (%)	29.27 ± 1.37	29.01 ± 1.45	-0.27 (-0.79; 0.26)
Fat mass (kg)	23.83 ± 1.91	22.89 ± 2.08	-0.94 (-2.53; 0.65)
Visceral fat (cm^2)	83.53 ± 7.57	81.73 ± 7.38	-1.80 (-3.77; 0.17)
VO_2max (ml/kg^{-1}/min^{-1})	29.31 ± 1.26	34.07 ± 1.94*	4.76 (1.27; 8.25)
Total cholesterol (mg/dl^{-1})	193.73 ± 10.89	190.47 ± 8.98	-3.27 (-12.98; 6.45)
LDL-C (mg/dl^{-1})	115.53 ± 10.18	112.40 ± 8.44	-3.13 (-15.67; 9.70)
HDL-C (mg/dl^{-1})	55.80 ± 2.49	54.80 ± 1.97	-1.00 (-5.21; 3.21)

Abbreviations: BMI = body mass index; LDL-C = low-density lipoprotein cholesterol; HDL-C = high-density lipoprotein cholesterol; VO_2max = maximum oxygen consumption. * indicated significant different from Pre-intervention ($p < 0.05$)

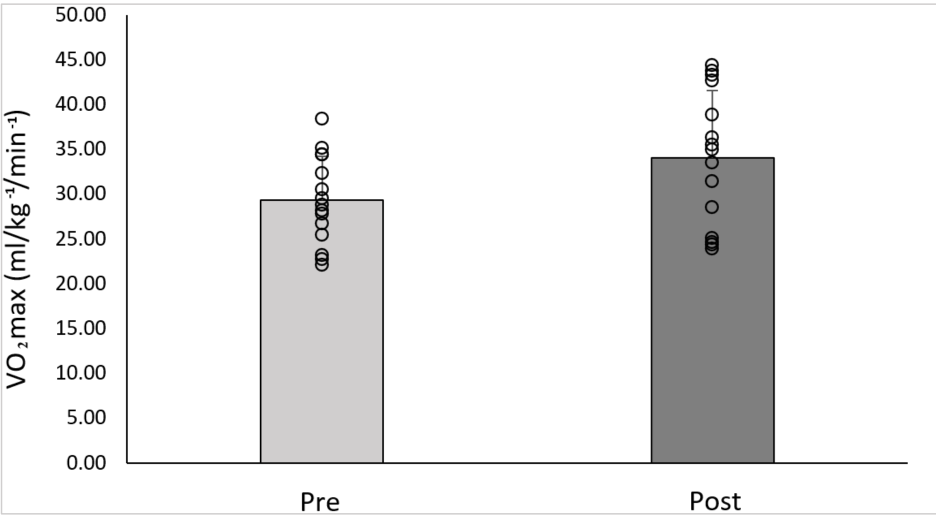

Figure 2. Means and standard deviations of maximum oxygen consumption (VO_2max) at pre-intervention and post-intervention, with individual analyses in open circle. * indicating significant different from pre-intervention (*p* < 0.05).

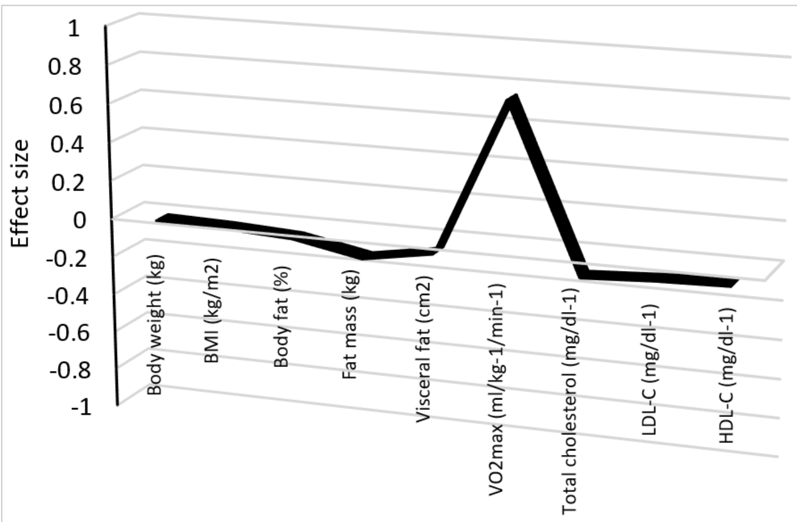

Figure 3. Cohen's effect sizes of each parameter.

Discussion

The findings of this study emphasized the potential of progressive cycling interval training to significantly enhance cardiovascular fitness, as reflected by an improvement in VO_2max. This outcome aligns with existing literature identifying certain types of HIIT as an alternative modality to steady-state exercise for improving aerobic capacity [20, 21, 22, 23]. The 16.24% improvement in VO_2max observed in this study demonstrates the effectiveness of structured progressive 3 by 3 cycling interval training protocols, even in overweight individuals. This increase in VO_2max is potentially associated with reduced cardiovascular risks and improved metabolic health [24], making it a critical target for intervention strategies in populations at risk of obesity-related comorbidities [10].

The absolute improvement in VO_2max in this study was 4.76 $ml \cdot kg^{-1} \cdot min^{-1}$, or approximately 0.28 $l \cdot min^{-1}$ (ES = 0.75). This level of improvement is consistent with findings from a previous meta-analysis, which reported a mean VO_2max increase of 0.26 $l \cdot min^{-1}$ (ES = 0.68) when interval training was performed at an intensity of 80–92.5% [25]. These results collectively suggest that the capacity for VO_2max improvement might not differ significantly between overweight and normal-weight healthy individuals. Furthermore, prior research demonstrated that VO_2max trainability in healthy individuals could reach up to 0.43–0.60 $l \cdot min^{-1}$ with training durations of 6 to 12 weeks [26]. This suggests that participants in the current study could achieve even greater VO_2max improvements if training were continued.

Despite the improvement in cardiovascular fitness, this study found no significant changes in body composition, including body weight, body fat percentage, or visceral fat (all $p > 0.05$). This finding challenges the commonly held assumption that HIIT is an effective standalone strategy for body weight or fat loss [27]. Similarly, previous research employing a battle rope HIIT protocol reported a significant increase in VO_2max by 3.68 $ml \cdot kg^{-1} \cdot min^{-1}$ but found no significant changes in participants' body composition [13]. Additionally, a previous study reported that participants undergoing resistance training without caloric restriction also failed to achieve body weight reduction [28].

Taken together, these findings highlight the importance of energy balance in achieving body composition changes, emphasizing that caloric intake must align with expenditure for fat loss to occur [29]. The absence of dietary control in this study likely contributed to the unchanged body composition, as participants might have compensated for the energy expenditure during exercise by increasing caloric intake [30]. Therefore, the findings underscore the need for combined interventions incorporating both structured exercise and dietary modifications to achieve meaningful changes in body composition.

Moreover, the lack of improvement in the blood lipid profile also warrants consideration. While aerobic exercise is generally associated with improved lipid metabolism [31], our results demonstrated no significant differences post-intervention. It is possible that the duration of this study's intervention was not sufficiently long to elicit measurable changes in this parameter among overweight individuals. Additionally, the trivial effect sizes suggest that more prolonged or higher-intensity training programs might be necessary to significantly influence lipid profiles [10]. Another potential factor is the variability in participants' baseline lipid levels, which might have masked subtle improvements.

In practical terms, this study contributes to the growing body of evidence supporting HIIT as an efficient exercise modality, particularly for improving cardiovascular fitness in time-constrained individuals [32]. The intentional progressive design of the protocol, which gradually increased session duration, likely enhanced adherence and minimized the risk of participant overtraining [33].

Moreover, the findings underscore the importance of tailoring interventions to specific health goals. Progressive cycling interval training proved highly effective for improving cardiovascular fitness; however, for individuals targeting fat loss or metabolic health, combining such protocols with dietary adjustments and other lifestyle changes may yield better outcomes.

Study Limitation

The single-group design of this study limits the generalizability of its findings, as there was no comparison group to assess the relative effectiveness of this protocol against alternative exercise modalities. Additionally, the small sample size and narrow demographic scope restrict the applicability of the results to broader populations.

Future research involving larger, more diverse cohorts and a comparative approach would provide more comprehensive insights. Such studies could also help practitioners manage expectations, emphasizing that no single exercise modality delivers immediate or universal benefits across all health parameters.

Conclusions

This study demonstrated that progressive 3 by 3 cycling interval training is an effective intervention for enhancing cardiovascular fitness in overweight individuals, as evidenced by a significant increase in VO_2max. However, its limited impact on body composition and blood lipid profiles suggests that HIIT alone may not suffice for comprehensive health improvements. These findings reinforce the importance of a multifaceted approach to obesity management, combining exercise, nutrition, and behavioral strategies to optimize health outcomes.

Acknowledgement

We sincerely thank all participants for their involvement in this study.

Conflict of Interest

The authors declare no conflict of interest.

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ORIGINAL ARTICLE

The effect of bodyweight circuit training on flexibility and strength endurance in male tennis 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 Flexibility and strength endurance are essential components of tennis performance. This study aims to evaluate the effectiveness of bodyweight circuit training (BCT) in enhancing flexibility and strength endurance in male university tennis players.

Material and Methods This study employed a true experimental design with a pretest-posttest control group. A total of 30 male tennis players, aged 19–23 years, were recruited from a university. Participants were randomly assigned to either a control group (CTr, n=15) or a training group (TRg, n=15) based on predefined criteria. The training group underwent a bodyweight circuit training (BCT) program three times per week for four weeks. Flexibility was assessed using the Sit and Reach Test. Strength endurance was evaluated through three tests: upper body strength endurance with the 60-second Push-Up Test, abdominal strength endurance with the 60-second Sit-Up Test, and back strength endurance with the 60-second Back Extension Test. Measurements were taken at baseline (pre) and after four weeks (post). Data analysis was conducted using paired and independent sample t-tests, with a significance level set at 5%.

Results Significant improvements in flexibility, upper body strength endurance, abdominal strength endurance, and back strength endurance were observed in the training group (TRg) between pre- and post-intervention ($p \leqslant 0.05$). In contrast, no significant changes were found in the control group (CTr) ($p \geqslant 0.05$). At baseline, no significant differences were detected between the TRg and CTr groups ($p \geqslant 0.05$). However, post-intervention analysis revealed significantly greater improvements in the TRg group compared to the CTr group ($p \leqslant 0.05$).

Conclusions BCT implementation in training programs may contribute to improved physical performance. These findings suggest that BCT could be integrated into structured training regimens to support athletic development.

Keywords: bodyweight circuit training, flexibility, strength endurance, tennis player

Introduction

Flexibility and strength endurance are essential components of tennis performance [1]. As a sport that involves rapid movements, precise shots, and high mobility, tennis requires stable muscle strength and optimal flexibility to enhance movement efficiency, reduce injury risk, and sustain endurance throughout matches [2]. Good flexibility allows players to reach difficult shots more easily, while high strength endurance supports consistent performance, particularly during extended rallies that demand greater physical resilience [3]. Limited flexibility can restrict movement and negatively impact performance, especially in strokes requiring maximum reach [4, 5]. Therefore, training programs that incorporate flexibility and strength endurance development are essential for tennis athletes.

Various training methods have been implemented to enhance the physical capabilities of tennis players, including conventional exercises such as weight training and plyometrics, as well as functional training methods [3, 6]. Functional training aims to improve strength, endurance, and body stability by incorporating movement patterns that mimic sports-specific activities [7]. These exercises focus on core muscle strengthening, joint stabilization, and explosive strength development, all essential for optimal tennis performance [7]. However, while functional training is generally effective in improving several physical attributes,

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its impact on flexibility and muscle endurance remains a subject of debate among coaches and researchers [3]. This limitation is believed to result from training approaches that primarily emphasize muscle strengthening within a restricted range of motion, thereby failing to adequately develop muscle elasticity and joint mobility.

Bodyweight Circuit Training (BCT) was developed as an extension of functional training to overcome its limitations by incorporating broader and more dynamic movements. Inspired by natural animal movements such as crawling, jumping, and lateral motions, BCT integrates functional training elements, including push-ups, walking lunges with torso twists, bicycle crunches, back extensions, lateral squats, and supinated Australian pull-ups [8]. These movement patterns not only enhance strength, endurance, and stability but also improve dynamic flexibility and agility. For example, walking lunges with torso twists increase hip and spinal flexibility [9, 10], while bicycle crunches strengthen core muscles through rotational patterns relevant to forehand and backhand strokes [11, 12]. This combination makes BCT a comprehensive approach to developing flexibility, strength, and agility, aligning with the physical demands of tennis athletes.

The effectiveness of BCT in improving flexibility and strength endurance lies in its design, which emphasizes multidimensional and function-based movements. Exercises such as crawling and jumping engage a full range of motion, directly stretching major muscles while enhancing the elasticity of connective tissues [13, 14]. The combination of dynamic and isometric movements provides optimal stimulation to strengthen the core, back, and other muscle groups [15, 16]. Additionally, the circuit training format of BCT incorporates high-intensity exercises, which not only enhance muscular endurance but also improve neuromuscular coordination, enabling more efficient movement and greater resistance to fatigue [17]. By integrating movement patterns that resemble natural body mechanics, BCT supports flexibility development and optimizes the strength required for tennis performance [2, 8, 18]. This approach makes BCT valuable not only for improving athletic performance but also for reducing the risk of injuries associated with flexibility limitations and repetitive motions common in tennis.

Although BCT has been applied in various sports, such as gymnastics and martial arts, research on its effectiveness for tennis athletes remains limited. Most previous studies have focused on conventional training methods or functional training without examining more comprehensive approaches that simultaneously enhance flexibility and muscle endurance [6]. Additionally, the optimal training duration for maximizing BCT benefits has yet to be determined.

Therefore, this study aims to evaluate the effectiveness of a four-week BCT program in improving flexibility and strength endurance in male university tennis players.

Materials and Methods

Participants

This study employed a true experimental design with a pretest-posttest control group. A total of 30 male tennis players aged 19–23 years, with a normal body mass index (BMI) (19–24 kg/m^2), normal blood pressure, resting heart rate, and oxygen saturation, were recruited from Universitas Negeri Surabaya (UNESA). Participants who met the eligibility criteria were randomly assigned to either the control group (CTr, n=15) or the training group (TRg, n=15). Before participation, all players received verbal and written explanations about the study. Informed consent was obtained through signed consent forms prior to their involvement.

Research Design

Bodyweight Circuit Training Protocol

The Bodyweight Circuit Training (BCT) protocol was implemented and supervised by personal trainers from the Department of Sports Coaching Education, Faculty of Sport and Health Science, Universitas Negeri Surabaya. Trainers ensured the proper execution of all movements throughout the program. The BCT program included exercises such as push-ups, walking lunges with torso twists, bicycle crunches, back extensions, lateral squats, and supinated Australian pull-ups. Each session consisted of 4–6 sets of 12–15 repetitions and was conducted three times per week for four weeks. Training sessions took place outdoors at the UNESA Tennis Courts every morning between 6:00 and 8:00 AM.

Data Collection

Flexibility and strength endurance were assessed at baseline (pre) and after four weeks (post) in both groups. Flexibility was measured using the Sit and Reach Test (cm). Upper body strength endurance was evaluated using the 60-second Push-Up Test (repetitions), abdominal strength endurance using the 60-second Sit-Up Test (repetitions), and back strength endurance using the 60-second Back Extension Test (repetitions) [19].

Statistical Analysis

Statistical analysis was conducted using SPSS Statistics for Windows, Version 21.0. Data normality was assessed using the Shapiro-Wilk test. Paired sample t-tests were used to compare flexibility and strength endurance within each group at baseline (pre) and after four weeks (post). Independent sample t-tests were applied to compare differences between the control and training groups. Effect sizes were calculated using Cohen's d and categorized as small (d = 0.2), medium (d = 0.5), and large (d ⩾ 0.8) [20]. Statistical significance was set at p ⩽ 0.05 for all analyses.

Results

The general characteristics of the participants are presented in Table 1. No significant differences were found between the control (CTr) and training (TRg) groups in age, body height, body mass index, blood pressure, or resting heart rate (all p ⩾ 0.05). The flexibility and strength endurance results at baseline (pre) and after four weeks (post) for each group are shown in Figure 1.

Based on the trend shown in Figure 1, significant improvements in flexibility, upper body strength endurance, abdominal strength endurance, and back strength endurance were observed in the training group (TRg) between baseline (pre) and post-intervention (all p ⩽ 0.05). In contrast, no significant changes were found in the control group (CTr) (all p ⩾ 0.05). To compare differences between groups, an independent sample t-test analysis was performed, and the results are presented in Table 2.

At baseline, no significant differences were observed between the TRg and CTr groups in flexibility, upper body strength endurance,

Table 1. General Characteristics of Participants

Parameters	CTr (n=15)	TRg (n=15)	p-value
Age, yrs	20.47 ± 0.99	20.60 ± 1.12	0.733
Body height, m	1.66 ± 0.04	1.67 ± 0.04	0.249
Body weight, kg	58.20 ± 4.01	59.47 ± 5.06	0.453
Body mass index, kg/m^2	21.24 ± 0.89	21.28 ± 1.05	0.920
Systolic blood pressure, mmHg	117.33 ± 7.04	115.33 ± 5.17	0.383
Diastolic blood pressure, mmHg	78.00 ± 6.76	78.67 ± 5.16	0.764
Resting heart rate, bpm	69.60 ± 4.97	68.80 ± 11.23	0.804

CTr: Control group; TRg: Training group. p-values were obtained using independent sample t-tests. Data are presented as mean ± standard deviation (SD).

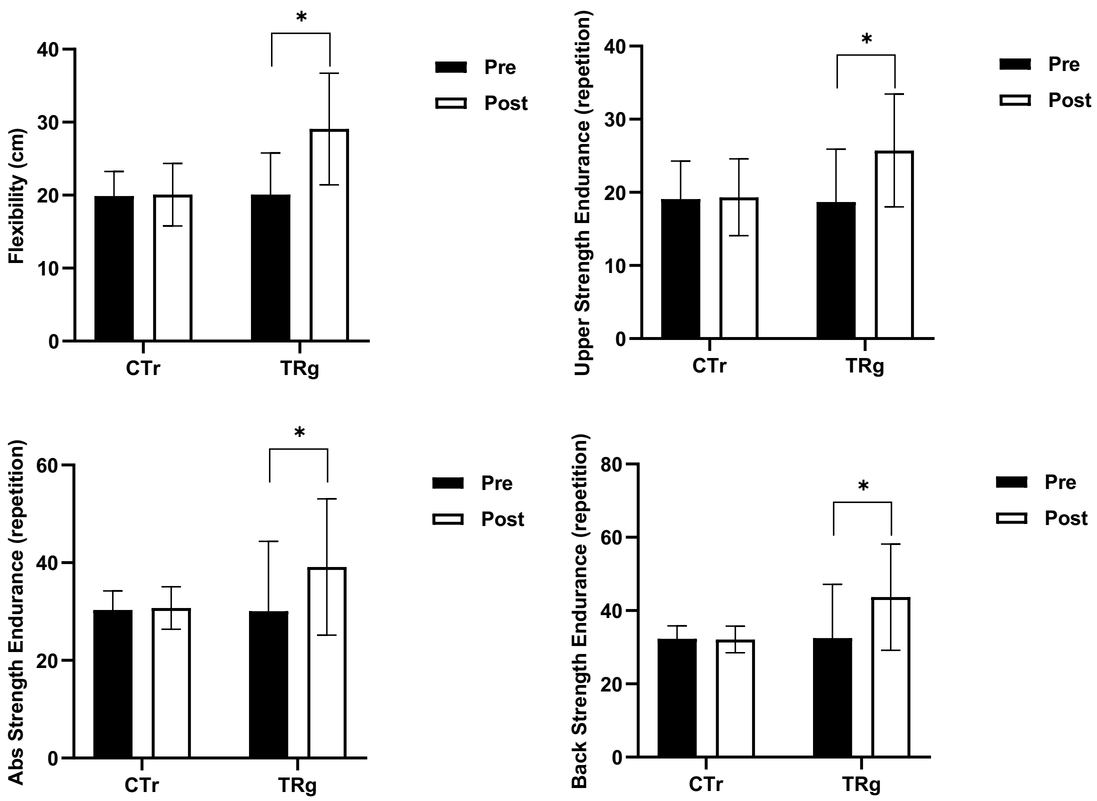

Figure 1. Assessment of flexibility (cm), upper strength endurance (repetition), abs strength endurance (repetition), and back strength endurance (repetition) baseline (pre) and 4 weeks (post) in each group. *significant at pre in TRg (p ⩽ 0.05). p-value was obtained from the results of paired sample t-test analysis. CTr: Control group; TRg: Training group.

Table 2. Assessment of Flexibility and Strength Endurance Between Groups

Parameters	CTr (n=15)	TRg (n=15)	95% CI	p-value	ES
Flexibility (cm)					
Pre	19.87 ± 3.39	20.07 ± 5.70	-3.75 to 3.35	0.908	0.042
Post	20.06 ± 4.27	29.07 ± 7.66*	-13.69 to -4.31	0.001	1.452
Delta	0.20 ± 1.37	9.00 ± 4.58*	-11.41 to -6.19	0.000	2.601
Upper Strength Endurance (repetitions)					
Pre	19.07 ± 5.23	18.67 ± 7.26	-4.35 to 5.15	0.864	0.063
Post	19.33 ± 5.26	25.73 ± 7.71*	-11.36 to -1.44	0.013	0.971
Delta	0.27 ± 0.96	7.07 ± 2.92*	-8.47 to -5.13	0.000	3.133
Abdominal Strength Endurance (repetitions)					
Pre	30.33 ± 3.87	30.07 ± 14.29	-7.84 to 8.37	0.945	0.025
Post	30.73 ± 4.35	39.13 ± 13.96*	-16.38 to -0.42	0.034	0.812
Delta	0.40 ± 1.18	9.07 ± 1.03*	-9.49 to -7.84	0.000	7.803
Back Strength Endurance (repetitions)					
Pre	32.27 ± 3.57	32.53 ± 14.66	-8.54 to 8.01	0.946	0.024
Post	32.13 ± 3.66	43.67 ± 14.51*	-19.73 to -3.34	0.009	1.091
Delta	-0.13 ± 1.51	11.13 ± 6.93*	-15.16 to -7.37	0.000	2.247

CI: Confidence Interval; ES: Effect Size; CTr: Control group; TRg: Training group. *Significant at CTr ($p \leqslant 0.05$). Data are presented as mean ± standard deviation (SD).

abdominal strength endurance, or back strength endurance (all $p \geqslant 0.05$). However, post-intervention and delta analyses revealed significantly greater improvements in the TRg group compared to the CTr group (all $p \leqslant 0.05$).

Discussion

The findings of this study demonstrate that a four-week Bodyweight Circuit Training (BCT) program significantly improved flexibility by 49.29%, upper body strength endurance by 44.27%, abdominal strength endurance by 37.64%, and back strength endurance by 40.21%. These improvements highlight the effectiveness of BCT as a comprehensive training method that meets the physical demands of tennis players by integrating flexibility and muscular endurance to support optimal on-court performance. Enhanced flexibility allows athletes to reach difficult shots more efficiently, while greater strength endurance contributes to body stability and stroke consistency during long matches or intense rallies [2, 21]. The combination of these two elements is essential for improving movement efficiency and reducing the risk of injuries caused by repetitive or sudden movements [4, 5]. These findings emphasize the importance of training programs that simultaneously enhance flexibility and muscular endurance for tennis players.

The observed results can be attributed to the design of BCT exercises, which include push-ups, walking lunges with torso twists, bicycle crunches, back extensions, lateral squats, and supinated Australian pull-ups. Each movement plays a specific role in enhancing flexibility and strength endurance. For example, walking lunges with torso twists improve hip and spinal mobility, promoting muscle elasticity and dynamic flexibility [10]. Bicycle crunches not only strengthen the core muscles but also incorporate rotational patterns relevant to forehand and backhand strokes [12]. Additionally, exercises such as push-ups and supinated Australian pull-ups target upper body strength, which is essential for supporting overhead movements in tennis [22, 23, 24]. The back extension exercise strengthens the lower back, playing a crucial role in maintaining posture during explosive strokes [25, 26]. Thus, the combination of these movements in BCT provides targeted stimulation to major muscle groups, making it a more sport-specific and relevant training method compared to conventional or other functional training approaches.

The effectiveness of BCT in improving flexibility and muscular endurance can also be explained by its underlying physiological mechanisms. Full-range-of-motion exercises, such as walking lunges and lateral squats, enhance connective tissue elasticity and joint mobility [27, 28]. Additionally, the high intensity of BCT promotes metabolic adaptations in muscles, increasing energy efficiency and reducing fatigue during physical activity [17]. Dynamic movements, such as walking lunges, combined with isometric exercises, such as push-ups, strengthen neuromuscular coordination, allowing the body to respond more rapidly and efficiently to changing match conditions. This movement-based approach positions BCT as a training method that not only enhances physical performance but also improves movement efficiency and postural stability, both of which are essential in tennis.

These findings are consistent with previous research. This study supports the results of Polsgrove et al., who reported that full-range-of-motion exercises effectively enhance lower body flexibility [10]. Similarly, the findings align with James et al., who demonstrated that combining dynamic and isometric movements significantly improves muscular endurance compared to traditional training methods [8]. A key contribution of this study is the application of BCT specifically to address the physical demands of tennis players, who require dynamic flexibility, core strength, and high muscular endurance.

The practical relevance of these findings extends to both tennis coaches and athletes. Optimal flexibility allows players to expand their range of motion and reduce the risk of injuries associated with repetitive or sudden movements. Improved strength endurance helps maintain stroke intensity and body stability during long matches. Beyond tennis, BCT has potential applications in other sports, such as badminton, squash, and basketball, which require a combination of flexibility, endurance, and muscular strength. Due to its simple yet effective structure, BCT can be incorporated as a primary or supplementary program within functional training regimens to enhance overall physical performance.

However, this study has several limitations that should be acknowledged. The relatively short training duration (four weeks) may not have been sufficient to assess the long-term effects of BCT on athletes' physical performance. Additionally, the study was limited to tennis players from a single institution, which may restrict the generalizability of the findings to a broader population or other sports. Responses to BCT may also vary among athletes with different skill levels or prior training experience. Furthermore, key physical parameters such as agility, explosive strength, and injury risk were not evaluated, despite their relevance to optimal performance in competitive sports.

Based on these limitations, future research should include a more diverse population, incorporating athletes from different sports and skill levels to improve the generalizability of the findings. A longer training duration is also necessary to evaluate the long-term effects of BCT on various physical parameters, such as agility, explosive strength, and injury prevention. Further studies could explore the integration of BCT with other training methods to develop more comprehensive and holistic approaches. Expanding the scope of research will help refine BCT as an innovative and effective training method that meets the needs of athletes across various sports disciplines.

Conclusions

The findings of this study demonstrate that four weeks of bodyweight circuit training (BCT) significantly improve flexibility (49.29%) and strength endurance, including upper body strength endurance (44.27%), abdominal strength endurance (37.64%), and back strength endurance (40.21%). The BCT program can be effectively applied to optimize the physical performance of tennis players.

Additionally, with its design based on natural body movements, BCT provides a comprehensive and relevant training approach not only for tennis players but also for athletes in other sports that require a combination of flexibility, strength, and endurance. This study contributes to the sports training literature, though further research is needed to fully explore the potential benefits of bodyweight circuit training.

Conflict of Interest

The authors declare no competing interests related to this work.

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ORIGINAL ARTICLE

The effect of proprioceptive training on lower extremity response time in kung fu athletes: Responses between dominant and non-dominant feet

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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 Proprioceptive training influences neuromuscular control and reaction time in athletes. Its impact on response time in different limbs remains an area of interest. This highlights the need for further research to identify effective training approaches. The present study examined the immediate effects of proprioceptive training on response times in the dominant and non-dominant feet of kung fu athletes.

Material and Methods The sample included 21 female volunteer kung fu athletes (age: 14.43 ± 1.21 years; height: 157.90 ± 4.59 cm; weight: 53.10 ± 8.26 kg; sports experience: 8.24 ± 2.41 years). Response times were measured before and after proprioceptive training using the Light Trainer Pro device. One-way repeated measures ANOVA assessed the effects of proprioceptive training. A paired t-test compared pretest-posttest response time differences between the dominant and non-dominant feet.

Results A significant effect of proprioceptive training on response times was found ($p < 0.05$). In the pretest, no significant difference was observed between the dominant and non-dominant feet ($p > 0.05$). However, in the post-test, the response time of the dominant foot was significantly lower than that of the non-dominant foot ($p < 0.05$). The dominant foot's response time significantly decreased after proprioceptive training ($p < 0.05$), while no change was observed for the non-dominant foot ($p > 0.05$). No significant difference was found in the pretest-posttest response time changes between the dominant and non-dominant feet ($p > 0.05$).

Conclusions Acute proprioceptive training improved the response time of the dominant foot in kung fu athletes. Proprioceptive training programs may enhance athletes' performance before training and competition.

Keywords: athletes, proprioceptive training, response time, Kung Fu

Introduction

Proprioceptive training is widely used in sports to enhance neuromuscular control and movement efficiency. In kung fu, where rapid and precise responses are essential for performance, optimizing reaction time is particularly important. Understanding its effects on the dominant and non-dominant limbs can help develop targeted training strategies for kung fu athletes.

Proprioception is defined as awareness of position and movement. It includes elements such as static position, displacement, speed, acceleration, and the force and effort exerted by muscles [1]. Joint positions and movements rely on neurons located in the skin, muscles, joints, tendons, and ligaments, making them a key aspect of proprioception [2].

Proprioceptive training aims to enhance kinesthetic awareness of body posture and movement [3, 4]. It also develops complex neuromuscular mechanisms, including balance, somatosensory stimulation, and joint repositioning [4, 5]. Common exercises involve maintaining balance with eyes closed, using a balance board or ankle disk, standing on one leg while throwing and catching a ball, and dribbling a ball [6, 7, 8]. These activities improve adaptability to changing conditions [9] and help athletes make rapid movement adjustments based on visual and tactile inputs [10].

Systematic reviews indicate that proprioceptive training positively influences various aspects of sports performance. Reported benefits include enhanced physiological capacity, explosive power, postural stability, balance, and muscle activation. Additionally, it improves knee joint position awareness, reduces chronic joint instability, and enhances agility, passing, dribbling, and ball control skills [11].

Studies on athletes have primarily examined the chronic effects of proprioceptive training [11].

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Research on its acute effects has shown mixed results. Some studies report improvements in both static and dynamic balance [12], while others indicate gains in dynamic balance but no significant changes in static balance [13]. Additionally, proprioceptive training has been found to increase quadriceps strength [14] and reduce response time [15].

Reaction is the process in which a stimulus reaches the central nervous system via nerves, is processed, and then triggers a return signal to activate the relevant muscle [16, 17]. Response time refers to the interval between the initiation of neurological processes in reaction to a stimulus and the start and completion of the resulting movement [18]. This process begins with the retina cycle and concludes with muscle activation [19, 20]. Response time is defined as the ability to execute a movement in the shortest possible time and to coordinate body parts efficiently [21].

Rivera et al. [9] reported that proprioceptive exercises enhance the ability to adapt quickly to changing conditions. Additionally, proprioceptive training contributes to stimulus-response synchronization, improving joint stability performance [22]. These findings support the hypothesis that proprioceptive training may be beneficial in reducing response time.

Response time is a fundamental factor that allows athletes to perform at their best in many sports. The ability to quickly decide on and execute a movement underscores its importance [23]. In kung fu, which translates to "martial art" in Chinese [24], rapid responses to an opponent's attacks are crucial. This makes it an ideal sport for studying environmental perception.

Kung fu involves punches, kicks, jumps, and the use of various weapons. However, its core elements include postural control, flexibility, and circular movements [25]. Developing both the dominant and non-dominant limbs to a similar level may provide an advantage over athletes who rely primarily on their dominant side [26].

The tendency of one side of the body to be more specialized for certain movements is known as lateralization [27]. This phenomenon has been studied in athletes by several researchers [28, 29, 30]. In a study by Arguz et al. [28], basketball players' response times for the dominant and non-dominant hands and feet were analyzed during warm-up. The results indicated that the dominant hand exhibited a faster response time.

Despite extensive research on proprioceptive training and response time, there is still no consensus on the most effective methods for optimizing neuromuscular responses in athletes. Studies have produced mixed findings, particularly regarding the effects on dominant and non-dominant limbs. Some report improvements in dynamic balance and muscle activation, while others indicate limited benefits for static balance and joint stability. This variability suggests the need for further research to refine training protocols and develop more effective approaches for enhancing response time. Identifying targeted proprioceptive training strategies could provide valuable insights for improving athletic performance across different sports disciplines.

In martial sports such as kung fu, both feet are developed to complement each other. While the dominant foot is generally preferred for offensive movements, the non-dominant foot plays a significant role in defense, posture, and movement skills. This posture enhances the athlete's body flexibility and strength, allowing for a more dynamic and effective combat performance. Therefore, the aim of this study is to investigate how acute proprioceptive training affects the response times of the dominant and non-dominant feet in kung fu athletes.

Materials and Methods

Participants

The sample consisted of 21 female volunteer kung fu athletes (age: 14.43 ± 1.21 years; height: 157.90 ± 4.59 cm; weight: 53.10 ± 8.26 kg; sports experience: 8.24 ± 2.41 years). Athletes with no injuries in the preceding six months were included in the study. Before participation, all athletes were informed about the study details. The research was approved by the Ethics Committee (Date: 11.11.2024, Decision number: 119).

Study Design

This study employed a within-subjects repeated-measures design. To eliminate the learning effect, response time measurements were randomly taken for the dominant and non-dominant foot. Athletes participated in measurements on different days, but response times for both feet were recorded on the same day. All experiments were conducted in a laboratory setting at the same time of day to maintain comparable chronobiological conditions. Before proprioceptive training, the movements were demonstrated both verbally and practically. The number of repetitions and the duration of exercises were monitored and implemented by the researchers.

Proprioceptive Training

The proprioceptive training session consisted of a sequence of exercises performed on a Bosu ball, emphasizing awareness and control of the lower limbs. The exercises were conducted with the Bosu ball positioned side up. The training protocol was adapted from previously established proprioceptive training programs [31, 12]. The exercise program is presented in Table 1.

Visual Response Time

The response times of athletes for their dominant and non-dominant foot were measured both before and after proprioceptive training. To minimize learning and practice effects, the measurements were conducted in a randomized order for the dominant and non-dominant foot. The response time was assessed using the Light Trainer Pro system (Light Trainer® Visuo-Motor Devices Company) (Figure 1). This device consists of a lighted disk with eight RGB LEDs and is controlled via a smartphone or tablet. The experimental design involved measuring the athletes' response time to extinguish the illuminated target on the disk. During the test, athletes were randomly positioned on a level surface in a semicircle. They responded to a visual stimulus by using either the dominant or non-dominant foot to deactivate a sequence of five targets. The setup included a 180° semicircle, with each light disc positioned at 45° intervals. The lights, numbered 1 to 5, were calibrated according to the athletes' height. After each light was turned off, athletes were instructed to reposition their dominant or non-dominant foot to the starting position [32, 33].

Statistical Analysis

The data in this study are presented as the mean ± standard deviation (SD). The normality assumption for the ANOVA model was tested using the Shapiro-Wilk test. One-way repeated measures ANOVA was conducted to assess the effects of proprioceptive training. Post hoc comparisons were performed using the Bonferroni correction.

A paired t-test was used to compare pre-test and post-test response time differences between the dominant and non-dominant foot. Effects with $p < 0.05$ were considered statistically significant. All statistical analyses were performed using SPSS 26.0.

Results

The mean, standard deviation, minimum, and maximum values for age (years), height (cm), body weight (kg), and sports experience (years) of the kung fu athletes are presented in Table 2.

Figure 2 illustrates the changes in response times before and after proprioceptive training for both the dominant and non-dominant foot. As shown in Figure 2, a significant effect was found for response times across the measurements ($F(3,60) = 9.471$; $p < 0.001$; $\eta^2 = .321$). In the pre-test, there was no significant difference in response time between the dominant and non-dominant foot ($p = .104$). However, in the post-test, the response time of the dominant foot was significantly lower than that of the non-dominant foot ($p = .036$). The response time of the dominant foot significantly decreased after proprioceptive training ($p = .024$), whereas no significant change was observed for the non-

Table 1. Proprioceptive Exercise Session

No	Exercises	Duration
1	Squat on Bosu	10 r
2	Standing on two legs on Bosu	60 s
3	Standing on one leg on Bosu (right/left)	60 s + 60 s
4	Standing on one leg on Bosu, throwing and catching a ball (right/left)	60 s + 60 s
5	Jumping on two legs on Bosu	10 r
6	Jumping on one leg on Bosu (right/left)	10 r
7	Standing on two legs with eyes closed on Bosu	60 s
8	Standing on one leg with eyes closed on Bosu (right/left)	60 s + 60 s

Note: s – seconds; r – repetitions.

Figure 1. Assessment of reaction time response (32).

Table 2. Descriptive information about the participants

Variable	N	Mean	Std. Deviation	Minimum	Maximum
Age (years)	21	14.43	1.21	12.00	16.00
Height (cm)	21	157.90	4.59	148.00	167.00
Body weight (kg)	21	53.10	8.26	41.00	69.00
Sports experience (years)	21	8.24	2.41	5.00	12.00

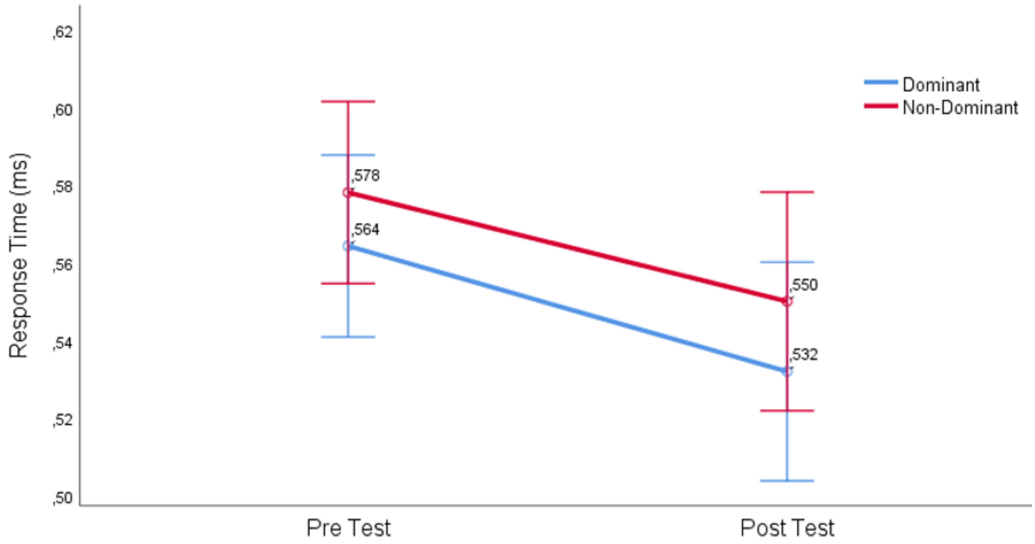

Figure 2. Response times after proprioceptive training. The error bars indicate the standard error of the mean.

dominant foot (p = .084). No significant difference was found between the dominant foot (M = .032, SD = .046) and the non-dominant foot (M = .028, SD = .048) in pre-test and post-test response time differences (t = .297, df = 40, p = .768).

Discussion

This study examined the effect of acute proprioceptive training on the response times of the dominant and non-dominant feet in female kung fu athletes. The results showed no significant difference in response times between the dominant and non-dominant foot before training. However, after acute proprioceptive training, the response time of the dominant foot improved significantly more than that of the non-dominant foot.

Compared to traditional exercise methods, proprioceptive training enhances muscle activation, sensorimotor performance, central nervous system function, and arousal levels during exercise [34, 35, 36, 11]. These factors may contribute to a reduction in response time following proprioceptive training. A similar study also reported a decrease in response time after acute proprioceptive training [15].

The literature on the acute effects of proprioceptive training remains limited. However, several studies have examined its chronic effects. For example, an 8-week proprioceptive training program significantly improved response time and dominant hand-eye coordination skills [37]. Bokil et al. [38] found that a 6-week upper extremity proprioceptive training program enhanced response time in table tennis athletes. Another study reported statistically significant reductions in visual, auditory, and compound response time performance following proprioceptive training [39].

The primary objective of proprioceptive training is to enhance proprioceptive function, a complex neuromuscular process responsible for the natural awareness of body position and movement [4, 36, 3]. Additionally, proprioceptive sensory stimulation has been shown to improve exercise performance by enhancing balance, postural stability, muscle activation, joint stability, and functional mobility of the lower extremities [40, 11]. Consequently, this training method may contribute to a reduction in response time by increasing the functional speed of the nervous system.

Brighenti et al. [29] reported that after a warm-up activity, the dominant leg showed greater improvement compared to the non-dominant leg. Similarly, the present study found that acute proprioceptive training significantly enhanced the response time of the dominant foot relative to the non-dominant foot. This suggests that proprioceptive training has a more pronounced effect on the functional speed of the dominant foot, which is used more frequently.

Several studies have indicated that proprioceptive training positively influences response time [37, 15]. Ceylan and Saygın [37] found that an 8-week proprioceptive training program improved visual response time in students. Mazbouh et al. [15] examined the effects of a 2-week, 6-session proprioceptive training program on response time and observed improvements in the training group compared to the control group. Both studies emphasized that long-term (chronic) proprioceptive training contributes to improvements in response time.

Long-term training programs may be challenging for athletes seeking rapid performance gains. However, acute proprioceptive training sessions that enhance performance could be implemented before training or competition. The present study demonstrated that acute proprioceptive training functionally improved standing response time.

Athletes who develop both their dominant and non-dominant feet to the same level may gain an advantage over those who focus on only one foot. The findings of this study indicate that acute proprioceptive training improved the response time of the more developed foot. However, limited research has examined the effects of acute proprioceptive training on the response time of both dominant and non-dominant feet.

Due to this gap in the literature, studies investigating the effects of warm-up activities on dominant and non-dominant feet, such as those by Brighenti et al. [29] and Arguz et al. [28], were considered for comparison. Brighenti et al. [29] found that a 10-minute warm-up had a greater effect on postural control in the dominant leg compared to the non-dominant leg. Arguz et al. [28] examined the response times of dominant and non-dominant hands and feet in basketball players following a warm-up. Their findings showed that warm-up activities improved the response times of both the dominant and non-dominant hands. However, no significant difference was observed in the reaction times of the dominant and non-dominant feet before and after the warm-up.

In contrast, the present study demonstrated that acute proprioceptive training significantly improved the reaction time of the dominant foot. This suggests that proprioceptive training may have a more direct influence on neuromuscular response compared to traditional warm-up activities.

Limitations and Future Research

This study has certain limitations that should be considered when interpreting the results. First, the participants were adolescent kung fu athletes with a young age profile and amateur-level experience. As a result, the findings may not be generalizable to athletes of different age groups, skill levels, or sports disciplines. Future research should include a broader age range, various sports, and different experience levels to provide a more comprehensive understanding of the acute effects of proprioceptive training.

Additionally, this study focused primarily on the impact of proprioceptive training on response time. However, response time alone does not fully capture all factors influencing athletic performance. Future research should examine additional variables such as agility, sprint performance, balance, technical skills, and performance sustainability to offer a more holistic perspective. Addressing these gaps in future studies will contribute to the development of evidence-based training protocols applicable across different sports.

Conclusions

This study contributes to the growing body of evidence on the importance of short-term proprioceptive training in athletes. Proprioceptive training has both acute and long-term effects on neuromuscular performance. From a practical perspective, the ability to respond quickly is essential for executing kung fu techniques effectively. Therefore, these findings offer valuable insights for coaches and practitioners in designing pre-match routines to enhance athletic performance.

Conflict of Interest

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

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REVIEW ARTICLE

Scientific support for strength sports: analysis of scientific resources from the Web of Science Core Collection

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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 Strength is a key physical attribute that contributes to success in sports. Strength training plays a crucial role in enhancing athletes' physical condition, improving skill levels, and achieving competitive success. This study aims to analyze publications on strength sports using bibliometric methods to identify priority research areas in this field.

Material and Methods The Web of Science Core Collection (WoS) bibliometric database was analyzed. A total of 589 sources published between 2021 and 2025 that met the search criteria were selected for primary analysis. Bibliometric methods were applied to process the data. VOSviewer 1.6.18 software was used for keyword analysis and direct citation analysis, including the construction of bibliometric maps, cluster density visualization, and weighted citation analysis.

Results The leading publication categories in WoS were Sports Sciences, Physiology, Orthopedics, Hospitality, Leisure, Sport, Tourism, and Rehabilitation. The highest number of publications appeared in 2022 and 2024. The top five countries in terms of publication output were Spain, Brazil, England, the USA, and Australia. The top five universities with the highest publication activity were identified. The most cited authors were also determined. The constructed bibliometric maps helped identify the main research themes and current directions in strength sports. Six research clusters were identified, covering the following topics: strength training in sports, rehabilitation and return to sport after injuries, athlete performance dynamics under strength training, strength training in fitness, strength development across different sports, and the impact of nutrition on training effectiveness. The keywords associated with each cluster were analyzed.

Conclusions A bibliometric analysis of the WoS database on strength sports has been conducted. The priority research directions in this field have been identified. These include sports-related topics, such as strength training methods, testing, and evaluation of athletes' strength, as well as rehabilitation and recreational aspects, including strength training for recovery, rehabilitation after injuries, and injury prevention. Various tests and assessment methods are used to evaluate athletes' strength. These methods must meet the principles of specificity, simplicity, reliability, and practicality. The most commonly used assessments include body composition indices, anthropometric criteria, and strength performance measures. Among strength exercises, the most frequently analyzed are the bench press, grip strength, squats, and jumps. The effectiveness of these tests for athlete monitoring, selection, and performance prediction has been confirmed.

Keywords: strength sports, bibliometric mapping, VOSviewer.

Introduction

Strength training plays a fundamental role in sports performance, influencing athletes' physical capabilities, endurance, and overall success. Over the past decades, research on strength sports has expanded significantly, covering various aspects such as training methodologies, physiological adaptations, injury prevention, and rehabilitation. The increasing scientific interest in this field is reflected in a growing number of publications exploring the optimization of strength training programs and their effects on athletic performance. Given the diverse applications of strength training across competitive sports, fitness, and rehabilitation, a systematic analysis of existing scientific literature indicates the need to search for key research trends and priority areas for future investigations.

In this context, many studies provide detailed results on the physiological effects of strength training, including its role in sports performance, rehabilitation after injuries, injury prevention, fitness applications, and strength development across various sports. Strength is a fundamental physical quality that determines success in sports, and strength training serves as a key tool for enhancing athletes' physical condition, improving

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skill levels, and achieving competitive success [1, 2]. It is widely applied across different sports disciplines [3, 4, 5, 6, 7], with strength indices commonly used to assess training effectiveness. Strength analysis plays a crucial role in monitoring athletes' condition in team sports [4, 6, 8, 9], swimming [10], martial arts [11, 12, 13, 14], and rock climbing [15, 16, 17]. These indicators serve as predictors of success and contribute to forecasting performance progression. Effective athlete training requires continuous monitoring of key physical attributes [18, 19, 20], with strength being one of the most significant. The selection of appropriate tests for strength assessment is essential for optimizing the training process, yet this task is complicated by the vast array of available tests and measurement methods.

Strength exercises have been known to humanity since ancient times, with the origins of weightlifting and strength feats traced back to ancient Egypt, China, and Greece. However, it was not until the 1950s that strength training began to be incorporated into team sports and athletics, while research on weightlifting in peer-reviewed journals became prominent in the 1970s [21]. Strength sports (SS) are distinguished by their primary focus on strength training and encompass a broad range of disciplines, including weightlifting, kettlebell lifting, powerlifting, bodybuilding, and arm wrestling. These sports enjoy high popularity among both young people and adults [22, 23, 24, 25], and their accessibility makes them suitable for fitness recommendations [22, 24, 26]. Although most SS are not part of the Olympic program, this does not diminish their popularity or the high level and spectacle of competitions. This growing interest underscores the need for scientific support in SS, with key objectives including enhancing athletic performance and skill development. Achieving these goals requires the optimization of athlete monitoring and the implementation of reliable, informative tests and functional assessments.

The results of the study [27] confirmed the possibility of using the index method to assess the condition of armwrestling athletes of different skill levels. Experienced lifters were characterized by high values of indices reflecting muscle development. These include body mass, shoulder width, the Erisman index, Livi index, Vervek index, body surface and relative body surface indices, and the strength index. The indices of massiveness and conditional moments of strength of limb segments were highly informative and served as predictors of success in armwrestling.

A study [28] analyzed the influence of kettlebell lifting exercises on the development of strength qualities in military school cadets. A set of test exercises assessing the strength of individual muscle groups was used as an evaluation tool. The effectiveness of kettlebell exercises in improving the physical fitness of future officers was confirmed.

A comparative analysis of the effect of kettlebell exercises and rowing machine exercises on adaptation status was conducted [29]. An increase in oxygen consumption and heart rate was observed, leading to the conclusion that kettlebell exercises provide an adequate aerobic stimulus for improving the cardiorespiratory system.

The growing popularity of powerlifting has led to a significant amount of research aimed at evaluating competitive performance and identifying predictors of success [30, 31, 32]. A study [30] analyzed competitive performance strategy in powerlifting, assessing key factors through regression analysis and reporting them as odds ratios. The likelihood of victory increased when lifters selected a higher weight for their initial squat attempt compared to their competitors and successfully completed the lift. The initial squat attempt is considered one of the most critical exercises during competition.

In another study [32], the effect of competition frequency on the strength of powerlifting athletes (both relative and absolute) was examined. Strength performance was assessed based on competition scores, confirming that an increase in the success rate was associated with the number of competitions. An upper limit of four competitions per year was identified as the threshold affecting success.

An analysis of para powerlifting athletes' performances [31] identified absolute and relative load, chronological age, and the nature of health disorders (congenital or acquired) as key evaluation criteria. Correlations between performance and these factors were confirmed, leading to the recommendation that they should be considered when designing training programs.

Similar results were obtained, as shown in the study [33], where the authors examined the influence of relative age on athletes' success in top-level modern wrestling competitions. Age as a predictor was most evident at the cadet level.

An analysis of grip strength indicators in armwrestling athletes was conducted, as described in the study [34]. The specificity of the sport necessitates studying grip strength in both static and impulse modes. Additionally, somatotype characteristics play a crucial role in armwrestling success. These indicators serve as predictors of performance in the sport.

The condition of kettlebell lifting athletes was analyzed using anthropometric, physiological, and electromyographic methods, as reported in the study [35]. Training in an aerobic mode induces high physiological stress and requires significant energy expenditure. Optimal exercise technique enables athletes to maximize their potential and helps prevent injuries.

In another study [36], the influence of kettlebell lifting on endurance development and adaptive capabilities was examined. The findings indicated an increase in endurance and an expansion of adaptive potential due to the optimization of cardiovascular system indices (pulse, blood pressure), improved physiological parameters derived from these indices, and enhanced tolerance to physical loads.

A comparative analysis of morphological and functional indices in armwrestling and street wrestling athletes was conducted, as shown in the study [37]. The findings confirmed the specific influence of these sports on athletes' physical characteristics. Grip strength was identified as one of the key predictors of success in both disciplines. The informativeness of grip strength indices in pulse mode for monitoring the functional state of athletes was also established.

The trajectory of kettlebell lifting was analyzed, as shown in the study [23]. The results enabled researchers to estimate strength indices across different phases of the jerk exercise. Additionally, the data allowed for predictions regarding the dynamics of athletes' condition and contributed to optimizing their training.

Similar results were obtained, as shown in the study [38]. The authors evaluated the biomechanical characteristics of strongmen when lifting the Atlas stone, dividing the process into five phases. Each phase was characterized by specific joint movements. Differences in movement execution based on gender and performance level were identified. The findings were proposed to inform training adaptations and enhance performance in weightlifting.

Training with kettlebells has been proposed as an alternative to weightlifting [24, 26]. It contributes to increased strength, power, and endurance in traditional weightlifting exercises. One of its key advantages is its applicability beyond professional and elite lifters.

The existing research confirms the relevance and significance of scientific support for strength sports. A bibliometric analysis of available studies will provide a comprehensive examination of the issue and identify leading research directions.

This study aims to analyze publications on strength sports using the bibliometric method and establish priority scientific directions in this field.

Methodology

Data sources

The Web of Science Core Collection (WoS) bibliometric database was selected for analysis as of November 6, 2024. The research sample was formed using the keywords "strength sports" and "strength sport" for the period 2021–2025. A total of 589 publications were included in the sample. The highest number of publications appeared in 2022 (138, 23.4%) and 2024 (133, 22.6%).

The WoS database enables an initial analysis of the top five main categories and indicators within the sample. The results of this analysis are presented in Table 1.

Method of Study

The WoS database was used to identify priority trends in strength sports (SS) research. The review period covered 2021–2025. The primary search results are presented in Table 1.

The data in Table 1 confirm the strong sports orientation of the publications, as reflected in the structure of the publication categories. The majority of publications in the sample (over 70%) align with this focus. In this context, studies categorized under *Sport Sciences, Physiology,* and *Rehabilitation* are of particular interest. An analysis of publication frequency by country, journal, and institution indicates no pronounced dominance by any single entity.

Data analysis

Bibliometric methods were applied to identify priority research areas in strength sports (SS). VOSviewer 1.6.18 [39] was used as the primary tool, enabling the construction and visualization of bibliometric networks for further analysis. Keyword analysis [40] and direct citation analysis [41] were employed. The methodology for calculating

Table 1. Results of the analysis of Web of Science category fields

Analysis Indicator	Items (N; %)
Subject area (top 5 items)	Sport Sciences (351; 59.6%), Physiology (62; 10.5%), Orthopedics (49; 8.3%), Hospitality, Leisure, Sport, Tourism (45; 7.6%), Rehabilitation (38; 6.5%)
Country (top 5 items)	Spain (109; 18.5%), Brazil (94; 15.6%), England (88; 14.9%), USA (83; 14.1%), Australia (73; 12.4%)
Journals (top 5 items)	Journal of Strength and Conditioning Research (32; 5.4%), Sports (25; 4.2%), International Journal of Environmental Research and Public Health (21; 3.6%), International Journal of Sports Physiology and Performance (19; 3.2%), Frontiers in Physiology (18; 3.1%)
Institutions (top 5 items)	Universidad Andres Bello (26; 4.4%), Edith Cowan University (22; 3.7%), Auckland University of Technology (19; 3.2%), University of the Basque Country (16; 2.7%), Universidade de São Paulo (15; 2.5%)

Note: The source of information is the authors› research (November 6, 2024).

key indicators to analyze and identify the most significant research categories was outlined by van Eck and Waltman [42].

Priority research areas were determined based on the most cited references. The results were graphically represented as bibliometric maps and summarized in tables containing bibliometric characteristics of keywords. The fundamental principle of these maps is that the distance between items reflects the strength of the link between them, with smaller distances indicating stronger relationships.

To enhance the depth of the study and strengthen scientific argumentation, the methodological technique of double citation was applied in the analysis [43].

Results

The sample was analyzed based on the authors' keywords, totaling 1,430 unique terms. To enhance the quality of the analysis, only keywords that appeared at least 10 times were selected, resulting in a final set of 37 keywords. The analysis enabled the creation of corresponding visualization maps. The network visualization is presented in Figure 1.

The VOSviewer program divided the keywords into 6 clusters and assessed the number and strength of links. The total number of links was 238 and the total strength of these links was 1103. The size of the keywords corresponds to the number of links obtained. Spatial proximity depicts the strength of links between topics. Keywords were analyzed number of links, total link strength, occurrences, and avq. citations. The cluster composition and characteristics of each keyword are summarised in Table 2.

The second cluster, displayed in green, consists of 9 keywords. "Athletes" and "Reliability" had the highest number of links and the strongest link

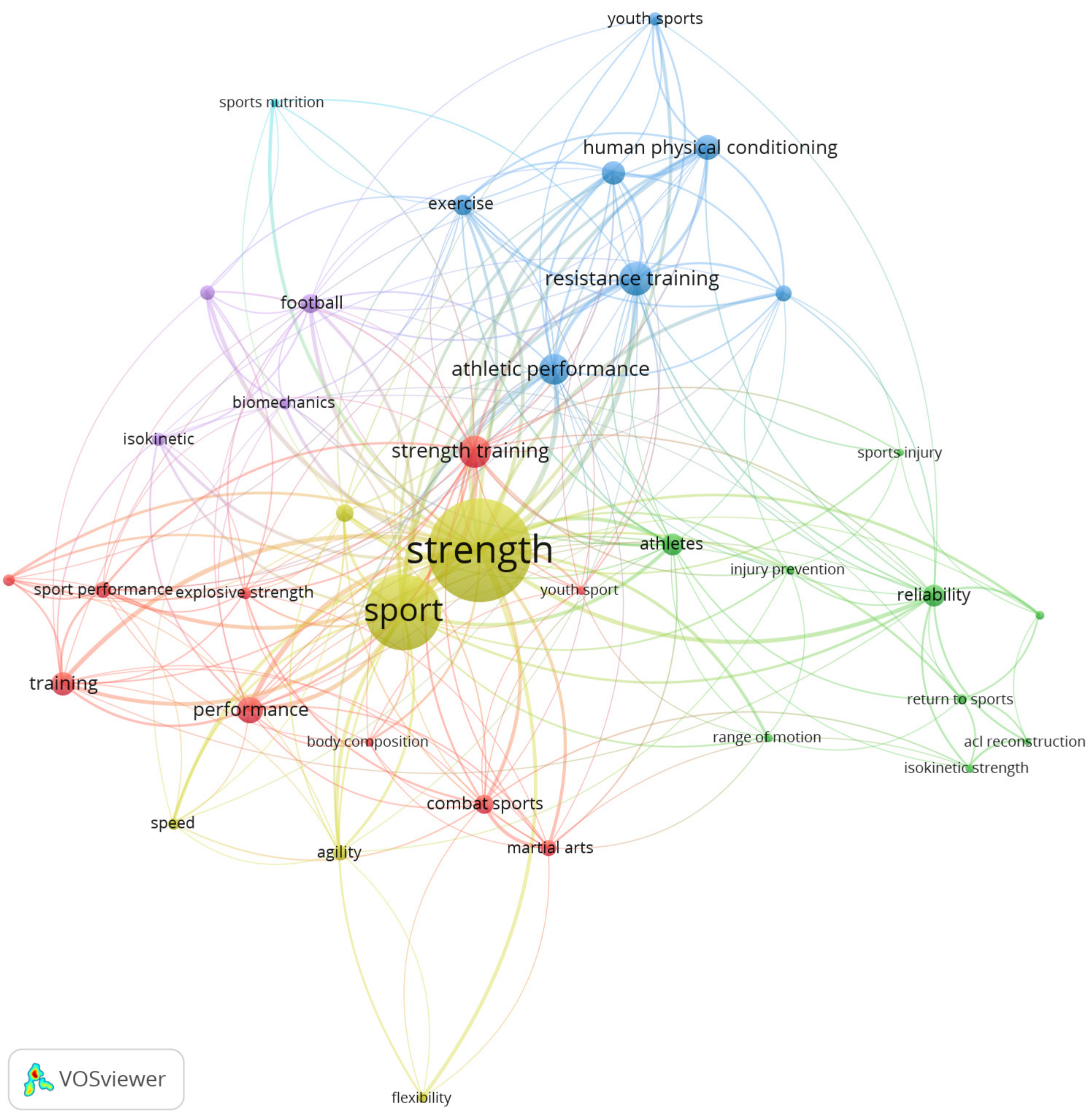

Figure 1. Main keywords in strength sports publications: network visualization. The source of information is the authors' research based on data obtained from WoS and analyzed using VOSviewer (November 6, 2024).

Table 2. Characteristics of keywords

Keyword	Link	Total link strength	Occurrences	Avq. citations
Cluster 1				
Body composition	9	16	14	6.86
Combat sports	14	45	31	4.52
Explosive strength	13	25	13	7.77
Fatigue	10	25	10	8.80
Martial arts	14	37	16	3.38
Performance	17	73	32	6.00
Sport performance	11	35	24	5.71
Strength training	24	96	75	5.64
Training	14	60	25	4.36
Youth sport	11	18	12	4.00
Cluster 2				
Act reconstruction	4	13	10	11.90
Anterior cruciate ligament	6	18	12	2.92
Athletes	17	57	23	2.30
Injury prevention	10	17	10	4.10
Isokinetic strength	6	16	12	7.58
Range of motion	7	17	10	12.00
Reliability	17	55	44	7.07
Return to sports	8	19	12	7.42
Sports injury	6	10	10	4.30
Cluster 3				
Athletic performance	20	93	32	5.09
Exercise	17	53	19	5.11
Human physical conditioning	14	66	15	8.87
Plyometric exercise	14	65	16	6.00
Resistance training	20	106	36	7.78
Sports medicine	13	38	17	3.76
Youth sports	9	28	12	4.25
Cluster 4				
Agility	5	19	16	5.81
Flexibility	5	19	13	3.69
Physical fitness	15	42	16	5.19
Speed	9	25	14	6.07
Sport	28	324	186	6.26
Strength	34	510	308	5.35
Cluster 5				
Biomechanics	9	25	15	6.00
Football	17	48	17	7.82
Isokinetic	9	27	10	4.80
Sports performance	9	34	31	5.61
Cluster 6				
Sports nutrition	6	18	15	5.33

The first cluster, shown in Figure 1 in red, includes 10 keywords. The term “Strength training” appeared most frequently and had the highest association strength. This cluster represents research on strength training in sports.

strength within the cluster. The keyword analysis highlights the specificity of these studies, which focus on the organization of athlete rehabilitation and their return to sport after injury.

The third cluster, shown in blue, includes seven keywords. The most frequent terms, "Athletic performance" and "Resistance training," have the highest association strength. This cluster represents research on the dynamics of athletes under the influence of strength training and its application in fitness.

The fourth cluster, marked in yellow, consists of six keywords. The most significant terms in this cluster are "Strength" and "Sport." The keywords indicate that strength is considered the primary physical quality in sports, suggesting that research in this cluster focuses on strength development across various sports disciplines.

The fifth cluster, marked in purple, includes four keywords. The most frequent term is "Football." This cluster appears to be focused on performance analysis and the role of strength training in enhancing athletic performance in this sport.

The sixth cluster is the smallest, consisting of a single keyword, "Sports nutrition," and is marked in blue. This cluster represents studies incorporating the nutritional factor. The links associated with this keyword reflect the influence of nutrition on athletes' training performance.

An analysis of the keyword clusters based on Table 1 confirms the overlap of research areas. This observation is supported by the similarity of research focus across different clusters and the recurrence of keywords among them. Another notable aspect is the minimal representation of strength sports topics in the keywords. On the one hand, this significantly broadens the scope of analysis. On the other hand, it slightly shifts the focus away from the study's stated objective.

The results of the overlay visualization are shown in Figure 2.

Keywords in Figure 2 are analyzed based on

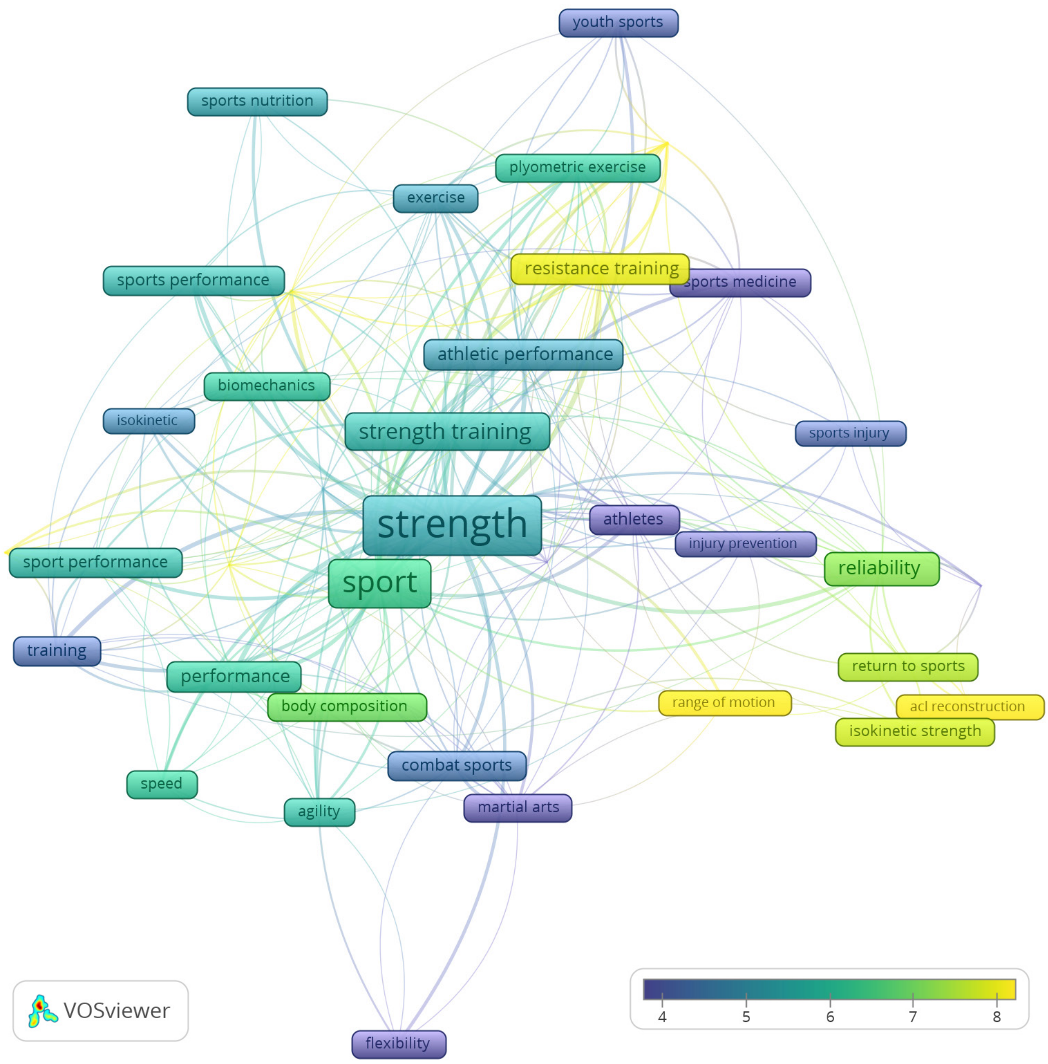

Figure 2. Average number of keyword citations in publications on power sports and overlay visualization. The source of information is the authors' research based on WoS data and analyzed using VOSviewer (November 6, 2024).

citation frequency and are color-coded accordingly. Purple represents the lowest average number of citations, while yellow indicates the highest. Analyzing the map and the data in Table 2 reveals that the keywords with the highest citation numbers are: "Range of motion" (12.00), "Act reconstruction" (11.90), "Human physical conditioning" (8.87), "Fatigue" (8.80), "Football" (7.82), "Resistance training" (7.78), and "Explosive strength" (7.77). Overlay visualization suggests that studies with a rehabilitation or recreational focus, as well as those investigating the use of strength training for recovery in other sports, can be considered promising for citation.

VOSviewer software also enables the analysis of publication datasets by author. The results of this analysis are presented in Figure 3. This map highlights the most influential authors in this research area. The total number of authors in the sample publications was 2,619. For the analysis, authors with a minimum of five publications and at least five citations were selected, narrowing the sample to 24 authors and allowing for the construction of the corresponding map.

An analysis of Figure 3 shows that the authors were divided into five clusters. The largest is the red cluster, which includes seven authors, with Rodrigo Ramirez-Campillo (22 publications) and Urs Granacher (10 publications) being the most active. The green cluster consists of six authors, with Irineu Loturco (14 publications) as the most active. The blue cluster includes four authors, with Marco Beato (8 publications) as the most active. The yellow cluster comprises three authors, with Chris Bishop (9 publications) leading in activity. The purple cluster also includes three authors, with Tomas Herrera-Valenzuela (10 publications) as the most active.

The bibliometric characteristics of the authors were taken as before to improve the quality of the analysis (Table 3).

According to the data in Table 3, the most cited authors on the studied topic are Jason Moran in cluster 1, Tomas T. Freitas and Irineu Loturco in cluster 2, Antonio Dello Iacono in cluster 3, Chris Bishop in cluster 4, and Alex Ojeda-Aravena in cluster 5.

The bibliometric analysis confirms and expands the results of the primary sample analysis, helping to establish priority research directions and identify the most influential specialists in this field.

Discussion

Literature analysis is a fundamental component of scientific research, enabling researchers to assess the current state of the problem, identify key objectives, and determine priority research areas. It also provides a basis for selecting appropriate approaches to address the issue under study. Therefore, the purpose of this study is of significant importance for the advancement of sports science. Additionally, the high popularity of strength sports among the general population further underscores the relevance of the chosen research direction.

The bibliometric method can significantly enhance the quality of analysis. VOSviewer is one of the widely used and publicly available tools for bibliometric analysis in scientific research. It is frequently applied in sports science, enabling researchers to examine publications on various topics. For instance, it has been used to analyze studies on the rehabilitation of patients with Alzheimer's disease through physical activity [44], as well as publications on kickboxing [45] and esports [46], helping to establish priority research areas in these fields.

Most publications in the sample were related to the research and evaluation of strength in sport, as confirmed by the keyword analysis (Fig. 1, Table 1).

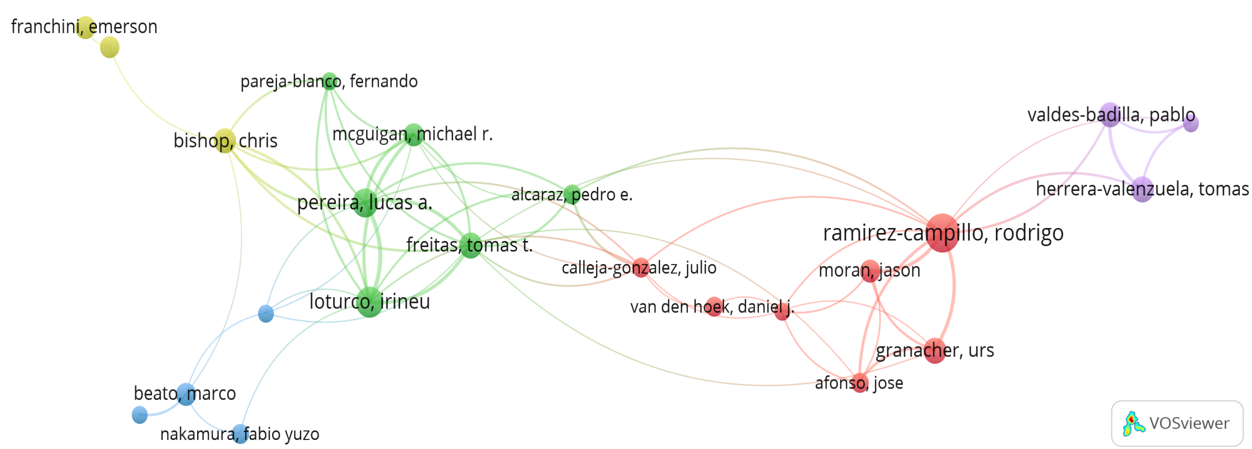

Figure 3. Main authors in strength sports research (direct citation analysis, visualization of item density, weights – citations). The source of information is the authors' research based on data retrieved from WoS and analyzed using VOSviewer (November 6, 2024).

Table 3. Bibliometric characteristics of the authors of the publications

Keyword	Link	Total link strength	Occurrences	Avq. citations
Cluster 1				
Afonso, Jose	5	16	6	3.33
Calleja-Gonzaltz, Julio	8	15	6	7.67
Clemente, Filipe Manuel	6	9	5	5.60
Granacher, Urs	5	20	10	8.50
Moran, Jason	4	16	8	10.88
Ramirez-Campillo, Rodrigo	10	39	22	8.00
Van den Hoek, Daniel	2	2	6	6.33
Cluster 2				
Alcaraz, Pedro E.	6	17	6	8.33
Freitas, Tomas T.	11	37	10	`12.00
Loturco, Irineu	9	44	14	12.00
Mcguigan, Michel R.	8	29	8	6.50
Pareja-Blanco, Fernando	5	17	5	9.60
Pereira, Lucas A.	8	43	12	11.08
Cluster 3				
Beato, Marco	4	7	8	8.50
Dello Iacono, Antonio	5	5	5	9.60
Nakamura, Fabio Yuzo	2	2	6	1.33
Raya-Gonzalez, Javier	1	4	5	5.00
Cluster 4				
Bishop, Chris	7	22	9	10.89
Detanico, Daniele	2	2	7	8.71
Franchini, Emerson	1	1	8	4.50
Cluster 5				
Herrera-Valenzuela, Tomas	3	18	10	4.50
Ojeda-Aravena, Alex	3	10	5	5.20
Valdes-Badilla, Pablo	3	17	9	4.78

However, these publications cover not only strength sports but also other sports that incorporate strength-based training. This distinction is likely due to terminological differences between English-language scientific literature and national sources on strength sports.

Most of the keywords (Table 1) reflect research methods applied to athletes, their physical condition, various training approaches, and preparation specifics. This suggests that the issue of strength training in sports is closely linked to sports monitoring. The main stages of this process include collecting and analyzing data on athletes' condition and training specifics, predicting success and skill development, and implementing corrective and optimization measures. Publications assessing training effectiveness illustrate the application of the feedback principle.

The analysis of publications in the WoS database identified the most prioritized research directions related to the studied problem. These directions can be categorized into sports-related (strength training in sports, tests, and methods for assessing and evaluating athletes' strength) and rehabilitation and recreational (the use of strength training for recovery, rehabilitation after injuries, and injury prevention in strength training).

Use of strength training in sports

Strength training enhances not only strength but also other physical qualities of athletes. A review [47] assessed the effects of weightlifting training on jumping ability, short-distance running, and change-of-direction performance. The results confirmed that such training significantly improves athletic performance.

The monitoring and diagnostics of functional parameters in strength sports athletes are described in the study [20]. Morphological parameter monitoring provides insights into adaptive potential, forming the basis for training program adjustments. The dynamics of the fat component of the somatotype allow coaches to determine optimal body composition parameters. Key risk factors have been identified, including excessive body weight and the risk of cardiovascular diseases, necessitating adjustments in athlete training.

The use of speed training in strength training is discussed in the study [48]. Interviews with high-performance coaches confirmed the importance of monitoring athletes' condition and implementing the feedback principle. A promising approach to improving training is the use of gamification. Specialized applications enhance planning, provide objective guidelines for training adjustments, monitor athletes' readiness, and assess training quality.

A review [2] discusses and summarizes the evidence on optimal strength loading, defined as the load that maximizes power output in a given exercise. This value can be determined through testing based on relative percentages of body mass. The testing protocol is characterized by its adequacy and simplicity, making it a viable alternative to traditional strength training strategies. This method can be applied across various sports and for assessing the physical health of the population.

Another review [49] investigated the effectiveness of strength training in young athletes, with the vast majority of studies supporting its benefits. Strength training enhances muscle development in young athletes. However, difficulties in formulating recommendations arise due to variations in training programs and techniques. The authors suggest guidelines on training frequency, rest intervals, intensity, and volume.

Similar results are reported in the review [25], which analyzes the potential of strength training and weight-bearing exercises for young athletes. Various performance, physical, and physiological variables, such as body composition, strength, and power, have been shown to improve with training. Designing an effective and appropriate training program requires an understanding of the sport, the scientific principles of training, and musculoskeletal development.

Another study [21] highlights the importance of strength training in non-power sports, attributing this to the biomechanical similarities between weightlifting, jumping, and sprinting movements. Incorporating weight-bearing exercises into training has been found to be more effective than general or plyometric training, as confirmed by numerous studies and meta-analyses.

In the study [1], the relative weight of physical strength factors across different sports was evaluated. Participants were classified into four types based on their dominant physical qualities: Type A – short-term muscular strength and short-term muscular endurance, Type B – medium-term muscular strength, Type C – long-term cardiorespiratory endurance, and Type D – coordination ability, agility, flexibility, and balance.

The relative weights of physical factors in Type A were: power 30%, muscular strength 18%, coordination 16%, agility 11%, flexibility 10%, cardiorespiratory endurance 1%, and balance 0%. In Type B, the relative weights were: muscular endurance 43%, muscular strength 25%, balance 9%, cardiorespiratory endurance 2%, flexibility 1%, agility 0%, and coordination 0%.

The specificity of many sports necessitates the development of strength qualities, which is particularly relevant in martial arts [14]. Strength is a key factor determining the effectiveness of techniques and strikes, as well as offensive and defensive actions. The study [3] examines the peculiarities of strength manifestation and the monitoring of strength qualities. The authors provide recommendations for their application in training wrestling techniques and strikes in mixed martial arts.

The review [50] examines strategies for optimizing training effectiveness to enhance motor skills, support long-term athletic development, and prevent injuries in young athletes. Training should follow a structured approach that ensures a gradual increase in load. A variety of equipment and implements should be incorporated to achieve a comprehensive impact on the body. When designing and monitoring strength and conditioning programs, factors such as the athlete's age, maturity level, cognitive ability, stage of puberty, training volume, and readiness level should be taken into account.

Another review [7] investigated the effects of strength, power, and speed training on change-of-direction ability. The PRISMA protocol was used as a meta-analysis tool. Strength, speed, power, and agility training were found to be effective in improving change-of-direction performance, with each quality influenced by one or more variables.

Another review [51] examined the effects of resistance training (RT) on the performance of elite athletes. A comprehensive search was conducted following the PRISMA protocol in the PubMed, Scopus, SPORTDiscus, and Web of Science databases. Studies were categorized based on competition level among elite athletes, athlete gender, performance outcomes, and training focus. The results of the meta-analyses revealed a significant overall effect of RT on sport-specific outcomes. Weight training was shown to be effective in enhancing performance in elite athletes. The findings emphasize the need for personalized RT regimens and the implementation of advanced RT techniques.

Strength is a key predictor of success in American football, making strength training a central component of athletic preparation in this sport. The study [4] examined the effectiveness of strength training with varying loads on the performance of professional football players. A six-week strength training program was implemented, with anthropometric indices and motor test results used as criteria for training effectiveness. The findings confirmed an increase in hip circumference and maximum sprint speed following the program.

Success in throwing is largely dependent on strength levels. The study [5] highlights the importance of upper body strength training for throwing performance. The aerobic intervention method has been identified as an effective approach to enhancing upper body strength in athletes involved in this sport. It is recommended that athletes incorporate upper extremity strength training into their daily workouts.

Volleyball requires high levels of maximal strength, reactive strength, and power at the elite level. The study [8] evaluated the effects of a six-week strength training program on professional athletes. A three-phase training method was implemented to enhance muscle actions by integrating eccentric, isometric, and concentric phases. The effectiveness of the program was confirmed.

Success in basketball is also influenced by strength, speed, and agility [52]. The study presents a comparative analysis of the relationships between anthropometric and physical measures in elite young athletes, identifying key predictors of speed and agility. Body fat percentage was found to be a significant predictor for speed and agility tests across all age groups but a negative predictor of muscle strength. It is recommended that this indicator be taken into account when designing individual training programs for players and in talent identification processes.

A review [10] examined the influence of physiological, biomechanical, and anthropometric characteristics on swimming performance. The findings indicate that higher levels of muscle strength, muscle power, and lean body mass contribute positively to swimming performance. Muscle strength and power are particularly crucial for starts and turns. Additionally, anaerobic and aerobic metabolic rates were identified as important performance determinants, with aerobic capacity being especially significant in middle- and long-distance events.

Lifting in kettlebell sport is performed through pushing and jerking movements. However, the specific mechanics of these movements remain insufficiently studied. It has been suggested that findings from other sports can be used as reference points. For instance, the kinematics of unilateral and bilateral overhead jerks were analyzed in the study [53]. The range of motion in the shoulder joint and the strength of rotator muscles during these movements were examined and compared. The study involved athletes from sports requiring unilateral (badminton) and bilateral (swimming) jerks. The results indicated that athletes performing unilateral jerks exhibited greater shoulder motion asymmetry and rotational strength than those engaged in bilateral jerks.

A study [9] examined the relationships between strength, speed, and performance in ice hockey, considering participants' age and training level. The findings indicated that maximal strength influences sprinting performance on ice, as well as performance differences between age groups and professional players. It was suggested that strength and jump performance assessments be incorporated into regular ice hockey testing protocols.

A review [11] examined the role of strength development in successful punching in boxing. The study identified key factors influencing punching power, including body mass, gender, technique, and punching characteristics. A direct correlation between strength development and punching power was confirmed. The findings highlight the need for further research in this area.

The use of tests and samples to assess and analyze strength in sports

The importance of using tests for monitoring athletes is undisputed. These tests must be adequate, informative, and valid. A study [54] assessed the reliability of the squat test, suggesting that reliability should be evaluated using correlation values and the coefficient of variation. The findings confirmed that the squat test is a valid and reliable measure of lower limb performance.

The study [18] proposed a method for selecting measurement tests to assess athletes' physical fitness. This method incorporates multiple levels of validity by linking test measurements with competition results. Test selection is based on factors influencing athletic performance, ensuring that the most appropriate and informative assessments are chosen.

The correct selection of a battery of tests for analysis significantly enhances its effectiveness. The study [55] applied a set of anthropometric indicators and physical fitness tests to assess the condition of young handball players. Evaluations were conducted at the beginning and end of the season to monitor athletes' physical status. The observed increase in body weight and decrease in fat percentage were interpreted as indicators of muscle mass gain. Physical fitness parameters were shown to improve over the course of the season.

Similar findings were reported in the study [56], where a set of indicators and tests was used to assess the condition of elite basketball players based on their playing positions. The study confirmed the informativeness of assessing strength development, body composition, and the cardiorespiratory system.

A similar study design was used in the study [57], where the authors evaluated the physical profile of sub-elite female cricket players across different playing roles. The assessment included body composition analysis, muscle strength testing using dynamometry, a 2 km run, countermovement jump (CMJ), single-leg jump (SLJ), isometric mid-thigh pull, push-up, and jumping jacks on weight plates. Body composition and musculoskeletal profiles were identified as baseline markers for determining playing roles in sub-elite women's cricket. This information can be utilized to enhance fitness, support player selection, and predict skill development.

The relevance of tests to the specificity of the sport is the primary criterion for their selection. The study [15] applied a battery of strength tests for a comparative analysis of climbing athletes. General muscular strength was assessed using arm dynamometry, the bent-arm hang, and the bar hang. Specific muscular strength was evaluated through the maximal finger flexor strength test, the finger hang on bent arms on the fingerboard, and the finger hang. The results suggest that assessing both specific and general muscular strength can serve as a useful tool for sport-specific selection.

The specificity of climbing necessitates the analysis of strength not only in the hand and forearm but also in individual fingers. The study [17] proposed and tested tests to assess these parameters, concluding that intermittent muscular endurance is a key predictor of success in difficult climbing.

A similar research focus was observed in the study [16], where the authors compared forearm muscle and grip strength in climbers performing different types of finger hangs. Maximum loads of individual muscles, as well as flexors and extensors of the fingers and hands, were recorded. The study identified the grip type that allows for the most efficient load execution.

A similar approach was used in the study [58], where the authors assessed the reliability of a battery of handball strength tests using a functional electromechanical dynamometer (FEMD) and examined the relationship between these tests and performance metrics. The findings confirmed high reliability across all exercises and significant correlations with sprint time and throwing speed. It was recommended that these tests be used to evaluate training effectiveness in handball teams.

A review [13] analyzed the performance of Greco-Roman and freestyle wrestlers, with strength indices serving as key comparison criteria. These included grip strength, isometric back and leg strength, power endurance, and anaerobic power indices. The findings indicated that Greco-Roman wrestlers exhibited greater isometric strength, muscle power, and speed indices, whereas freestyle wrestlers demonstrated higher flexibility. The results were interpreted in the context of the specific demands of each wrestling style.

The study [19] presents the results of monitoring the anthropometric and physical characteristics of international women's rugby union players over five seasons. Body weight, skinfold thickness, and fat deposits were analyzed, while physical fitness was assessed using the bench press, single-leg squats, and sprint time. The findings confirmed the applicability of these criteria for evaluating the dynamics of athletes' fitness.

The importance of strength development in rugby is highlighted in the study [6]. The authors examined the strength-velocity profile of young rugby players in strength exercises and compared gender differences. The squat and bench press were used as test exercises, confirming the relationship between strength and speed performance. The findings are suggested for improving the quality of rugby training.

Another informative test for assessing strength capabilities was proposed in the study [59]. The authors applied the isometric pull-to-mid-thigh test to examine the relationship between strength and momentum. The findings confirmed correlations between the results of this test, jumping tests, and sprint performance. It was concluded that the isometric mid-thigh pull test can be used to assess maximal and rapid force expression.

Similar results were reported in the study [60], where the authors used an isometric hip stability test to evaluate the strength of the posterolateral thigh muscle. The study confirmed that this field test serves as a quick and convenient screening tool for monitoring muscle strength in an athletic setting.

Grip performance, including strength and endurance, is a key predictor of success in martial arts. The study [61] conducted a comparative analysis of these parameters in judo athletes and non-athletes. The assessment included the maximum isometric grip test (three repetitions of 5 seconds each with 90-second intervals) and the isometric grip strength and endurance test (ten repetitions of an isometric grip for 10 seconds each with 20-second intervals) performed with both the dominant and non-dominant hands. The grip strength-to-body weight ratio was used as an evaluation metric, while the strength ratio at the beginning and end of the test served as an index of fatigue. The results indicated that most indices were significantly higher in athletes.

Similar results were reported in the study [34], which examined grip strength in static and impulse modes among armwrestlers with different training backgrounds. The study proposed the use of multiple indices linking grip strength to body weight. Higher indices were observed in more experienced lifters, confirming the importance of grip strength in various modes as a predictor of success in armwrestling.

A similar analysis was conducted in the study [62], where the authors investigated grip strength characteristics in judo athletes and correlated these parameters with the performance of sport-specific tasks. Grip strength was assessed in standing and sitting positions, using one hand and both hands simultaneously, as well as in dynamic and isometric modes. Special indices were calculated based on the obtained results.

The study [63] examined possible relationships between hand grip strength and anthropometric characteristics, body composition, and sport-related parameters. The findings confirmed that gender, dominant hand, fat mass, and muscle mass are significant predictors of grip strength.

The development of specific research protocols is essential for assessing athletes' grip strength. This objective was addressed in the study [64], which evaluated the functional status of female pole dancers. Maximum voluntary isometric contractions were measured in three sport-specific positions on the pole (shoulder extension and adduction, hip adduction). The study concluded that the strength assessment protocol is a reliable and functional analysis tool, suitable for objective strength testing.

The study [65] applied the Delphi method to develop an index system for assessing the specific physical fitness of Chinese wheelchair badminton players. The authors established a hierarchical structure of key indices based on their weighting: sport-specific skills (0.4406), athletic qualities (0.2928), cardiorespiratory system status (0.1828), and body proportions (0.0838). The index system demonstrated high reliability and specificity for evaluating wheelchair badminton players.

The study [12] examined limb strength in kickboxers by measuring the isometric strength of the extensors and flexors of the upper and lower limbs. The BTE PrimusRS system (BTE USA, New Hampshire) was used as a dynamometer. The findings confirmed upper extremity strength symmetry, while the lead leg exhibited a higher level of muscle strength. A comparison of strength test results with technical and tactical training indicators highlighted the necessity of developing extensor and flexor strength in the lower limbs.

Another study [66] compared the maximal isometric and dynamic strength of MMA athletes, considering their competitive level and weight category. Isometric strength was assessed using grip strength and isometric lumbar strength tests, while dynamic strength was evaluated through a single maximal bench press and leg press. A one-way analysis of variance revealed differences between groups in absolute and relative bench press performance, as well as in absolute isometric lumbar strength. The study suggested that these tests could be used to differentiate MMA athletes based on strength characteristics.

A set of tests and assessments was applied in the study [67] to examine the relationship between performance, anthropometric indices, somatotype characteristics, and strength performance in swimmers. Anthropometric data were collected using the ISAK protocol with a Tanita HD 357 digital scale and a Rosscraft Centurion kit. Jump height was measured using a DmJump® contact platform. Strength was assessed through a maximal bench press and pull-ups, while hand grip strength was evaluated with a digital dynamometer. The findings confirmed an inverse correlation between swimming performance and the studied indices.

A promising test for talent identification and success prediction in sports is the ratio of the lengths of the second and fourth fingers of the right hand (2D:4D). The study [68] analyzed this index in martial arts athletes and non-athletes, revealing that athletes had a lower 2D:4D ratio compared to the control group. A negative correlation between this index, grip strength, and the muscular component of somatotype was confirmed. The findings suggest that 2D:4D could be included as one of the indices for assessing strength potential.

A review [69] presents data on the assessment of isokinetic torso strength in athletes of different ages. Muscle assessment methods using an isokinetic dynamometer are considered reliable, demonstrating a strong correlation with peak strength values and flexor/extensor ratios across various age groups. Isokinetic performance data for torso muscles also correlate with anthropometric parameters, sport type, and training volume. The impact of sports training on muscle strength is evaluated both as a positive factor and as a potential risk factor for back injuries.

Another review [70] examined evidence on improving motor competence in young athletes. Functional movement screening was the most commonly used assessment method, with squats being the most frequent test. The squat load varied from bodyweight to barbells of different weights.

The use of strength training for wellness, recovery, and rehabilitation after injury, and injury prevention.

A review [71] analyzed the occurrence of overexertion (OR) and overtraining syndrome (OTS) in strength sports and resistance training (RT). The findings confirm that short periods of OR caused by high-volume or high-intensity RT can lead to functional overexertion (FOR). Additionally, evidence suggests that chronic high-volume and/or high-intensity RT can result in non-functional overexertion (NFOR). The development of practical tools for detecting and diagnosing the transition from FOR to NFOR, and subsequently to OTS, in strength sport athletes is recognized as a promising research direction.

The high incidence of injuries in sports necessitates the search for effective rehabilitation methods, with strength training playing a key role. The study [72] examined the effect of a nine-week strength training protocol on the prevalence and incidence of overexertion injuries in young tennis players. However, the small sample size prevented confirmation of the study's hypothesis.

A review [73] discussed the significance of methods for testing the strength and stability of major muscle groups in both sports and rehabilitation. The review emphasized the importance of exercises that assess muscle strength, speed, and power, highlighting their relevance for designing rehabilitation and training programs aimed at enhancing athletic performance and reducing the risk of back pain.

Hamstring injuries are among the most common muscle injuries in sports, often resulting from excessive strain and insufficient hamstring strength. The study [74] investigated the relationship between hamstring flexibility and the concentric and eccentric strength of the hamstring and quadriceps muscles in athletes. Flexibility of the posterior thigh muscles was assessed by measuring the active knee extension angle using a goniometer, while muscle strength was evaluated with an isokinetic dynamometer. The findings suggest that flexibility may negatively affect concentric muscle strength in female athletes, as they tend to be more flexible and have lower muscle strength compared to male athletes. Based on these results, it is recommended that concentric and eccentric strength exercises be incorporated into female athletes' training programs, while flexibility-enhancing exercises should be prioritized for male athletes.

A similar research focus was observed in the study [75], which examined the effects of training on the hamstrings and investigated risk factors for hamstring injuries. The findings indicate that increased hamstring strength can reduce the risk of injury.

The study [76] compared functional test results and injury rates in relation to different strength measures of the thigh muscles. Strength-to-weight ratio indices were used for assessment, revealing that participants with lower strength scores exhibited poorer hamstring functional status.

Assessing rehabilitation effectiveness also necessitates the development of specialized tests. The study [77] validated a shoulder strength test to evaluate an athlete's readiness to return to sport after injury. This test measures strength in three shoulder extension positions (90, 135, and 180 degrees) using weight plates. The authors compared its effectiveness with dynamometer-based force testing, confirming the test's reliability and validity.

Another study [78] compared the lower limb muscle strength of the intact limb in individuals with a history of hamstring injury to the dominant limb in those without such an injury. Maximal isometric strength was assessed in six muscle groups using a hand-held dynamometer. Separate two-factor analyses of variance were conducted for each muscle group, considering limb and sex as factors. The study design can be applied to assess the effectiveness of rehabilitation programs.

The study [79] analyzed the preventive and therapeutic effects of functional strength training on calisthenics injuries. Training outcomes were evaluated using a functional motor test scale. The findings confirmed that functional strength training enhances overall strength development, improves movement coordination, control, and stability, and increases athletes' overall strength. Additionally, it was shown to be an effective method for preventing sports injuries.

Another study [80] examined differences in maximal strength, flexibility, and body composition among CrossFit® participants based on their competition category. Strength was assessed using the maximal bench press and bodyweight squats, flexibility was measured with the Flexitest, and body composition was analyzed using bioimpedance. The results revealed statistically significant differences in maximal strength between competition categories, while no significant differences were observed in body mass, fat mass, or muscle mass.

Conclusions

An analytical review of publications in the WoS database on power sports was conducted using the bibliometric method. The priority research directions in this field were identified, including sports-related aspects (strength training in sports, tests, and methods for assessing and evaluating athletes' strength) as well as rehabilitation and recreational aspects (the use of strength training for recovery, rehabilitation after injuries, and injury prevention).

A wide range of tests and measurements are employed to assess athletes' strength, which must meet the principles of specificity, simplicity, reliability, and practicality. The most commonly used assessments include body composition indices, anthropometric criteria, and strength performance indicators. Among strength exercises, the most frequently applied are the bench press, grip strength tests, squats, and jumps. The effectiveness of these tests for monitoring athletes' condition, selection, and performance prediction has been confirmed.

Conflict of interests

The authors declare that there is no conflict of interests.

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ORIGINAL ARTICLE

Effectiveness of two different recovery process on blood lactate removal pattern of soccer players

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Abstract

Background and Study Aim Soccer is a high-intensity intermittent sport that requires players to alternate between explosive activity and recovery. This often leads to significant blood lactate accumulation, a by-product of anaerobic metabolism, which can impair performance by inducing muscular fatigue and reducing the ability to sustain optimal effort. This study aimed to examine the effect of two different recovery processes on the blood lactate removal pattern of soccer players in Tripura.

Material and Methods Ten male junior national soccer players from Tripura were purposively selected for the study. Participants performed graded exercise on a treadmill, followed by either active or passive recovery on two separate days. Blood samples were collected before exercise, after 10 minutes of graded exercise, and after five minutes of treadmill running at 90% intensity. Additional samples were taken immediately after five minutes of active or passive recovery and at 10, 20, 30, 40, 50, and 60 minutes of rest. Data were analyzed using a paired t-test, with the level of significance set at 0.05.

Results Statistical analysis showed a significant difference in blood lactate removal between active and passive recovery ($P<0.05$). Active recovery led to peak removal at the 5th and 20th minutes, while passive recovery showed maxima at the 10th and 40th minutes. Neither method restored blood lactate to baseline within one hour. Active recovery facilitated the highest lactate removal between phases III-IV (28.44%) and V-VI (28.04%), while passive recovery peaked at 23% between phases IV-V. After 60 minutes, lactate clearance reached 96% with active recovery and 91% with passive recovery. Logistic model analysis ($p=0.06$) suggested that active recovery was more effective, though significance was observed at the 0.10 level.

Conclusions The findings of this study indicate that low-intensity active recovery is a more effective strategy for accelerating blood lactate removal in soccer players compared to passive recovery. Incorporating active recovery into training and competition protocols can enhance post-exercise physiological recovery and support sustained performance.

Keywords: blood lactate, graded exercise, active, soccer, passive recovery

Introduction

The study of recovery methods in sports science is essential for understanding and enhancing athletic performance. Among the key factors influencing recovery is the removal of blood lactate, a by-product of anaerobic metabolism that accumulates during high-intensity exercise. Soccer, a sport characterized by its dynamic, intermittent nature, requires effective recovery strategies to mitigate the physiological challenges of accumulated fatigue and maintain optimal performance.

Soccer is classified as an intermittent sport, with activity changes occurring every 4–6 seconds [1]. Soccer players experience temporary fatigue during different phases of the game [2]. The onset of fatigue has been linked to high muscle lactate concentration, low muscle creatine phosphate levels, extracellular potassium accumulation, muscle glycogen depletion, thermal stress, and dehydration [1]. Jimenez et al. [2] reported that impaired sarcolemma excitation and disturbances in ion homeostasis within muscle cells may contribute to fatigue.

According to scientists and sports trainers, the two most important physiological parameters for analyzing aerobic capacity are heart rate and blood lactate responses [3]. Several studies have indicated that lactic acid, which accumulates during intense exercise, can be removed from the blood by various organs, including the liver, myocardium, renal medulla, and brain. However, the majority of lactate is cleared by skeletal muscle [4, 5].

Blood lactate removal is influenced by the type of exercise, training status, muscle fiber composition, and intensity of recovery exercise [4]. Gur reported that the recovery process enhances blood flow to working muscles, accelerates the resynthesis of high-energy phosphates, replenishes oxygen in the blood, and facilitates lactate clearance. Furthermore, post-exercise basal blood lactate levels are typically restored within an hour, and light exercise during recovery can enhance lactate removal.

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One of the most important aspects of the recovery process is the removal of lactic acid from the blood and muscles. Additionally, active recovery has been found to be more effective for lactic acid clearance compared to passive recovery. However, the optimal intensity of active recovery remains unclear [6].

Davis and Gass [7] reported that after high-intensity exercise, the rate of blood lactate removal increased with low-intensity active recovery. Another study demonstrated that blood lactate removal was higher at 40% of maximum speed compared to passive recovery and 60% of maximum speed [8]. Eliakim et al. found that motivational music during non-structured recovery enhanced lactate clearance. Fox et al. [9] stated that maximal lactic acid removal occurs within 1 hour and 15 minutes of passive recovery following maximal exercise.

Recovery processes, both active and passive, play a crucial role in facilitating blood lactate clearance. Active recovery, involving low-intensity physical activity, is widely recognized for promoting faster lactate removal through enhanced blood circulation and metabolic activity. In contrast, passive recovery, characterized by rest or minimal physical activity, allows the body to restore energy stores but is less effective in lactate clearance. Understanding the comparative effectiveness of these two recovery modalities is essential for optimizing recovery strategies tailored to soccer players.

Previous research has emphasized the importance of recovery in various sports contexts, but few studies have specifically examined soccer players, particularly in relation to positional roles and physical demands. Furthermore, the influence of different recovery methods on lactate removal patterns in soccer-specific scenarios remains underexplored. The present study aimed to assess the effect of low-intensity (25%) active recovery and passive recovery on blood lactate clearance in junior-level soccer players from Tripura.

Materials and Methods

Participants

The selected subjects of the study were 10 male U-17 National-level soccer players, age 15.6±0.52 years, height 167.25±6.09 cm, weight 53.45±4.07 kg, from Tripura Sports School (TSS). They were also members of the State Junior Football team. The subjects were informed in detail about the experimental procedure and agreed to volunteer for the study. They also provided written consent, including parental consent for participation. Prior to the test, ethical approval was obtained from the ethical committee of Tripura University.

Research Design

Exercise protocol

The maximum speed ability of the subjects was assessed using a repeated 50-meter flying start test. The laboratory tests were conducted in the morning under controlled conditions. Subjects were instructed to refrain from training for 24 hours before each test day. Each participant completed a submaximal exercise test followed by two recovery sessions (active or passive) on separate days.

The test began at 40% intensity, with increments of 10% every 2 minutes until reaching 80% intensity. Participants then ran at 90% intensity for 5 minutes. Exercise intensity was determined using a standard maximum speed ability test for each individual. The exercise sessions were conducted one week apart, with the same protocol applied on both days.

Recovery Protocol

Active Recovery – After submaximal exercise, participants ran for 5 minutes at 25% intensity on a treadmill, followed by 1 hour of seated rest. Passive Recovery – After submaximal exercise, participants rested in a supine position (Shavasana) on a yoga mat for 5 minutes, followed by 1 hour of seated rest.

Blood Sampling

Blood samples were collected before exercise, after submaximal exercise, immediately after 5 minutes of active or passive recovery, and at 10, 20, 30, 40, 50, and 60 minutes during rest. Samples were obtained from the fingertips and analyzed using the Lactate Pro 2 Blood Lactate Test Meter (Arkray, Koka-shi, Japan). Heart rate was continuously monitored throughout the test.

Statistical Analysis

Statistical analysis was performed using Microsoft Excel 2021. A paired t-test was used to compare blood lactate removal patterns between active and passive recovery, with the significance level set at $P<0.05$. Additionally, a logistic model was applied to the data to identify the most effective recovery method for U-17 soccer players.

Results

Statistical analysis indicated a significant difference in blood lactate removal patterns between active and passive recovery ($P<0.05$). Blood lactate removal was highest immediately after 5 minutes of active recovery and again after 20 minutes. In contrast, during passive recovery, the maximum removal was observed at the 10th and 40th minutes. However, neither recovery method restored blood lactate to baseline within one hour, indicating that complete recovery was not achieved under these testing conditions.

Table 1 presents the descriptive statistics for age and physical characteristics of U-17 soccer players from Tripura. The mean age was 15.6±0.52 years, height was 167.25±6.09 cm, and weight was 53.45±4.07 kg.

Table 1. Descriptive statistics of age and physical measurements of soccer players

Variables	N	Range	Mean ± SD
Age (years)	10	15–16	15.6 ± 0.52
Height (cm)	10	160.5–181	167.25 ± 6.09
Weight (kg)	10	48–60	53.45 ± 4.07

Figure 1 illustrates the accumulation and removal patterns of blood lactate in soccer players. The blood lactate pattern was formed based on mean values recorded at different phases of the program. During exercise, lactate accumulated progressively, and its removal followed the given exercise protocol. The figure demonstrates similar blood lactate removal patterns in both recovery processes.

In the active recovery process, the highest lactate removal occurred between phases III-IV and V-VI, with percentage reductions of 28.44% and 28.04%, respectively. The lowest removal rate (13.73%) was recorded between phases VI-VII at the 30th minute. In passive recovery, the maximum removal (23%) occurred between phases IV-V, with a steady removal rate of 15% observed after 50 minutes. This indicates that low-intensity active recovery initiates lactate clearance earlier than passive recovery.

Table 2 presents the percentage change in blood lactate removal for both recovery processes. The values clearly show that low-intensity activity promotes faster lactate clearance compared to passive recovery (Shavasana). Active recovery facilitated a 96% lactate removal after 60 minutes, whereas passive recovery resulted in 91% clearance.

Table 2. Percentage Change in Blood Lactate Removal During Active and Passive Recovery

Phase	Time (min)	Active Recovery (%)	Passive Recovery (%)
IV	5	33.46	21.45
V	10	52.13	45.78
VI	20	70.64	59.08
VII	30	77.35	71.15
VIII	40	84.93	80.38
IX	50	91.51	85.97
X	60	96.14	91.12

Logistic model analysis yielded a p-value of 0.06, indicating that the slope was not significant at the 0.05 level but was significant at the 0.10 level. Consequently, a logistic model was developed at the 0.10 significance level, which may help determine the most effective recovery method for soccer players.

$$\text{Model:} \quad P = \frac{1}{1+e^{-}\,[\beta_0+\beta_1 x_1]}$$

$$\text{Model:} \quad \mathrm{P} = \frac{1}{1+e^{-}\,[-7.5169+0.5310x_1]}$$

Discussion

Blood lactate removal is a critical factor in sports recovery, particularly in high-intensity sports such as soccer, swimming, and judo. Various studies have investigated the efficacy of different recovery methods, providing valuable insights into optimal lactate clearance strategies.

Active recovery combined with compression therapy and neuromuscular electrical stimulation (NMES) has been shown to be more effective than passive recovery and massage therapy [9]. Evans and Cureton reported that optimal lactate removal occurred at 25% to 65% of VO_2 max during treadmill and bicycle ergometer exercises [10]. Another study demonstrated that, in the initial phase of recovery, active recovery at 60% of maximum heart rate was more effective than at 55% or 65% of maximum heart rate, as well as passive recovery [11]. Additionally, motivational music during non-structured recovery enhanced activity levels, improved lactate clearance, and reduced perceived exertion [12]. Furthermore, increased inspiratory resistance during recovery from intense exercise has been shown to accelerate lactate removal. Bakers and King [4] suggested that continuous activity was more beneficial for lactate removal than intermittent activity.

The current study showed that 25% active recovery was more beneficial for Tripura's U-17 National-level football players in the early stages of recovery compared to passive recovery. Xie et al. [11] supported these findings, which are consistent with the present study.

A study on judokas demonstrated a similar recovery pattern after active and passive recovery. In competitive situations, judokas required approximately one hour to return to baseline levels of blood lactate, heart rate, and respiratory rate following a bout [13]. A recent study found that, 24 hours after a lactate tolerance exercise test, elite male swimmers exhibited blood lactate levels below baseline [14]. Devlin et al. reported that maximal lactic acid removal occurs within 1 hour and 15 minutes of passive recovery following maximal exercise [15].

In the present study, soccer players removed approximately 96% of blood lactate after 5 minutes of active recovery, whereas around 91% was cleared after 5 minutes of passive recovery. These results indicate that a 5-minute active recovery is more effective for blood lactate removal, while passive recovery shows a slower clearance rate.

A logistic model was applied to determine the optimal recovery method for U-17 soccer players at a 0.10 level of significance. However, further studies with a larger sample size are recommended to refine the model and enhance its applicability.

The study's findings demonstrate a significant difference in blood lactate removal patterns between active and passive recovery ($P<0.05$). Active recovery facilitated faster lactate removal, with peak clearance observed at the 5th and 20th minutes. This aligns with previous research indicating that active recovery enhances blood circulation, thereby accelerating lactate clearance through oxidation or gluconeogenesis [11]. In contrast, passive recovery exhibited peak lactate removal at the 10th and 40th minutes. Despite these patterns, neither recovery method restored lactate levels to baseline within one hour, suggesting that this duration was insufficient under the given testing conditions [16].

The developmental stage of adolescent athletes plays a crucial role in recovery, as physiological adaptations significantly impact performance. These factors are essential when assessing lactate dynamics, as body composition and metabolic capacity influence the rate of lactate removal [17].

During active recovery, the highest removal rates occurred between phases III-IV (28.44%) and V-VI (28.04%), aligning with findings from [20], which suggest that moderate-intensity activities enhance lactate metabolism. The passive recovery process exhibited a peak removal rate of 23% between phases IV-V, followed by a consistent but slower clearance after 50 minutes. This slower pace is attributed to the lack of circulatory stimulation in passive recovery, corroborating studies by Baldari et al. [18]. Active recovery achieved a clearance rate of 96.14% within 60 minutes, surpassing the passive recovery rate of 91.12%. The faster clearance in active recovery highlights its effectiveness in promoting lactate metabolism, supporting previous studies on the role of low-intensity exercise in maintaining muscle contraction and venous return [19]. Passive recovery methods, such as Shavasana, rely on natural metabolic processes, resulting in slower clearance rates.

These findings provide practical insights for soccer coaches and sports scientists. Implementing active recovery protocols, such as light jogging or dynamic stretching, between intense training sessions or matches can accelerate lactate removal, enhance recovery, and optimize performance. However, further research is needed to determine whether extending the recovery duration beyond one hour could facilitate baseline lactate clearance and improve post-exercise recovery outcomes.

Conclusions

The study found that low-intensity active recovery (at 25% intensity) significantly improves blood lactate clearance rates compared to passive recovery strategies such as Shavasana among Tripura U-17 national football players. Active recovery showed a faster onset and higher efficiency in lactate elimination, with approximately 96% clearance within 60 minutes. In contrast, passive recovery resulted in around 91% clearance over the same period. However, neither approach was successful in totally restoring lactate levels to baseline within the one-hour monitoring period. This emphasises the better efficacy of active recovery while simultaneously highlighting its limitations in reaching complete recovery within the period.

Study Limitation

A limited sample size of ten male participants limits the generalisability of the study's findings. Furthermore, the study focused primarily on two recovery modalities and only tracked recovery for an hour. To address these limitations, future research should investigate a larger range of recovery approaches, lengthen the monitoring period, and evaluate additional physiological and biochemical markers to gain a more complete understanding of recovery processes.

Future Research Direction

While the logistic model employed to predict recovery efficiency was statistically significant at the 0.10 level, additional refining and validation with a larger sample size may improve its resilience and dependability. Future research that incorporate more diverse populations, different recovery protocols, and more variables may improve the practical applicability of our findings, assisting in the optimisation of recovery techniques for football players and athletes in other sports disciplines.

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Conflict of Interest

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

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