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The Journal welcomes articles on different aspects of physical education, sports and health of students which cover scientific researches in the related fields, such as biomechanics, kinesiology, medicine, psychology, sociology, technologies of sports equipment, research in training, selection, physical efficiency, as well as health preservation and other interdisciplinary perspectives.

In general, the editors express hope that the journal "Physical Education of Students" contributes to information exchange to combine efforts of the researchers from the East-European region to solve common problems in health promotion of students, development of physical culture and sports in higher educational institutions.

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CONTENTS

PHYSICAL EDUCATION OF STUDENTS

ORIGINAL ARTICLE

The effect of a 10-week aerobic exercise program on cardiorespiratory endurance and resting heart rate in university students

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Abstract

Background and Study Aim Physical inactivity during young adulthood is associated with reduced cardiorespiratory fitness and elevated resting heart rate. Both are predictors of long-term cardiovascular risk. The present study aimed to examine the effects of a 10-week structured aerobic exercise program on cardiorespiratory endurance and resting heart rate in sedentary university students.

Material and Methods This controlled experimental study employed a pretest–posttest design with an exercise group (n = 15) and a control group (n = 10). Participants were sedentary individuals aged 18–25 years. The exercise group completed supervised aerobic training three days per week for 10 weeks at 50–75% of maximum heart rate. The control group maintained usual daily activities. Cardiorespiratory endurance was assessed using the Cooper 12-minute run test. Resting heart rate was measured under standardized seated conditions. Data were analyzed using IBM SPSS Statistics (Version XX). Normality was assessed via the Shapiro–Wilk test. Between- and within-group comparisons were performed using independent and paired samples t-tests (or non-parametric equivalents where appropriate). Effect sizes (Cohen's d) were calculated based on pooled standard deviations of change scores.

Results The exercise group demonstrated significant improvements in cardiorespiratory endurance ($p = .01$; $d = 0.98$) and significant reductions in resting heart rate ($p = .007$; $d = 1.21$). No significant changes were observed in the control group.

Conclusions A 10-week aerobic exercise program significantly improves cardiorespiratory endurance and lowers resting heart rate in sedentary young adults. Given the modest sample size, the findings should be interpreted as moderate-to-large effect estimates that require confirmation in larger trials.

Keywords: aerobic exercise, cardiorespiratory endurance, resting heart rate, sedentary lifestyle, university students

Introduction

Regular physical activity plays a central role in maintaining cardiovascular health and functional capacity during early adulthood. Cardiorespiratory endurance and resting heart rate are widely used physiological indicators reflecting the efficiency of the cardiovascular system and the overall level of physical fitness. Reduced levels of cardiorespiratory fitness together with elevated resting heart rate are associated with less favorable cardiovascular functioning and may indicate decreased adaptive capacity of the organism. In populations of young adults, lifestyle patterns characterized by limited physical activity can negatively influence these indicators and contribute to less optimal physiological regulation. This trend reflects a broader shift toward sedentary behavior observed in modern societies.

A sedentary lifestyle has emerged as a major public health concern, particularly among young adults, due to a marked decline in daily physical activity levels. The World Health Organization identifies physical inactivity as one of the leading risk factors for cardiovascular diseases, metabolic disorders, and premature mortality [1]. The increasing prevalence of sedentary behaviors during young adulthood adversely affects cardiovascular function, leading to reductions in cardiorespiratory endurance and overall physical fitness [2].

Cardiorespiratory endurance is defined as the ability of the cardiovascular and respiratory systems to supply oxygen to working muscles during prolonged physical activity and to utilize this oxygen efficiently. Higher levels of cardiorespiratory endurance are strongly associated with a reduced risk of cardiovascular disease and all-cause mortality [3, 4]. Conversely, low cardiorespiratory endurance is closely linked to physical inactivity. It is also considered an independent predictor of adverse health outcomes [5]. Therefore, improving cardiorespiratory endurance is a primary target in exercise-based health promotion strategies.

Resting heart rate is another important physiological indicator of cardiovascular health and autonomic nervous system regulation.

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A lower resting heart rate reflects enhanced parasympathetic activity and greater cardiovascular efficiency. In contrast, an elevated resting heart rate is associated with an increased risk of cardiovascular morbidity and mortality [6]. Previous studies have demonstrated that resting heart rate is a modifiable parameter. It responds favorably to regular physical activity and aerobic exercise interventions [7].

Aerobic exercise involves rhythmic and continuous movements of large muscle groups. It is widely recognized for its positive effects on the cardiovascular and respiratory systems. Regular participation in aerobic exercise has been shown to improve stroke volume and enhance myocardial efficiency. It also induces favorable adaptations in autonomic regulation. These adaptations result in increased cardiorespiratory endurance and decreased resting heart rate in sedentary individuals [2, 8, 9]. Despite these well-documented benefits, sedentary behavior remains highly prevalent among university-aged populations. Controlled experimental studies that compare exercise and control groups provide robust evidence regarding the physiological effects of structured exercise interventions. In addition, including both female and male participants allows for a more comprehensive evaluation of exercise-induced adaptations in young adults [10].

Analysis of research findings has shown that regular aerobic exercise contributes significantly to improvements in cardiorespiratory endurance and to favorable adaptations in cardiovascular regulation. Researchers emphasize that higher levels of cardiorespiratory fitness and lower resting heart rate are important indicators of cardiovascular health. They are strongly associated with reduced risks of cardiovascular diseases and adverse health outcomes. Authors also highlight the role of structured physical activity in promoting physiological adaptations that enhance cardiovascular efficiency and autonomic balance in young adults. At the same time, the growing prevalence of sedentary behavior among university-aged populations underscores the importance of further examining how structured aerobic exercise programs influence key cardiovascular parameters in this group. This gap continues to limit a comprehensive understanding of the physiological responses to aerobic exercise in sedentary young adults. It also highlights the need for further investigation in this area. However, there is still a need for controlled studies that examine the effects of structured aerobic exercise programs on key cardiovascular parameters in sedentary young populations.

Therefore, the purpose of this study is to investigate the effects of a 10-week aerobic exercise program on cardiorespiratory endurance and resting heart rate in sedentary females and males aged 18–25 years. It is hypothesized that participants who engage in the aerobic exercise program will demonstrate significant improvements in cardiorespiratory endurance. They will also demonstrate significant reductions in resting heart rate compared with a control group that does not participate in structured exercise.

Materials and Methods

Participants

The study sample consisted of 25 sedentary volunteers aged 18–25 years. Sedentary status was defined as not participating in regular physical activity at least three days per week during the previous six months. Participants were divided into an exercise group (N = 15; 8 females, 7 males) and a control group (N = 10; 6 females, 4 males).

The inclusion criteria were age between 18 and 25 years, absence of cardiovascular, respiratory, or neuromuscular disorders, and willingness to participate in the exercise program for the full duration of the study. The exclusion criteria included a history of chronic disease, regular medication use, or orthopedic conditions that could interfere with participation in exercise.

The study was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants before the commencement of the study.

Research Design

This study evaluated two primary physiological outcomes: cardiorespiratory endurance and resting heart rate. These variables represent related but physiologically distinct domains of cardiovascular adaptation (functional aerobic capacity vs. autonomic cardiac regulation). Given the limited number of primary outcomes and their conceptual independence, no formal multiplicity correction was applied.

This study was conducted using a controlled experimental design with a pretest–posttest setup and a control group. Participants in the exercise group completed a structured aerobic exercise program three days per week for 10 weeks (Table 1). Participants in the control group continued their usual daily routines.

All exercise sessions were supervised and performed in a gym setting. Each session included a 10-minute warm-up, a 25–40 minute main exercise phase, and a 5–10 minute cool-down. Exercise intensity was prescribed as a percentage of maximum heart rate (HRmax = 220 − age) [11].

Cardiorespiratory endurance was assessed using the Cooper 12-minute run test. Participants were instructed to cover the maximum possible distance within 12 minutes. Resting heart rate was measured in the morning after participants

Table 1. 10-Week Aerobic Exercise Program

Weeks	Frequency	Duration (min)	Intensity (%HRmax)	Exercise Type
1–2	3 days/week	45	50–60	Brisk walking
3–4	3 days/week	50	60	Brisk walking + light jogging
5–6	3 days/week	55	60–70	Continuous jogging
7–8	3 days/week	60	70	Continuous jogging
9–10	3 days/week	60	70–75	Jogging / brisk walking

had rested in a seated position for at least five minutes. Measurements were conducted using manual palpation or a heart rate monitor. They were recorded in beats per minute (bpm). Pretest and posttest measurements were conducted under identical conditions.

Power Analysis

An a priori power analysis was conducted using G*Power 3.1 for repeated-measures comparisons (within–between interaction), assuming a medium effect size (f = 0.25), α = .05, and power (1–β) = .80. The estimated required total sample size was 34 participants. The final analyzed sample (N = 25) did not fully reach the calculated target. Therefore, this study should be interpreted as having adequate sensitivity primarily for detecting moderate-to-large effects rather than small effects. The findings are considered confirmatory for large effects but exploratory for smaller magnitudes.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics (Version 25, IBM Corp., Armonk, NY, USA). Normality: Shapiro–Wilk test. Within-group comparisons: Paired-samples t-test (Wilcoxon test if non-normal). Between-group comparisons: Independent-samples t-test (Mann–Whitney U test if non-normal). To evaluate intervention effects, change scores (posttest − pretest) were calculated and compared between groups.

Cohen's *d* was calculated using the following formulas.

For within-group effects:

$$d = \frac{Mean_{post} - Mean_{pre}}{SD_{pooled}}$$

For between-group change comparisons:

$$d = \frac{Mean_{change,er} - Mean_{change,con}}{SD_{pooled-change}}$$

Where,

$Mean_{post}$ — mean value of the variable measured after the intervention (posttest).

$Mean_{pre}$ — mean value of the variable measured before the intervention (pretest).

SD_{pooled} — pooled standard deviation of the pretest and posttest measurements within the same group.

$Mean_{change,er}$ — mean change score in the exercise (experimental) group, calculated as (posttest − pretest).

$Mean_{change,con}$ — mean change score in the control group, calculated as (posttest − pretest).

$SD_{pooled\text{-}change}$ — pooled standard deviation of the change scores in the exercise and control groups.

Effect sizes were interpreted as follows: 0.2 = small, 0.5 = medium, 0.8 = large.

Results

The findings regarding the effects of the 10-week aerobic exercise program on **cardiorespiratory** endurance and resting heart rate in sedentary university students are presented in Table 2. Statistical significance was set at *p* < .05. Both within-group changes and between-group differences in change scores were evaluated.

Table 2. Baseline Characteristics of Participants

Variable	Exercise Group (n = 15) Mean ± SD	Control Group (n = 10) Mean ± SD	p
Age (years)	21.3 ± 2.0	21.6 ± 2.2	.71
Height (cm)	168.1 ± 6.2	167.3 ± 6.7	.76
Body Weight (kg)	62.8 ± 8.4	61.6 ± 9.1	.68
BMI (kg/m²)	22.2 ± 2.5	22.0 ± 2.8	.84
Cooper Test (km)	21.4 ± 2.1	22.1 ± 2.3	.42
Resting Heart Rate (bpm)	78.6 ± 6.4	77.9 ± 7.1	.81

Baseline comparisons showed no statistically significant differences between the exercise and control groups for age, anthropometric variables, or physiological measures (*p* > .05). These results indicate that the groups were comparable before the intervention.

Pretest and posttest results for cardiorespiratory endurance, assessed using the Cooper 12-minute run test, are presented in Table 3.

The exercise group demonstrated a statistically significant increase in the distance covered during the Cooper test following the 10-week intervention (*p* = .01), representing a large effect size (*d* = 0.98). In contrast, the control group showed no significant change (*p* = .84) and a trivial effect size (*d* = 0.09). Between-group comparison of change scores indicated a statistically significant improvement favoring the exercise group (*p* < .05).

Resting heart rate measurements before and

Table 3. Changes in Cardiorespiratory Endurance

Group	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Mean Change	p	Cohen's d
Exercise Group	21.4 ± 2.1	25.6 ± 2.4	+4.2	.01*	0.98
Control Group	22.1 ± 2.3	22.4 ± 2.2	+0.3	.84	0.09

Table 4. Changes in Resting Heart Rate

Group	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Mean Change	p	Cohen's d
Exercise Group	78.6 ± 6.4	71.2 ± 5.8	−7.4	.007*	1.21
Control Group	77.9 ± 7.1	77.1 ± 6.9	−0.8	.531	0.11

after the intervention are presented in Table 4.

The exercise group exhibited a statistically significant reduction in resting heart rate after the 10-week aerobic exercise program (*p* = .007), corresponding to a large effect size (*d* = 1.21). The control group showed no significant change (*p* = .531), with a negligible effect size (*d* = 0.11). The significant reduction in resting heart rate observed exclusively in the exercise group supports the effectiveness of the aerobic training intervention.

Discussion

The present study examined the effects of a 10-week structured aerobic exercise program on cardiorespiratory endurance and resting heart rate in sedentary university students aged 18–25 years. The findings demonstrate that regular aerobic exercise produced statistically significant and practically meaningful improvements in both physiological parameters when compared to a non-exercising control group.

The exercise group exhibited a significant increase in Cooper 12-minute run performance (p = .01), with a large effect size (d = 0.98), whereas the control group showed no meaningful change. These findings are consistent with previous research demonstrating that aerobic training improves aerobic capacity, stroke volume, peripheral oxygen utilization, and overall cardiovascular efficiency [12, 13], as well as with more recent studies reporting improvements in endurance performance and aerobic physiological adaptations following structured training interventions [14, 15].

Short-term aerobic interventions (8–12 weeks) have been shown to induce measurable improvements in cardiorespiratory fitness in previously sedentary individuals [16], supporting the results of the present study. Similar improvements in cardiorespiratory fitness following structured exercise interventions have also been reported in more recent randomized controlled trials examining inactive or overweight populations [17, 18]. Although maximal oxygen uptake (VO_2max) was not directly measured via metabolic gas analysis, improvements in Cooper test performance are widely accepted as valid field-based indicators of enhanced aerobic fitness. Therefore, the observed increase in running distance likely reflects improved cardiorespiratory function and aerobic work capacity.

A significant reduction in resting heart rate was observed in the exercise group (p = .007), with a large effect size (d = 1.21), whereas the control group showed no significant change. This finding aligns with prior evidence indicating that aerobic exercise enhances myocardial efficiency and autonomic regulation [9, 19], as well as with more recent research demonstrating exercise-induced improvements in cardiac autonomic modulation and cardiovascular function following structured training programs [20, 21]. Reductions in resting heart rate are commonly attributed to improved stroke volume and increased parasympathetic (vagal) activity accompanied by reduced sympathetic tone [9]. However, it should be noted that autonomic markers such as heart rate variability were not directly measured in this study. Therefore, while the decrease in resting heart rate is consistent with improved autonomic balance, mechanistic explanations remain theoretical rather than empirically verified within the present research.

Furthermore, sedentary individuals who do not participate in structured exercise programs typically demonstrate minimal cardiovascular change over similar time periods [2], which is consistent with the absence of significant change observed in the control group. Recent research examining sedentary behavior and reductions in sitting time has similarly demonstrated that low levels of physical activity are associated with limited cardiovascular adaptation and adverse cardiometabolic profiles [22, 23]. The magnitude of reduction observed (−7.4 bpm) may be considered clinically relevant, as elevated resting heart rate has been associated with increased cardiovascular morbidity and mortality risk [6]. Thus, these findings suggest that structured aerobic exercise may contribute to cardiovascular risk reduction even in young, apparently healthy adults.

Practical Implications

The results reinforce the importance of implementing structured aerobic exercise programs in university populations. Given that sedentary behavior remains prevalent among young adults [2], practical and accessible aerobic training models such as brisk walking and jogging may serve as effective interventions to improve cardiovascular health.

Limitations and Future Research

Although statistically significant effects were observed, the relatively modest sample size limits the precision of effect estimation and the generalizability of the findings. The study was adequately sensitive for detecting moderate-to-large effects but may have been underpowered for identifying smaller changes in the analyzed variables. In addition, the sample consisted of sedentary university students within a limited age range, which restricts the applicability of the results to other population groups with different activity levels or demographic characteristics. Therefore, the findings should be interpreted with caution. Future studies should confirm these results in larger randomized trials and examine the effectiveness of aerobic exercise programs across more diverse student populations.

Conclusions

In conclusion, a 10-week aerobic exercise program significantly improved cardiorespiratory endurance and reduced resting heart rate in sedentary individuals aged 18–25 years. These findings indicate that regular aerobic exercise enhances cardiovascular efficiency and overall physical fitness. It also mitigates the negative effects of a sedentary lifestyle. The lack of significant changes in the control group supports the effectiveness of the exercise intervention. Promoting regular aerobic exercise in young adults may contribute to the adoption of healthy lifestyle habits and the reduction of long-term cardiovascular risk. Future research should explore different exercise protocols and larger populations to expand and confirm these findings.

Conflict of Interest

The authors declare no conflict of interest.

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PHYSICAL EDUCATION OF STUDENTS

ORIGINAL ARTICLE

Strengthening the stage: intervention targeting muscular weakening in performing arts 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 Performing arts students, particularly musicians, face significant physical strain because of prolonged static postures and repetitive fine motor activity. These factors predispose them to performance-related musculoskeletal disorders (PRMDs). Despite increasing awareness, preventive training programs are rarely implemented in music education. This study examined the effects of a 6-week targeted intervention on postural muscle function in male performing arts students. The focus was on muscles commonly weakened by instrumental practice: deep neck flexors, musculus abdominis, and lower scapular stabilizers.

Material and Methods Twenty-six full-time male music students were assigned to experimental (N = 14, 53.85%) and control (N = 12, 46.15%) groups. The intervention group underwent bi-weekly 30-minute sessions over 6 weeks. The sessions incorporated mobility, strengthening, and control exercises. Muscle function was assessed pre- and post-intervention using standardized clinical tests. Statistical analysis was conducted using Wilcoxon and Mann-Whitney U-tests.

Results Significant improvements ($p < .01$) were found in the experimental group across all measured muscle groups, with large effect sizes. No significant changes ($p > .05$) were observed in the control group. Post-intervention comparisons confirmed significantly greater ($p < .01$) muscle function in the intervention group. A short, structured, and supervised intervention significantly enhanced ($p < 0.01$) postural muscle function among performing arts students.

Conclusions The findings support the integration of targeted physical conditioning into performing arts curricula as a preventative strategy to reduce PRMD risks and enhance physical literacy in music education.

Keywords: muscular weakening, musculoskeletal intervention, musculoskeletal health, performing arts students.

Introduction

The physical demands of performing arts training require sustained postural control and precise motor coordination over prolonged periods of practice and performance. Students engaged in intensive musical training are regularly exposed to static positions and repetitive movements that place considerable load on the musculoskeletal system. These conditions contribute to the development of muscular imbalance, particularly affecting stabilizing muscles responsible for maintaining head, trunk, and scapular alignment during instrumental practice. The resulting functional alterations may influence movement efficiency, physical comfort, and the overall capacity of students to tolerate the physical demands associated with performing arts education.

Performing arts, in particular music, require both exceptional artistic skills and significant physical endurance [1]. Music students, despite their aesthetic focus, are high-performance individuals akin to athletes. They engage in repetitive practice sessions that place significant strain on their musculoskeletal systems. However, unlike athletes, musicians often receive little formal education in physical conditioning or injury prevention [2]. Therefore, the prevalence of performance-related musculoskeletal disorders (PRMDs) among music students is alarmingly high, ranging from 39% to 87% depending on the instrument and playing posture [3]. This raises critical questions about the role of muscular strength, fatigue resistance, and physical training in sustaining healthy careers for young musicians.

Muscle weakness among music students is often insidious. It develops through prolonged static postures and fine motor repetitions. Unlike athletes who train to optimize movement competence, musicians are not trained to develop core strength, postural endurance, or biomechanical balance [4]. Retrospective ultrasound analysis of cellists with PRMDs revealed localized atrophy and dysfunction in deep stabilizer muscles. This suggests that prolonged use of improper technique may impair muscular function [4]. Muscle imbalances, particularly in the neck, shoulders, and lower back, play an important role in the development

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of overuse injuries and chronic pain. String and keyboard players are especially affected [5].

Emerging evidence suggests that targeted physical conditioning, including strength training and core stabilization, plays an important role in reducing injury risk among music students [6]. Interventions targeting proximal stability and shoulder girdle strength are associated with enhanced upper extremity endurance and a reduction in perceived exertion during performance [7]. Multidisciplinary interventions combining yoga and strength training result in significant reductions in muscle pain, perceived exertion, and psychological discomfort among performing arts students. This highlights the importance of integrating mental and physical conditioning for holistic well-being [6].

The biomechanical load placed on student musicians is intensified by fatigue, which often leads to compromised technique and compensatory movements [8]. Subtle muscle fatigue in the lower extremities significantly altered gait patterns in flatfooted participants. This finding highlights how even minor deficits in muscle function can have cascading effects on biomechanics. For musicians, this is particularly relevant during prolonged rehearsals or performances, where static postures are maintained for hours [2]. Fatigue accumulation without adequate recovery impairs neuromuscular control and increases susceptibility to acute injuries [9].

Despite widespread evidence of physical challenges in musical training, few music schools integrate structured physical education into their core curriculum [10]. Qualitative analysis revealed that less than 30% of institutions offered health and wellness support programs. Students often lacked basic knowledge of ergonomics, injury prevention, or strength conditioning [11]. The omission of musculoskeletal education creates knowledge gaps. This leaves students ill-equipped to manage the physical demands of their discipline.

Targeted, evidence-based interventions have proven effective in addressing muscular weakening and PRMDs in music students. Early research demonstrated that structured resistance training, such as a 12-week program for piano students, could significantly improve grip strength, posture control, and shoulder endurance [12]. These foundational results have since been expanded by more recent research applying holistic, multidisciplinary approaches. An educational intervention focusing on spine mobility, postural correction, and dynamic stretching led to reductions in musculoskeletal discomfort among performing arts students. Benefits remained evident during follow-up six months after the program, indicating the potential for lasting postural change [2].

Research involving university piano students has exposed high incidences of upper-body musculoskeletal strain. This strain is often linked to prolonged practice in suboptimal environments. When tailored programs integrating ergonomic correction and localized strength training were introduced, participants reported increased comfort and reduced strain. This finding underscores the importance of context-sensitive intervention models [13].

An investigation into corrective spinal training delivered over ten weeks demonstrated measurable improvements in thoracolumbar alignment and core strength among performing arts students. The intervention led to significant functional benefits and enhanced postural control. These results illustrate that even short-duration programs can yield structural changes with performance implications [2].

Taken together, these findings suggest that interventions targeting musculoskeletal health must be both evidence-based and adaptable to the unique demands of music performance. Programs combining diagnostic assessments, physical methods, corrective exercises, and ergonomic education provide comprehensive strategies that reduce injury and promote long-term literacy. As such approaches become more refined and accessible, they offer valuable tools for preserving performance capacity and supporting student well-being across the disciplines of performing arts [5, 6].

Gender differences in muscle endurance and anatomical structure also play an important role in injury exposure. Female music students, for example, have been shown to report higher rates of neck and shoulder discomfort [4]. Instrument-specific ergonomics is another underexplored area. Cellists and violinists are more prone to lateral flexion-related injuries, whereas pianists often suffer from wrist and finger overload. Understanding these nuances allows for more precise interventions tailored to both individual and instrument-specific needs [6].

Despite mounting evidence supporting the role of physical training, implementation remains limited. Barriers include lack of faculty awareness, curriculum constraints, and resistance to non-musical content. Institutional inertia and limited funding often hinder health-focused curricular reforms. Therefore, stigma around physical pain remains, with students often reluctant to report symptoms for fear of being perceived as weak or uncommitted [10].

“Strengthening the stage” requires systemic change. Institutions must move beyond reactive injury management and embrace proactive health education. This includes inserting musculoskeletal health modules into the curriculum, offering supervised physical training sessions, and promoting a culture of wellness. Partnerships with physiotherapists and ergonomics specialists can bridge the gaps between artistic demands and physical sustainability [6]. As music students continue to face high physical demands, the integration of structured interventions becomes both beneficial and essential for sustaining performance over time.

Despite increasing recognition of PRMDs and growing advocacy for preventive conditioning in music education, important gaps remain in the literature. First, many existing studies primarily rely on self-reported pain reduction and subjective measures, whereas fewer investigations employ objective clinical assessments of specific postural muscle function. Second, although intervention programs are described, limited evidence exists regarding short-term, time-efficient models that are feasible for integration into university curricula without disrupting artistic training schedules. Third, little research has simultaneously targeted deep neck flexors, deep abdominal stabilizers (m. transversus abdominis), and lower scapular stabilizers. These muscle groups are involved in postural endurance and neuromuscular control during instrumental performance. The present study aims to examine the effects of a structured 6-week neuromuscular intervention targeting these key postural muscle groups on objectively assessed muscle function in male performing arts students. By focusing on clinically graded outcomes and curriculum-compatible intervention formats, this study seeks to provide practical and scalable evidence supporting preventive strategies in performing arts education.

Materials and Methods

Participants

The study involved 26 performing arts students (N = 26, 100%), divided into two groups: the experimental group (N = 14, 53.85%) and the control group (N = 12, 46.15%). All participants were male full-time students enrolled in performing arts programs (i.e., Faculty of Performing Arts, Academy of Arts in Banská Bystrica). All participants met the inclusion criteria of active instrumental practice and regular engagement in academic performance training. Group allocation was determined by existing class cohorts and scheduling logistics, consistent with quasi-experimental designs. Exclusion criteria included any diagnosed neuromuscular disorders, acute musculoskeletal injuries, or ongoing physiotherapeutic treatments.

Descriptive statistics for the two groups are presented in Table 1. The mean age of the experimental group was 21.28 ± 1.24 years, and for the control group it was 20.96 ± 1.48 years, with no statistically significant difference between them (t(24) = .592, p = .560). Mean weight was 68.64 ± 4.82 kg in the experimental group and 68.28 ± 4.42 kg in the control group (p = .844). Mean height was 174.42 ± 4.26 cm (experimental) and 176.64 ± 2.86 cm (control), with no significant difference (p = .128).

Daily practice time averaged 2.68 ± .82 hours in the experimental group and 2.62 ± .68 hours in the control group (p = .840), indicating comparable instrumental workloads. The mean length of musical training (career duration) was 16.28 ± 1.86 years in the experimental group and 16.84 ± 1.26 years in the control group (p = .373).

Participants represented various instrumental families. In the experimental group, 42.86% played wind instruments, 28.57% string instruments, and 28.57% keyboard instruments. In the control group, 33.33% were wind players, 50% string players, and 16.67% keyboard players.

Independent samples t-tests showed no statistically significant differences (p > .05) between the experimental and control groups on any baseline variable, including age, weight, height, daily practice duration, or musical experience. These findings confirm the comparability of the two groups at the start of the intervention, supporting the internal validity of subsequent analysis.

Participants provided written informed consent prior to the commencement of the study. Participation was voluntary, and the study protocol was approved by the Ethics Committee of the Artistic and Pedagogical Council of the Faculty of Performing Arts, Academy of Arts in Banská Bystrica (Approval No. 01, FMU-AU/26) in accordance with the ethical principles of the Declaration of Helsinki [14].

Table 1. Characteristics of performing arts students (N = 26, 100%)

Variable	Experimental group	Control group
Anthropometrics		
Age (years; M ± SD)	21.28 ± 1.24	20.96 ± 1.48
Weight (kg; M ± SD)	68.64 ± 4.82	68.28 ± 4.42
Height (cm; M ± SD)	174.42 ± 4.26	176.64 ± 2.86
Instruments		
Wind (N; %)	6; 42.86%	4; 33.33%
String (N; %)	4; 28.57%	6; 50%
Keyboard (N; %)	4; 28.57%	2; 16.67%
Practice		
Day (hours; M ± SD)	2.68 ± .82	2.62 ± .68
Career (years; M ± SD)	16.28 ± 1.86	16.84 ± 1.26

Note. N = Number, % = Percentage, cm = centimeter, kg = kilogram, M = mean, SD = standard deviation.

Research Design

This study employed a quasi-experimental controlled design with two parallel groups: an experimental group (N = 14, 53.85%) and a control group (N = 12, 46.15%). Group allocation was based on existing class enrollment and cohort structure rather than individual randomization. Although participants were not randomly assigned, baseline comparability between groups was statistically verified across demographic and practice-related variables, supporting internal validity. The design adhered to established guidelines for physical conditioning trials in performing arts health research [15].

The recruitment process was conducted in accordance with ethical guidelines, ensuring voluntary participation, anonymity, and confidentiality [16]. Participants were informed about the study's purpose, procedures, and potential risks and benefits. The right to withdraw at any time without consequence was guaranteed. All data were anonymized, securely stored, and used strictly for research purposes.

The intervention lasted six weeks ($\Delta t = 6$ weeks) and was implemented 2x/week, every Tuesday and Thursday, with each session lasting 30 minutes. Baseline assessments (pre-intervention) were completed during Week 1 (October 14, 2025), and post-intervention assessments during Week 6 (November 20, 2025). All sessions were carried out in small-group settings within the university movement space (i.e., Ďatelinka, approximately 60 m^2), equipped with exercise mats and light-to-moderate resistance bands [17]. No specialized biomechanical or instrument-specific equipment was required. Sessions were conducted in small groups (experimental group) under the supervision of instructors with an academic background in Physical Education and neuromuscular training.

The scheduling format (2x/30 minutes weekly) was integrated into the existing semester timetable without altering core artistic coursework. These contextual characteristics suggest that replication is feasible in institutions with access to basic movement facilities and qualified supervision.

The intervention was designed to address muscular weakening patterns often observed in music students, with a primary focus on deep neck flexors, musculus abdominis, and lower scapular stabilizers [3, 6]. Although the phased structure (mobility-strengthening-control) reflects established principles of neuromuscular conditioning, the novelty of the present intervention lies in three key aspects. First, the program simultaneously targets deep cervical stabilizers, transversus abdominis, and lower scapular stabilizers. These muscle systems are biomechanically interdependent yet rarely examined together within controlled performing arts cohorts. Second, the intervention duration (6 weeks; 2x/30 minutes weekly) was intentionally designed as a minimal-dose, curriculum-compatible model to enhance institutional feasibility. Third, results were evaluated using standardized clinical muscle grading rather than self-reported symptom reduction. This enabled objective assessment of neuromuscular adaptation. The study focuses on a homogeneous sample of male performing arts students, allowing clearer interpretation of postural muscle responses within defined demographic groups.

Each session followed standardized, progressive formats consisting of mobility, control, and strengthening (Table 2). No participant advanced to higher dosage parameters unless correct technique was maintained across all prescribed repetitions or hold durations.

Table 2. 6-week intervention for muscular weakening

Week	Focus	Exercise
1-2	Mobility & Activation	- Chin tucks - Scapular setting - Cat-cow mobilization - Pelvic tilts - Diaphragmatic breathing - Pectoralis doorway stretch - Shoulder blade squeezes - Supine thoracic rotations
3-4	Strengthening & Reeducation	- Prone Y-T-W holds - Bird-dog with neutral spine - Wall planks - Neck flexor isometrics - Wall angels - Glute bridge with arm drive - Resistance band rows - Levator scapulae stretch
5-6	Control & Integration	- Standing "W" posture holds - Dead bug with resistance band - Seated thoracic rotation with arm reach - Scapular retraction rows - Wall push-ups - Bird-dog with leg extension and cervical alignment - Arm wall slides - Supine chin tuck with overhead reach

During Weeks 1-2 (mobility and activation), exercises were performed in 2 sets of 8-10 controlled repetitions or 15-20-second holds (for isometric tasks), with 30-second rest intervals between sets. Emphasis was placed on low-load activation, breathing coordination, and movement precision.

During Weeks 3-4 (strengthening and reeducation), exercises progressed to 2-3 sets of 10-12 repetitions or 20-30-second holds, with 30-45 seconds of rest between sets. Resistance bands (light to moderate tension) were introduced where applicable (e.g., rows, dead bug variations). Progression was contingent upon the participant's ability to maintain neutral alignment and avoid compensatory activation patterns.

During Weeks 5-6 (control and integration), exercises were performed in 3 sets of 12-15 repetitions or 30-40-second holds, with 45-second rest intervals. Functional integration tasks required sustained postural control combined with coordinated limb movement. Advancement was permitted only when participants demonstrated consistent motor control quality. This was defined as maintenance of cervical alignment, scapular stability, and abdominal activation without visible compensation or tremor.

Over the 6-week intervention, all sessions were supervised directly by the research team to ensure protocol fidelity. Attendance was recorded at each session. Adherence rate was calculated as the percentage of completed sessions out of the total 12 prescribed sessions. Participants in the experimental group attended on average 92.3% (± 5.8%) of scheduled sessions. Attendance ranged from 10 to 12 sessions per participant. No participant attended fewer than 10 sessions (83.3%), and no dropouts occurred during the intervention period.

Intervention fidelity was monitored using structured observation checklists documenting exercise completion, adherence to prescribed sets and durations, and compliance with predefined movement quality criteria. Any deviations from the protocol (e.g., reduced hold time due to fatigue or compensatory movement) were documented and corrected immediately during supervision. No adverse events or musculoskeletal injuries were reported during the intervention period.

The control group did not receive structured physical training and maintained their usual academic and instrumental practice routines throughout the study period. Participants were specifically asked not to initiate new strength, core, or rehabilitation programs during the six-week period. Informal weekly check-ins were conducted to confirm adherence to this instruction. No participant reported engaging in additional targeted neuromuscular training.

To minimize contamination between groups, intervention sessions were scheduled separately from shared coursework. Participants were requested not to discuss specific exercise content with peers from the control cohort.

Standardized measures for evaluating muscular weakening, in particular the deep neck flexors, musculus abdominis, and lower scapular stabilizers [18], were employed at baseline (Week 1, October 14, 2025) and again after the intervention (Week 6, November 20, 2025):

- *Deep Neck Flexors (m. longus colli, m. longus capitis)*

These muscles are important for cervical spine stabilization, prevention of neck pain (cervical syndrome), and maintenance of upright posture, particularly in today's lifestyles. The subject lies in a supine position with knees bent (to relax abdominal muscles). The subject performs a chin tuck, lifting the head toward the chest just enough so that a pillow could fit under the chin. The ability to maintain the position without activating superficial neck muscles is observed.

Grade 0 - No activity: No visible or palpable contraction; complete weakness.
Grade 1 - Minimal activity: Palpable or visible muscle contraction without actual movement.
Grade 2 - Basic function: Able to perform the motion (head flexion) through full range in a gravity-eliminated position (lying down), indicating functional activation.

- *Musculus Abdominis (m. transversus abdominis, m. obliquus internus)*

These muscles are important for core stability, lumbar spine support, and prevention of low back pain. Proper activation is essential in both daily and athletic movements. The subject lies on their back with knees bent and feet flat on the floor. The subject performs an abdominal hollowing maneuver, drawing in the abdominal wall toward the spine without movement of the pelvis or rib cage. The test assesses the ability to isolate deep abdominal activation.

Grade 0 - No activity: No contraction detected.
Grade 1 - Minimal activity: Slight muscle tension without visible movement.
Grade 2 - Basic function: Able to perform isolated abdominal wall movement (in a supine position) without engaging superficial muscles.

- *Lower Scapular Stabilizers (m. serratus anterior, m. lower trapezius, m. rhomboideus)*

These muscles are important for scapular positioning, shoulder stability, and prevention of neck and shoulder pain. Dysfunction often leads to abnormal scapular movement and impingement syndromes. The subject lies in a prone "superman" position with the arms extended overhead. The subject attempts to lift the arms off the ground while maintaining scapular control and avoiding upper trapezius compensation. Observers evaluate coordination, scapular motion, and symmetry.

Grade 0 - No activity: No movement of the scapula or contraction detected.
Grade 1 - Minimal activity: Slight scapular movement or contraction without arm motion.
Grade 2 - Basic function: Able to raise the arms with proper scapular stabilization and without compensatory movement.

The clinical system (i.e., Grade 0-2) employed in this study was selected on purpose from standardized and widely accepted functional muscle testing frameworks rather than as a novel diagnostic instrument. The aim was not to develop a new classification system but to apply an established, clinically interpretable grading method to objectively assess postural stabilizing muscle function within a preventive performing arts context. Such scales are frequently used in musculoskeletal and rehabilitation research due to their feasibility, reproducibility, and suitability for small-sample experimental designs.

The selected muscle function tests are derived from established manual muscle testing frameworks with documented clinical reliability and validity in musculoskeletal and rehabilitation research [18]. To enhance measurement reproducibility, all assessments were performed by the same examiners (authors), who had prior clinical training in functional muscle testing and completed standardized procedural calibration before data collection. A pilot familiarization session was conducted to ensure consistent grading criteria, palpation technique, and movement observation standards. Standardized verbal instructions and positioning protocols were used across all participants to minimize inter-session variability.

In the present study, the grading system served as a functional screening tool capable of detecting meaningful neuromuscular changes over a short intervention period. Its simplicity allows practical implementation in educational settings without requiring specialized equipment, thereby enhancing translational applicability. The methodological contribution of this study lies not in scale refinement but in the structured and systematic application of standardized clinical grading to evaluate targeted neuromuscular adaptation in performing arts students.

While the absence of individual randomization may limit full experimental control, baseline equivalence testing indicated no significant differences between groups prior to the intervention. This reduces the likelihood that observed post-intervention effects were attributable to pre-existing group disparities.

Statistical Analysis

Statistical analysis was conducted using IBM SPSS Statistics (Version 24.0; IBM Corp., Armonk, NY, USA). Descriptive statistics, including means (M) and standard deviations (SD), were calculated to summarize participant demographics and results [19].

The sample size was determined by cohort availability within the performing arts program during the academic semester rather than by a priori power calculations. Eligible students meeting the inclusion criteria were invited to participate, resulting in a total sample of 26 participants. Given the large effect sizes observed in the primary outcomes ($r = .56\text{-}.74$), post hoc estimation indicates that the study achieved adequate statistical power ($> .80$) to detect between-group differences at $\alpha = .05$ for non-parametric comparisons. While larger samples would increase generalizability, the present sample size is comparable to previous intervention studies conducted in musician populations [2, 17].

In terms of assessing the normality of data distributions, the Shapiro-Wilk test was employed [20]. Results indicated violations of normality for some variables, prompting the use of non-parametric procedures for inferential analysis. However, anthropometric variables, including age, height, and weight, conformed to normal distribution assumptions. Therefore, independent-samples t-tests were employed to assess group differences at baseline.

Non-parametric methods were employed in alignment with methodological guidelines for research involving small sample sizes and data that deviate from normal distribution assumptions. Within-group differences (pre- vs. post-) were analyzed using the Wilcoxon test, while between-group comparisons (experimental vs. control) were analyzed using the Mann-Whitney U-test [21]. The level of statistical significance was set at $p < .05$. For all significant results, effect sizes (r) were calculated using the formula $r = Z / \sqrt{N}$, where N is the total number of observations. Effect sizes were interpreted using Cohen's [22] classification: small ($r = .10$), medium ($r = .30$), and large ($r = .50$). Results are reported with corresponding test statistics, p-values, and effect sizes, ensuring adherence to established guidelines in sports and health sciences research.

Results

Within-group comparisons revealed statistically significant improvements ($p < .01$) in all assessed muscle groups in the experimental group following the 6-week intervention (Table 3). Deep neck flexor function increased markedly from baseline (.57 ± .51) to post-intervention (1.57 ± .51). The Wilcoxon test confirmed a highly significant change ($Z = 3.27$, $p < .01$) and a large effect size ($r = .61$). Musculus abdominis activation demonstrated significant enhancement, improving from a pre-intervention mean of .71 ± .46 to 1.57 ± .51 after the intervention ($Z = 3.20$, $p < .01$; $r = .60$). Lower scapular stabilizer function followed the same pattern. It increased from .57 ± .51 at baseline to 1.57 ± .64 at post-intervention, with statistical significance ($Z = 3.27$, $p < .01$) and a large effect size ($r = .61$) (Figure 1).

No statistically significant within-group changes ($p > .05$) were observed in the control group across the six-week period (Table 3). Deep neck flexors slightly decreased from .50 ± .52 to .33 ± .65, but this change was not significant ($Z = .81$, $p > .05$; $r = .16$).

Musculus abdominis showed a minor decline from .50 ± .52 to .41 ± .51 (Z = .44, p > .05; r = .09). Lower scapular stabilizers demonstrated a small, non-significant increase from .50 ± .52 to .75 ± .62 (Z = 1.13, p > .05; r = .23) (Figure 1).

Between-group comparisons at baseline confirmed no statistically significant differences (p > .05) between the experimental and control groups in any of the assessed muscle functions (Table 4). Deep neck flexors (Z = -.35, p > .05), musculus abdominis (Z = -1.09, p > .05), and lower scapular stabilizers (Z = -.35, p > .05) demonstrated comparable baseline levels, indicating homogeneity between groups prior to the intervention.

Post-intervention intergroup analysis revealed statistically significant differences (p < .05) favoring the experimental group across all measured variables (Table 4). Deep neck flexor function was

Table 3. Intragroup (within) comparisons of performing arts students (N = 26, 100%)

Muscles (M ± SD)	Pre- (Week 1)	Post- (Week 6)	Wilcoxon test (p)
Experimental group			
Deep neck flexors	0.57 ± 0.51	1.57 ± 0.51	Z = 3.27, p < .01, r = 0.61**
Musculus abdominis	0.71 ± 0.46	1.57 ± 0.51	Z = 3.20, p < .01, r = 0.60**
Lower scapular stabilizers	0.57 ± 0.51	1.57 ± 0.64	Z = 3.27, p < .01, r = 0.61**
Control group			
Deep neck flexors	0.50 ± 0.52	0.33 ± 0.65	Z = 0.81, p > .05, r = 0.16
Musculus abdominis	0.50 ± 0.52	0.41 ± 0.51	Z = 0.44, p > .05, r = 0.09
Lower scapular stabilizers	0.50 ± 0.52	0.75 ± 0.62	Z = 1.13, p > .05, r = 0.23

Note. N = number of participants; % = percentage; M = mean; SD = standard deviation; p = significance level; Z = Wilcoxon test statistic; r = effect size. ** p < .01.

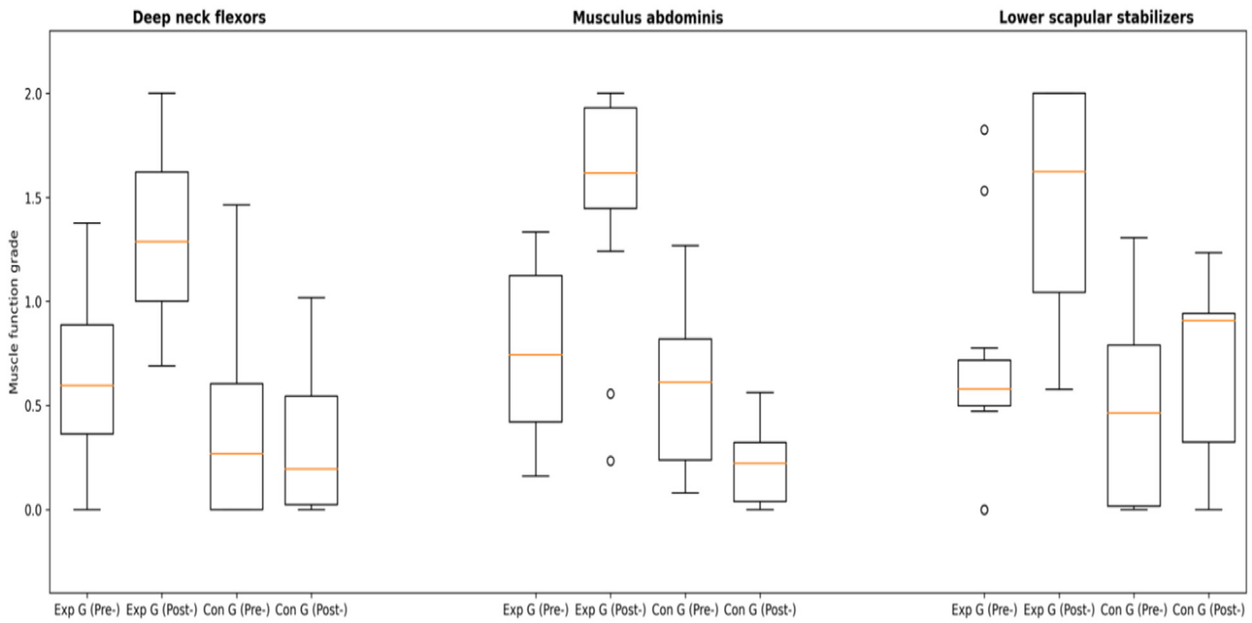

Figure 1. Distributions of grades in experimental (Exp G) and control (Con G) groups (N = 26, 100%)

Table 4. Intergroup (between) comparisons of performing arts students (N = 26, 100%)

Muscles (M ± SD)	Experimental group	Control group	Mann-Whitney U-test (p)
Pre- (Week 1)			
Deep neck flexors	0.57 ± 0.51	0.50 ± 0.52	Z = -0.35, p > .05, r = -0.07
Musculus abdominis	0.71 ± 0.46	0.50 ± 0.52	Z = -1.09, p > .05, r = -0.21
Lower scapular stabilizers	0.57 ± 0.51	0.50 ± 0.52	Z = -0.35, p > .05, r = -0.07
Post- (Week 6)			
Deep neck flexors	1.57 ± 0.51	0.33 ± 0.65	Z = -3.07, p < .01, r = -0.72**
Musculus abdominis	1.57 ± 0.51	0.41 ± 0.51	Z = -3.79, p < .01, r = -0.74**
Lower scapular stabilizers	1.57 ± 0.64	0.75 ± 0.62	Z = -2.85, p < .01, r = -0.56**

Note. N = number of participants; % = percentage; M = mean; SD = standard deviation; p = significance level; Z = Mann-Whitney test statistic; r = effect size. ** p < .01.

significantly higher in the experimental group (1.57 ± .51) compared to the control group (.33 ± .65), with a large effect size (Z = -3.07, p < .01; r = -.72). Musculus abdominis differed significantly between groups, with the experimental group achieving substantially higher scores (1.57 ± .51 vs. .41 ± .51; Z = -3.79, p < .01; r = -.74). Lower scapular stabilizer function was significantly greater in the experimental group (1.57 ± .64) compared to controls (.75 ± .62), with a large effect size (Z = -2.85, p < .01; r = -.56).

Discussion

The results of the study confirm that short-term (i.e., 6 weeks) muscular intervention significantly (p < .01) enhances postural muscle function in performing arts students, particularly in the deep neck flexors, musculus abdominis, and lower scapular stabilizers. The improvements indicate that even relatively short-duration, controlled physical programs may play protective and corrective roles in performance-related musculoskeletal health in performing arts students [23].

The results align with recent evidence from randomized trials on musicians, where strengthening programs focusing on spinal alignment and shoulder control reduced both the intensity and frequency of musculoskeletal complaints [24]. Activation of the deep neck flexors aligns with cervical stabilization results observed in resistance-based programs for musicians who engage in prolonged seated practice [25].

The improvements in the deep neck flexors found in this study resonate with integrated physical therapy interventions that combined strength training and kinematic analysis in music students, resulting in improved postural endurance and playing technique [26]. Similar interventions that addressed muscle imbalances in the upper body demonstrated measurable benefits in scapular mechanics, particularly for students playing violin and flute [27].

The improvements of the musculus abdominis observed in the current study mirror earlier findings showing that strengthening core muscles enhanced lumbar control and decreased fatigue symptoms during performance [28]. This reflects the interdependence between spinal stability and extremity movement. These concepts are often neglected in performing arts pedagogy but are important for healthy technique.

Improvements in the lower scapular stabilizers indicated enhanced neuromuscular control. This is an essential factor in preventing shoulder impingement and maintaining upper limb precision under fatigue. This supports results from interventions that reduced shoulder strain in string musicians through serratus anterior and trapezius reinforcement [11].

The phased structure of this intervention, combining mobility, strengthening, and control, is consistent with established frameworks advocating progressive and functional training in musicians at risk of PRMDs [28]. Education and activation strategies, when combined, provide multidimensional benefits in postural control and proprioceptive awareness.

Incorporating group-based delivery was a strategic choice that builds upon findings that small-group physical training enhances peer accountability and adherence among student musicians [17]. Group dynamics may reduce stigma associated with physical weakness or injury in university environments.

Preventative strategies are recommended in recent literature as the primary mode of protecting musicians from injury, particularly when applied early in their training trajectory [29]. This aligns with our findings, as preemptive muscle conditioning was effective even before any clinical symptoms had fully manifested.

In terms of a pedagogical standpoint, the originality of this study lies in proposing a structured 2x/30-minute weekly neuromuscular module explicitly designed for integration within existing university timetables without displacing artistic coursework. While previous health initiatives in music institutions often rely on optional workshops, short-term seminars, ergonomic lectures, or multidisciplinary wellness programs, they are frequently extracurricular, symptom-driven, or resource-intensive.

The present model demonstrates that a minimal-dose, supervised stabilization program can be embedded within standard semester structures while maintaining high adherence (92.3%) and producing significant objective results. This positions the intervention not as auxiliary health support but as a scalable curricular component aligned with performing arts training demands. The framework therefore advances existing approaches by offering a time-efficient, institutionally feasible, and performance-compatible conditioning structure that can be systematically implemented rather than sporadically delivered.

In terms of a curriculum standpoint, incorporating such interventions in standardized formats may close the current gap between physical literacy and performance training. Many music institutions lack embedded health modules, despite the high injury prevalence among students [30]. Institutional resistance to including non-musical content in the curriculum has been identified as a persistent barrier to implementing Physical Education for musicians, even when such content supports their performance health [2]. Yet, research consistently shows that students respond positively when they understand the practical impact on their practice quality and career longevity.

The results support the use of brief yet focused interventions. Similar to this study's 6-week model, interventions as short as ±6 weeks have demonstrated statistically and clinically meaningful outcomes in muscle endurance and postural coordination [25]. These can be feasibly embedded within semester schedules without conflicting with musical instruction.

There is increasing evidence that movement literacy should be recognized as an artistic skill in itself, particularly in disciplines involving repetitive motor patterns and high biomechanical demands [28]. Physical training should be viewed not as external to artistry but as foundational to sustainable performance.

In terms of a theoretical perspective, the present findings contribute to the growing integration of neuromuscular control principles within performing arts pedagogy, where postural regulation and fine motor coordination are increasingly understood as interdependent systems rather than isolated functions [31, 32]. Instrumental performance requires sustained postural endurance combined with fine motor precision. Such combinations depend on efficient proximal stabilization and coordinated motor control [10, 33]. According to contemporary motor control theory, distal precision is optimized when proximal segments provide stable yet adaptable support, reflecting principles of structured variability and hierarchical control within the motor system [31]. Evidence from postural control and spinal motor behavior research further demonstrates that adaptations in trunk and paraspinal muscle coordination influence movement efficiency and control strategy [32, 34]. Improvements in deep cervical, abdominal, and scapular stabilizers therefore extend beyond injury prevention. They reflect enhancement of foundational motor control systems that underpin technical execution and sustained performance capacity [10].

The findings align with the conceptual framework of physical literacy, which emphasizes competence, confidence, and knowledge in movement as lifelong capacities [35]. Within performing arts education, physical literacy should not be viewed as supplementary to artistic training but as enabling substrates for sustainable performance [36]. By demonstrating that structured neuromuscular conditioning can improve postural control within curriculum-compatible formats, this study supports pedagogical shifts from reactive injury management towards proactive motor competence development.

In this sense, the contribution of the study is not limited to musculoskeletal health results. It also provides empirical support for embedding structured movement education into the theoretical foundations of performing arts training [33].

Limitations of the Study and Future Research Directions

This study is limited by a small sample size (N = 26, 100%) and the homogeneity of the participant group, which included only male students. Gender-specific anatomical and hormonal factors may influence injury risk, particularly in the neck and shoulder region, and should be explored in future research. Another limitation is the absence of long-term follow-up. It is unclear whether the improvements observed in muscle function will persist beyond the immediate post-intervention period. Another limitation is the use of standardized clinical grading (0-2 scale) rather than instrument-specific biomechanical or electromyographic (EMG) assessments. This approach ensured feasibility and applicability within educational settings. More objective measures such as surface EMG or motion capture could provide deeper insight into neuromuscular coordination during actual performance.

Future research should adopt multi-institutional designs with larger, more diverse samples, including female students and various instrumental specializations. Given that different instruments impose different biomechanical demands, future research should tailor interventions to specific instrumental families. Interdisciplinary collaborations across physiotherapy, performing arts, and psychology may yield comprehensive models that combine physical, emotional, and cognitive strategies for enhancing performance resilience.

Conclusions

The results of this study confirm that short-term, structured physical intervention significantly improves ($p < 0.01$) the function of key postural muscles, particularly the deep neck flexors, musculus abdominis, and lower scapular stabilizers, in male performing arts students.

The results reinforce the value of preventive strategies that combine diagnostic assessments, mobility exercises, core strengthening, and ergonomic education in addressing the early stages of muscular weakening among musicians. The study demonstrates that performance-related musculoskeletal health can be improved through minimal time investment (2 sessions/week/30 minutes) over a six-week period, making this model both efficient and scalable.

The results suggest that structured neuromuscular interventions should be considered a foundational component of music education, particularly given the high prevalence of PRMDs in this demographic. This research contributes to a growing body of evidence advocating systemic change in university and performing arts training.

Its implications extend beyond injury prevention toward the promotion of lifelong physical literacy and sustainable artistic practice.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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Relationship between anthropometric characteristics and basketball-specific skills among South African university players

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Abstract

Background and Study Aim Anthropometric characteristics are commonly considered important determinants of performance in basketball. Variations in body size and composition may influence the execution of fundamental technical skills such as passing, shooting, and dribbling. Despite their practical relevance, the extent to which these characteristics relate to specific skill performance remains of practical interest in university players. This study aimed to examine the relationship between anthropometric characteristics and sport-specific skills among university-level basketball players in South Africa.

Material and Methods The study included 32 players (18 males and 14 females; mean age 21.71 ± 2.34 years). Selected skills were assessed using the AAHPERD standardized test battery. Data were analyzed using the Statistical Package for the Social Sciences (SPSS). The analysis included descriptive statistics, independent t-tests to examine sex differences, Pearson correlation coefficients to assess relationships among variables, and multiple regression analyses to predict passing skill.

Results The results among female players showed that body mass and body fat percentage (BF%) were strongly and negatively correlated with passing ($p < 0.01$). Females' muscular mass showed a strong negative correlation with shooting ($p < 0.01$). It also showed moderate negative correlations with left-hand control dribbling and a positive correlation with right-hand control dribbling ($p < 0.05$). Among male players, body height ($p < 0.01$) and leg length ($p < 0.01$) were strongly and negatively associated with passing skill. Males' muscularity was positively correlated with left- and right-hand dribble control time ($p < 0.05$). Body fat percentage was positively correlated with shooting skill ($p < 0.05$). No significant correlations were found between somatotype scores and basketball-specific skills in either group. Multiple regression analysis revealed that, for female players, lower body fat percentage and greater height significantly predicted better passing skill ($R^2 = 0.71$, $p = 0.016$). For male players, muscular mass was the only significant predictor ($R^2 = 0.43$, $p = 0.097$).

Conclusions The findings indicate that certain anthropometric characteristics, such as lower body fat percentage and greater muscular mass, may support basketball skill performance. However, overall success depends largely on technical skill proficiency. Skill execution is driven more by correct technique than by body characteristics alone. This highlights the importance of skill-focused training programs designed to enhance neuromuscular development in South African university basketball players.

Keywords: passing skill, dribbling skill, shooting skill, body composition, university basketball

Introduction

Basketball performance is determined by the interaction of physical attributes and technical execution during game situations. Players are required to perform passing, shooting, and dribbling actions under varying movement speeds and defensive pressure, where body dimensions and composition may influence movement control and coordination. Differences in height, limb length, muscular mass, and fat percentage can affect balance and reach, as well as ball handling mechanics, thereby shaping the effectiveness of skill execution. These relationships have practical relevance for training organization and player development in university basketball.

In context, basketball is an intermittent, physically demanding sport that requires players to possess a range of skills to play strategically and effectively and to score more points [1]. Previous research has shown that successful teams are characterized by a higher frequency of performing sport-specific skills such as accurate passing, efficient dribbling, and greater shooting opportunities [2, 3]. It is also emphasized that teams executing more passes and shot attempts tend to have an increased probability of winning in professional basketball [4]. In support of this, a study highlighted that teams that prioritize frequent passes enhance game tempo, increase shooting frequency, disrupt defensive structures, and create offensive balance [3].

Anthropometric characteristics often vary among athletes and may result in differences in skill execution and overall sport performance [5]. It has been reported that basketball skills improve as anthropometric characteristics improve [6]. Previous research has explored the influence and predictive value of anthropometric characteristics on basketball-specific skills, consistently highlighting

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the importance of attributes such as body dimensions, body composition, and somatotype in predicting success in elite competition [3, 4, 7, 8, 9]. Greater arm length in Greek wheelchair basketball players is positively associated with accurate long-pass performance [7]. Similarly, stretched arm length, body height, and raised arm height of young basketball players were identified as significant predictors of dribbling speed and obstacle dribbling ability [8]. Leg length of male basketball players from universities in Northern India positively contributes to their passing, shooting, and dribbling abilities [10]. These findings highlight the impact of anthropometric characteristics on basketball performance and positional roles.

Despite extensive global research examining the relationship between anthropometric profiles and basketball performance, there is limited evidence within the South African context. Existing studies in South Africa have primarily focused on describing the anthropometric and physical fitness profiles of female basketball players at the national, provincial, and university levels [11]. In South Africa, university basketball players often train in resource-constrained environments characterized by a lack of infrastructure and facilities dedicated to basketball. This results in limited opportunities for training and competition at both grassroots and elite levels [12], limited sport science support, and the absence of long-term athlete development systems [13, 14] compared with athletes in professional or well-resourced university leagues internationally. In addition, basketball is not a compulsory school sport in many public schools, and organized community or club-based development structures remain limited [14].

Analysis of research findings has shown that anthropometric characteristics are closely associated with the execution of basketball-specific skills and may influence performance outcomes and positional roles. Researchers emphasize that body dimensions and composition interact with technical actions such as passing, dribbling, and shooting under game conditions. At the same time, the expression of these relationships depends on training conditions, competitive structure, and athlete development pathways, which may modify how physical attributes translate into effective skill performance. In many cases, players are exposed to formal basketball training for the first time at the university level and may have had little or no structured technical development during adolescence. Such contextual factors can influence both anthropometric development and the acquisition of sport-specific skills, potentially altering the relationships observed between body composition and performance. Consequently, findings derived from elite or well-resourced populations may not be directly transferable to South African university athletes, indicating the relevance of examining these relationships within a specific competitive and developmental environment.

Investigating these relationships within this context is therefore important for developing locally appropriate training strategies, talent identification practices, and player development models. Therefore, the purpose of this study was to examine the relationship between anthropometric characteristics and basketball-specific skills among university-level basketball players in South Africa.

Materials and Methods

Participants

Thirty-two university-level basketball players (18 males and 14 females) with a mean age of 21.71 ± 2.34 years, who participated in University Sport South Africa (Males Division C and Females Division B), were recruited from one university for the study. The study included full-time and part-time registered South African and international students who played basketball for the selected university. Athletes with an injury lasting over 3 weeks, those who had previous surgery within the last 3 months, or those who were pregnant were excluded.

The researchers first obtained permission from the Health Research Ethics Committee at the University of Fort Hare (Certificate Reference Number: Ref #2024-04-04 HRECLVN05). The data collection process adhered to ethical principles.

Participants' confidentiality was ensured through anonymous identification codes, and all data were securely stored on OneDrive and accessible only to authorized users. Data were collected only from those who voluntarily participated in the study and provided consent. Participants were also informed that they had the right to withdraw from the study without consequences.

Study Design

The study followed a cross-sectional quantitative research design. Participants were recruited using a purposive sampling method, and all were assessed individually during data collection. The assessment of anthropometric characteristics lasted 1 week and was conducted at the gym facility laboratory. The assessment of sport-specific skills also lasted 1 week and was conducted at the university indoor basketball court. All anthropometric assessments were conducted by qualified ISAK Level 1 and Level 2 anthropometrists. Sport-specific skills were assessed by qualified Human Movement Science practitioners with prior experience to maintain reliability and validity. Standardized procedures were strictly followed for each participant.

Procedures

Anthropometric assessments

Standard procedures from the International Standards for Anthropometric Assessment (ISAK) were used for the assessments [15], using calibrated equipment and trained assessors. To minimize technical error of measurement (TEM), each variable was measured twice. If the two measurements differed by more than the acceptable ISAK tolerance (5% for skinfolds and 1% for girths, breadths, and lengths), a third measurement was taken, and the median value was recorded. This procedure is consistent with ISAK recommendations for reducing intra-observer variability and improving data reliability [15]. After all participants provided informed consent, each session began with a 10-minute briefing to explain the purpose of the assessments.

Body weight was measured using a weighing scale to the nearest 0.1 kg. Measurements were obtained in the morning, at least twelve hours after food intake and after voiding. The scale was set to zero before each measurement. Participants stood in the center of the scale without support and with weight evenly distributed on both feet.

Height was measured using a stadiometer to the nearest 0.1 cm. The participant stood with heels together, buttocks together, and the upper back touching the scale. Orbitale and tragion were aligned in the same horizontal plane to achieve the Frankfort plane. The participant was asked to take and hold a deep breath while keeping the head in the Frankfort plane. The headboard was firmly placed on the vertex, compressing the hair as much as possible. The measurement was taken before the participant exhaled.

Skinfold thickness was measured using a skinfold caliper at seven sites (biceps, triceps, subscapular, suprailiac, thigh, calf, abdomen) to the nearest 0.5 mm. All skinfold landmarks for the participant were marked with a demographic pen to minimize location errors across repeated measures. The skinfold was grasped at the marked site with the thumb and finger, perpendicular to the skinfold orientation, with the back of the hand facing the measurer. The contact face of the caliper was placed at 90 degrees, 1 cm away from the edge of the thumb and finger. The measurement was recorded 2 seconds after full caliper pressure was applied.

Girth measurements (arm relaxed, arm flexed and tensed, waist, gluteal, thigh, and calf) were conducted using an anthropometric tape. Each site was measured twice, and the average was recorded.

Arm length (acromiale–radiale, radiale–stylion, midstylion–dactylion) was measured using a segmometer. Participants stood in a relaxed position with their arms hanging by their sides. Measurements were taken twice, and the average values were recorded.

Leg length (trochanterion–tibiale laterale and tibiale laterale height) was measured using a segmometer and box. Participants stood with feet together. Measurements were taken twice, and the average values were recorded.

Breadths (humerus, bi-stylion, and femur) were measured using large and small sliding calipers. Participants were measured in a relaxed seated position. The caliper was held at right angles to the body segments being measured. Reliability was ensured by maintaining constant caliper pressure and correct placement on the designated landmarks.

Body fat percentage was estimated using the equations proposed by Withers et al. [16].

Equation 1

Male players

$$BD = 1.10326 - 0.00031\,(Age) - 0.0036\,(\Sigma 6SF)$$
$$\%Fat = (495 / BD) - 450$$

Female players

$$BD = 1.07878 - 0.00035\,(\Sigma 6SF) + 0.00032\,(Age)$$
$$\%Fat = (495 / BD) - 450$$

Where: BD — body density ($g \cdot cm^{-3}$); %Fat — body fat percentage (%); Age — age (years); Σ6SF — sum of six skinfold thicknesses (mm): biceps, triceps, subscapular, suprailiac, thigh, and calf.

Muscle mass was estimated using the anthropometric equation proposed by Lee et al. [17].

Equation 2

$$SMM = Ht\,(0.00744\,CAG^2 + 0.00088\,CTG^2 + 0.00441\,CCG^2) + 2.4\,(Sex) - 0.048\,(Age) + Race + 7.8$$

Where: SMM — skeletal muscle mass (kg); Ht — height (m); CAG — corrected arm girth (cm); CTG — corrected thigh girth (cm); CCG — corrected calf girth (cm); Age — age (years); Sex — sex (male = 1, female = 0); Race — ethnic coefficient (White/Hispanic = 0, Black = 1.4, Asian = −1.2).

Lean body mass was estimated from height and body mass using the equations proposed by Boer [18].

Equation 3

Men

$$eLBM = 0.407W + 0.267H - 19.2$$

Women

$$eLBM = 0.252W + 0.473H - 48.3$$

Where: eLBM — estimated lean body mass (kg); — body mass (kg); H — height (cm).

Basketball-specific skills assessments

All participants wore comfortable sportswear and basketball shoes. Each assessment began with a 10-minute standard warm-up. Adequate rest intervals of 3 minutes were provided between every sport-specific skill test to ensure that each evaluation reflected maximal effort. Two Human Movement Science practitioners with prior training carried out the assessments. All tests were administered in a standardized manner to ensure comparability with existing literature, and the same stopwatch and testers were used for all participants to ensure consistency.

The speed spot shooting test [19] was used to assess the speed and accuracy of shooting performance under time restrictions, including agility and ball handling. Five shooting spots were marked at 3.66 m from the basket. On the signal, the participant began behind a designated place, attempted a shot, retrieved the rebound, and moved to the next spot, repeating the sequence continuously for 60 seconds. Each successful shot was scored as 2 points, while 1 point was awarded after an unsuccessful shot. If a lay-up was successful with the ball returning from the hoop, it was scored as 2 points. If two successful lay-ups were made in a row, the second was not scored. No points were awarded for shots made with violations in dribbling, ball handling, or the shooting line [Hopkins et al., 1984]. The stopwatch was calibrated before each session. All scores were recorded on a data sheet.

The obstacle dribble test [19] was performed on an indoor basketball court. An obstacle course (3.6 m × 5.8 m) was marked by six cones placed in the free-throw lane. The participant started dribbling on the signal while passing the cones and changing hands. Participants were instructed to cover a distance of 17.9 m as fast as possible while maintaining control of the basketball. Each participant performed two trials per hand, and the time was recorded. The shortest time was used for analysis. The stopwatch was calibrated before each session. All scores were recorded on a data sheet.

The AAHPERD Basketball Passing Test [19] was conducted on a smooth wall surface 9 m in length. Each passing test station was set up according to the AAHPERD protocol. A restraining line, 8 m long, was marked 2 m from and parallel to the testing wall. Participants were instructed to execute only chest passes, emphasizing speed and accuracy, two fundamental components of basketball passing. Scoring was as follows: two points for each pass hitting the target or its boundary lines, one point for passes landing between targets, and zero points if the participant stepped on or over the restraining line or used a pass other than a chest pass

Statistical Analysis

All data were analyzed using the Statistical Package for the Social Sciences (IBM SPSS) version 28. Descriptive statistics (mean values, standard deviation, and minimum and maximum values) were reported for all variables. Independent t-tests were used to determine differences between male and female basketball players. The Kolmogorov-Smirnov and Shapiro-Wilk tests were used to assess normality. The Pearson correlation coefficient (r) was used to determine relationships between anthropometric characteristics and sport-specific skills when normal distribution was assumed. The strength of the Pearson coefficient was interpreted as follows: 0.00–0.199 very weak, 0.20–0.399 weak, 0.40–0.599 moderate, 0.60–0.799 strong, and 0.80–1.000 very strong. Assumptions were evaluated before conducting parametric tests. Multiple regression analyses were conducted separately for males and females to predict passing skill. Residual plots and variance inflation factors (VIF) were used to assess regression assumptions (multicollinearity). No severe multicollinearity was detected (all VIF < 10). Statistical significance was set at $p = 0.05$.

Results

Table 1 presents the comparison between male and female basketball players in terms of anthropometric characteristics and basketball-specific skills.

The mean and standard deviations for anthropometric characteristics and sport-specific skills are presented for males and females in Table 1. Analysis showed significant differences between males and females across all measures ($p < 0.05$) except for body mass and mesomorph scores. Males showed higher values across most anthropometric measures, except for body fat percentage (16.60 ± 5.77). In terms of somatotype, females were more endomorphic (4.55 ± 1.33), whereas males displayed greater ectomorphic characteristics (2.59 ± 1.46).

Table 2 presents Pearson correlations between anthropometric characteristics and basketball-specific skills in female players.

As shown in Table 2, muscular mass was strongly negatively correlated with shooting ($r = -0.680$) and with right-hand control dribble ($r = -0.635$), and moderately positively correlated with left-hand control dribble ($r = 0.587$). Body mass ($r = -0.682$) and body fat percentage ($r = -0.683$) showed strong negative correlations with passing skill. Body height ($r = -0.502$) and lean body mass ($r = -0.590$) showed moderate negative correlations with passing skill.

Table 3 presents Pearson correlations between anthropometric characteristics and basketball-specific skills in male players.

As shown in Table 3, body height ($r = -0.672$) and leg length ($r = -0.624$) demonstrated strong negative correlations with passing skill, while lean body mass ($r = -0.561$) and arm length ($r = -0.525$) showed moderate negative correlations with passing skill. A strong positive correlation was observed between muscular mass and left-hand control dribble ($r = 0.617$). Moderate positive correlations were observed between body mass and left-hand control dribble ($r = 0.523$), leg length and right-hand control dribble ($r = 0.529$), and lean body mass with left-hand ($r = 0.558$) and right-hand ($r = 0.459$) control dribble. Body fat percentage showed a moderate positive correlation with shooting skill ($r = 0.497$).

Table 4 presents the multiple regression analysis predicting the passing skill of university female basketball players.

Table 1. Comparison between male and female basketball players in anthropometric characteristics and basketball-specific skills

Variables	All players (N = 32) M ± SD	Range (Min–Max)	Female (N = 14) M ± SD	Male (N = 18) M ± SD	p-value
Basic body metrics					
Body mass (kg)	69.33 ± 10.26	52.70–101.50	68.81 ± 9.09	69.69 ± 11.23	0.08
Height (cm)	170.02 ± 8.48	154.80–188.50	164.54 ± 6.92	173.86 ± 7.40	<0.001**
Body composition					
BF%	19.36 ± 6.35	10.92–32.29	23.31 ± 5.03	16.60 ± 5.77	<0.001**
Muscular mass (kg)	29.20 ± 4.30	19.90–38.80	25.33 ± 2.51	31.91 ± 3.01	<0.001**
LBM (kg)	51.97 ± 6.92	38.80–72.40	46.86 ± 5.41	55.57 ± 5.50	<0.001**
Somatotype profile					
Endomorph score	3.19 ± 1.80	1–7	4.55 ± 1.33	2.25 ± 1.46	<0.001**
Mesomorph score	5.08 ± 1.28	2–8	5.29 ± 1.04	4.94 ± 1.45	0.452
Ectomorph score	1.98 ± 1.36	0–5	1.11 ± 0.47	2.59 ± 1.46	<0.001**
Limb dimensions					
Total arm length	75.10 ± 6.34	63.70–89.90	70.06 ± 4.40	78.63 ± 4.97	<0.001**
Total leg length	88.73 ± 6.75	71.20–102.80	85.11 ± 6.68	91.26 ± 5.70	<0.001**
Skills					
Passing skill	1.18 ± 0.30	5–19	8.00 ± 1.96	13.33 ± 3.46	<0.001**
Left-hand control dribble	11.00 ± 3.93	9.99–14.75	13.45 ± 0.85	11.57 ± 1.02	<0.001**
Right-hand control dribble	12.39 ± 1.33	9.76–14.75	13.03 ± 1.00	10.99 ± 0.77	<0.001**
Shooting skill	11.88 ± 1.34	14–29	19.29 ± 3.10	25.11 ± 2.61	<0.001**

Note. *p < 0.05, **p < 0.01. BF% — body fat percentage; LBM — lean body mass.

Table 2. Pearson correlation (r) between anthropometric characteristics and sport-specific skills in female players

Variables	Body mass	Body height	BF%	Muscular mass	LBM	Arm length	Leg length	Endo	Meso	Ecto
Passing skill (points)	-0.682**	-0.502*	-0.683**	-0.008	-0.590*	-0.473	-0.701	-0.420	-0.098	0.437
Left-hand control dribble (s)	0.334	0.456	-0.366	0.587*	0.414	0.216	0.207	-0.485	-0.121	0.153
Right-hand control dribble (s)	-0.121	-0.232	0.203	-0.635**	-0.190	0.009	0.260	0.116	-0.409	-0.208
Shooting skill (points)	-0.067	-0.202	0.417	-0.680**	-0.149	0.073	0.274	0.368	-0.242	-0.262

Note. *p < 0.05, **p < 0.01. BF% — body fat percentage; LBM — lean body mass.

Table 3. Pearson correlation (r) between anthropometric characteristics and sport-specific skills in male players

Variables	Body mass	Body height	BF%	Muscular mass	LBM	Arm length	Leg length	Endo	Meso	Ecto
Passing skill (points)	-0.282	-0.672**	-0.435	-0.236	-0.561*	-0.525*	-0.624**	-0.045	0.206	-0.375
Left-hand control dribble (s)	0.523*	0.193	0.329	0.617**	0.558*	0.196	0.405	0.225	0.260	-0.225
Right-hand control dribble (s)	0.321	0.372	0.331	0.374	0.459*	0.282	0.529*	0.105	0.023	0.105
Shooting skill (points)	0.333	0.264	0.497*	0.150	0.423	0.235	0.430	0.281	0.073	0.054

Note. *p < 0.05, **p < 0.01. BF% — body fat percentage; LBM — lean body mass.

Table 4. Multiple regression analysis predicting passing skill in university female basketball players

Predictor variables	B	SE B	β	t	p-value	Tolerance	VIF
Constant	-22.335	8.748	–	-2.553	0.031	–	–
Body fat percentage	-0.243	0.084	-0.622	-2.877	0.018	0.691	1.448
Muscular mass	0.130	0.195	0.166	0.666	0.522	0.518	1.929
Body height	0.174	0.066	0.614	2.654	0.026	0.602	1.660

Note. $R^2 = 0.71$, Adjusted $R^2 = 0.58$, $F(4, 9) = 5.502$, $p = 0.016$

Table 5. Multiple regression analysis predicting passing skill in university male basketball players

Predictor variables	B	SE B	β	t	p-value	Tolerance	VIF
Constant	-18.425	20.845	–	-0.884	0.393	–	–
Body fat percentage	0.157	0.169	0.207	0.929	0.370	0.885	1.130
Muscular mass	0.720	0.299	0.539	2.407	0.032	0.873	1.145
Body height	0.052	0.106	0.104	0.493	0.630	0.980	1.021

Note. $R^2 = 0.42$, adjusted $R^2 = 0.26$, $F(4, 13) = 2.465$, $p = 0.097$.

To determine whether anthropometric characteristics significantly related to passing skill could predict performance, multiple regression analysis was applied. As shown in Table 4, the regression model including body fat percentage, muscular mass, and body height was statistically significant ($R^2 = 0.71$, adjusted $R^2 = 0.58$, $F(4, 9) = 5.50$, $p = 0.016$), explaining 58% of the variance in passing performance. Body fat percentage emerged as a significant negative predictor of passing skill ($\beta = -0.62$, $p < 0.05$). Body height was a significant positive predictor ($\beta = 0.61$, $p < 0.05$). Muscular mass did not independently predict passing skill ($\beta = 0.166$, $p > 0.05$). No multicollinearity was observed among the predictors, as tolerance and variance inflation factor values were within acceptable ranges.

Table 5 presents the multiple regression analysis predicting passing skill in university male basketball players.

As shown in Table 5, the regression model was not statistically significant ($R^2 = 0.42$, adjusted $R^2 = 0.26$, $F(4, 13) = 2.47$, $p = 0.097$). Muscular mass was identified as a significant positive individual predictor of passing skill ($\beta = 0.54$, $p < 0.05$). Body fat percentage and body height were not significant predictors ($p > 0.05$). No evidence of multicollinearity was detected.

Discussion

The study aimed to determine correlations between anthropometric characteristics and basketball-specific skills in South African university basketball players. The sex differences observed in the current study show that males have more favorable anthropometric characteristics. These differences are consistent with previous findings. Fields et al. [20] reported similar differences among collegiate basketball players, Hernandez-Martinez et al. [21] among professional players, and Sansone et al. [22] across male and female basketball players competing at international, national, and regional levels. From the sport-specific skills perspective, males significantly outperformed females across all measures. The results align with the study by Argiriou [23] among top-ranking men's and women's teams in the Greek National Basketball Championship and with a study by Theoharopoulos et al. [24] among male and female basketball teams in Thessaloniki, Greece, in different group divisions. These differences are likely attributed to biological and hormonal distinctions between sexes, particularly post-puberty [21, 25].

The present study revealed that body mass and body fat percentage in female basketball players were strongly and negatively correlated with passing skill, whereas lean body mass and height were moderately negatively correlated with passing skill. This suggests that passing accuracy may be negatively affected by excessive body size, whether fat or lean mass. The results are consistent with the study by Eroğlu et al. [6], who reported that basketball players with greater body size demonstrated poorer passing skills, with a significant negative correlation ($r = -0.021$, $p = 0.000$). Passing skill is associated with agility and quick positioning, and heavier or taller players may struggle with agility, quick repositioning, and fine motor control, all of which are critical for producing accurate and timely passes [26]. Passing performance depends more on neurological abilities such as coordination and motor control, which are not determined by anthropometric characteristics across different competitive levels [27]. Although lean mass is typically associated with strength production, it does not appear to directly enhance technical skills.

Muscular mass showed a strong negative correlation with right-hand control dribble time and a moderate positive correlation with left-hand control dribble. This suggests that greater muscular mass was associated with faster right-hand dribbling but slower left-hand dribbling, likely because most players were right-handed and had reduced coordination on the non-dominant side. This aligns with the study by Franciosi et al. [28], who observed that explosive leg power and upper-body endurance positively contributed to ball-handling performance among youth basketball players, suggesting that it is not merely muscle mass alone but rather explosive and functionally applied strength that supports skill development.

Higher muscular mass was also associated with poorer shooting skill. No specific study was found examining the correlation between muscle mass and shooting skill; however, some studies reported a relationship between muscle mass and strength. Čabarkapa et al. [29] examined male and female collegiate basketball players with prior competitive and resistance training experience and found no significant relationship between maximal upper- or lower-body strength and shooting accuracy, emphasizing that raw strength alone may not directly enhance shooting performance. In contrast, Franciosi et al. [28] reported that explosive leg power and upper-body endurance positively influenced shooting performance, suggesting that it is not sheer muscle strength but rather explosive and functionally applied strength that supports skill development. Similarly, Ahmed [30] demonstrated that neuromuscular training improved shooting, dribbling, and passing, reinforcing the idea that training that enhances skill-specific motor control and stability, rather than muscular bulk, is more effective in developing basketball proficiency.

Among males, body height, arm length, leg length, and lean body mass were negatively and moderately correlated with passing skill. The results contrast with the study by Singh and Singh [10], who reported that leg length and arm length had a positive and significant correlation with passing skill ($r = 0.59$ and $r = 0.51$, $p < 0.001$, respectively) among male basketball players from the University of Northern India, suggesting that greater height or limb length may provide mechanical advantages in passing performance. Furthermore, Apostolidis et al. [8] reported that longer arms facilitated better passing, indicating that the advantages might be skill-specific or modulated by positional role. Lean body mass showed a moderate negative correlation with passing skill. This indirectly supports the notion that passing skill is associated with agility and quick positioning, and heavier or taller players may struggle with agility, quick repositioning, and fine motor control, all of which are critical for producing accurate and timely passes [26].

The current study showed a strong positive correlation between muscular mass and left-hand control dribble, likely because most players were right-handed and had reduced coordination on the non-dominant side. Moderate positive correlations were observed between body mass and left-hand control dribble, leg length and right-hand control dribble, and lean body mass and both left-hand and right-hand control dribbling skills. These results suggest that greater muscular mass may be associated with poorer execution of left-hand dribbling, which requires efficient coordination because it is performed with the non-dominant hand. A study by Zarić et al. [31] supports this by stating that basketball players who perform well in dribbling are usually point guards, who are typically smaller, suited for quick acceleration and deceleration, and possess good agility.

Body fat percentage was positively and moderately correlated with shooting skill. This contrasts with a study involving Ethiopian university players that found a significant negative correlation between body fat percentage and basketball skill performance, indicating that increased body fat adversely affects shooting accuracy [32]. A study by Ramos et al. [33] also reported weak negative correlations between body fat percentage and points scored per basketball game ($r = -0.200$, $p < 0.005$) among elite regional basketball players.

The study showed that in both sexes, higher body mass and lean mass were linked to poorer passing performance. Muscular mass influenced dribbling differently: in females, it improved dominant-hand speed but hindered non-dominant-hand control, whereas in males, greater body and lean mass, along with leg length, reduced right-hand dribbling ability. Overall, females with less muscular mass performed better in passing, while males with higher body fat achieved better shooting results. These differences between sexes suggest that the relationships between anthropometric characteristics and skill performance differ for males and females, similar to findings by Haïdara et al. [34] among male and female students, Sánchez-Díaz et al. [35] among elite male and female youth basketball players, Theoharopoulos et al. [24] among male and female basketball players in the Greek championships, and Gómez et al. [4] among elite male and female basketball players from Spanish professional leagues.

The current results indicate that excessive body fat is detrimental to performance, whereas lean or muscular mass contributes positively in specific contexts. However, contradictions arise concerning body size, as the Ethiopian study reported body mass, height, and limb lengths positively associated with skill performance [32]. In contrast, the present findings suggest that these traits can hinder technical precision, particularly in passing and shooting, with females disadvantaged by overall mass and fat, and males by height and limb length.

The quality of training, availability of facilities, and competitive levels across different countries could contribute to these contrasting outcomes, as many studies have involved elite or highly competitive basketball players, such as the study by Conte et al. [36] conducted among Italian elite women basketball players and the study by Zarić et al. [31] among elite basketball players in the FIBA World Cup. Compared with international studies, South African basketball players show higher body mass and lower muscular mass relative to international basketball fitness standards [11, 12], suggesting that South African players may not have developed the same basketball skills and anthropometric profiles that allow larger players at higher competitive levels to maintain technical proficiency despite greater body mass.

The stratified regression analyses revealed a noticeable difference in how the selected anthropometric characteristics explained passing skill variance between female and male basketball players. The results confirm gender-specific determinants of anthropometric characteristics and quantify the models' descriptive power and statistical robustness within each group. Previous studies have analyzed performance prediction using game statistics to predict overall basketball performance [37] or focused on shooting and dribbling performance [8, 38]. Garcia-Gil et al. [37] designed a model to predict basketball performance in terms of PIR per minute, whereas Apostolidis et al. [8] established a prediction model of dribbling and shooting technical skills based on significant anthropometric variables. To the best of our knowledge, the current study is the first to develop a prediction model for a specific basketball skill, namely passing skill.

The regression model among female basketball players was significant, and the predictors collectively accounted for a large proportion of variance in passing skill scores. The adjusted R^2 value indicated that over 58% of the variance in passing skill among females was explained by the model, suggesting a meaningful and well-specified model. This was further supported by the relatively low standard error of the estimate (1.27). In contrast, the regression analysis for male basketball players was not statistically significant, with the predictors accounting for only 43.1% of the variance, which, after adjustment, dropped to 25.6%. The high standard error of the estimate (2.99) for males also suggested greater prediction error and more unexplained variability in skill scores. This disparity in model efficacy indicates that the selected anthropometric variables were more strongly and linearly related to passing skill in females than in males within this cohort.

For females, the significant negative relationship between body fat percentage and skill performance is consistent with principles of dynamic efficiency, where excess adiposity may impede rotational agility, movement speed, and the fluid transmission of force required for skilled passing [39, 40]. Concurrently, the positive association with body height likely confers biomechanical advantages such as an elevated release point, extended reach, and improved visual perspective, which are critical in interceptive and projectile sports [41]. The non-significance of muscular mass suggests that, in this context, body composition and lever mechanics are more critical for skill expression than absolute muscularity.

For males, only muscular mass emerged as a significant unique predictor within a model of limited overall utility. Greater muscle mass may enhance the capacity to generate passing force, leading to improved passing effectiveness [3]. The lack of significance for body fat and height suggests a more homogeneous anthropometric range among skilled male athletes.

Summary of the main findings and their practical implications

The study revealed that anthropometric characteristics were associated with skill performance in both male and female players. Higher muscularity and lean body mass were associated with improved dribbling control but were negatively linked to passing and shooting, suggesting that non-functional or excessive muscle mass may hinder skills requiring precision and coordination. These findings support the theory of differentiated talent models across sexes in sport [21, 23]. The strong and significant female model indicated that skill was closely tied to optimal body composition for movement and structural advantages. The weaker significance among males suggested that skill execution was more dependent on the capacity to apply force but was also influenced by unmeasured factors such as neuromuscular control, technical proficiency, and decision-making.

From an applied perspective, this evidence supports sex-specific conditioning and talent identification frameworks:

- Female athlete development should prioritize achieving lean body composition and refining technique that maximizes height-based leverage.
- Male athlete development, while benefiting from strength training, should extend beyond the anthropometric variables measured here. Coaches and scientists should integrate technical-tactical assessments and, where appropriate, specific power diagnostics to better explain and enhance skill performance.

Limitations and Future Research

This study has several limitations that should be considered when interpreting the findings. The cross-sectional design does not allow causal conclusions. The difference in model fit may also have been influenced by the smaller female sample size (n = 14) compared with males (n = 18), which can affect stability; however, the significant results in the female group, despite the smaller n, underscore the strength of the relationships observed. The primary limitation is the omission of key variables, particularly technical proficiency metrics, training history, and sport-specific power tests, which likely account for the substantial unexplained variance, especially in the male model.

Future research should employ longitudinal designs to track how changes in these physical traits co-evolve with skill acquisition. Furthermore, studies should incorporate kinematic and kinetic analyses to explain why body fat was detrimental to female skill but not male skill, and why muscular mass was critical for males but not females in this specific task. Given the limitations of sample size and institutional scope, future research should investigate larger, sex-stratified samples across multiple universities and competitive levels.

Conclusions

The relationship between anthropometric characteristics and sport-specific skill performance appears to be mediated by technical proficiency and neuromuscular control. The lack of significant associations between somatotype and skill outcomes indicates that body type alone does not determine basketball proficiency. In a South African university basketball team, the passing skill of female basketball players was strongly predicted by lower body fat and greater height, whereas male skill depended more on muscular mass development, although to a lesser degree and with lower significance. These findings indicate that physical standards should not be applied uniformly across sexes and that, while physical attributes may support performance, skill shaped by neuromuscular control, technical training, and contextual adaptation ultimately determines success. Because prior studies assessed passing indirectly through assists or composite performance indices, the present study provides direct examination of passing performance and its anthropometric predictors. For coaches and talent developers working in resource-constrained environments, the results support skill-focused, sex-informed training strategies that prioritize technical mastery alongside monitored strength and conditioning when improving skill performance.

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Data availability statement

The data underlying the study are not publicly available but may be available upon reasonable request from the corresponding authors.

Conflict of Interest

There was no potential conflict of interest.

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ORIGINAL ARTICLE

Assessment of the association between foot arch profiles and single-leg dynamic postural control in male soccer players

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

Abstract

Background and Study Aim Postural control is a fundamental skill that emerges from the interaction between the central nervous system and sensorimotor structures. It enables the maintenance of body balance and plays a critical role in both athletic performance and injury risk, particularly in sports such as soccer, where unilateral loading patterns are common. Despite the application of various assessment approaches, including static and non-task-specific methods, their effectiveness in reflecting postural control under dynamic and limb-specific conditions remains a matter of practical interest. In this context, the present study aimed to examine the relationship between foot arch profiles and single-leg dynamic postural control in soccer players.

Material and Methods A total of 48 male university-level soccer players participated in the study. Participants were classified into three groups (high, normal, and low arch profiles) based on plantar pressure measurements. Single-leg dynamic postural control was assessed using a balance platform. Directional postural sway and the percentage of time spent within the target zone were analyzed using one-way ANOVA with post hoc comparisons.

Results The findings revealed that foot arch structure significantly influences postural control. Athletes with normal arch profiles demonstrated superior balance performance, maintaining their position within the target zone for longer durations (90.75 ± 2.30%) compared with the high arch (71.69 ± 3.95%) and low arch groups (77.31 ± 2.87%) ($p < 0.0001$). In contrast, the high arch group exhibited a more rigid and asymmetrical control strategy, with reduced right-directed sway (42.00 ± 2.42%) and increased left-directed sway (58.00 ± 2.42%). The low arch group showed increased anterior sway (57.88 ± 2.00%) compared with the normal (49.06 ± 0.85%) and high arch groups (47.63 ± 1.59%) ($p < 0.0001$). These differences were associated with large effect sizes ($\eta^2 = 0.81–0.90$), indicating strong group effects.

Conclusions Foot arch morphology plays a significant role in the organization of postural control strategies. A normal arch structure appears to provide advantages in terms of mechanical stability and sensory feedback. High and low arch profiles lead to distinct balance strategies. The use of a dynamic single-leg assessment provides a more task-specific perspective on postural control in soccer players. These findings suggest that evaluating foot arch structure and implementing individualized training programs may contribute to performance optimization and injury risk reduction in athletes.

Keywords: foot arch profile, postural control, balance, soccer players, plantar pressure

Introduction

Postural control represents a complex functional ability that underpins coordinated movement and stability during physical activity. In sports contexts such as soccer, maintaining balance during dynamic and unilateral actions is essential for effective performance and safe movement execution. The mechanisms of postural control involve the integration of sensory input and biomechanical factors, where structural characteristics of the foot may influence stability and movement patterns. Variations in foot arch profiles can alter load distribution, proprioceptive feedback, and movement control, thereby contributing to differences in balance performance under dynamic conditions.

Postural control is defined as the ability to maintain the body's center of mass within the limits of the base of support. This process is regulated through the continuous interaction between the central nervous system and peripheral sensorimotor structures [1, 2, 3]. In athletes, postural control is not merely a mechanism for maintaining balance. It is also considered a fundamental component for sustaining athletic performance and reducing injury risk [3, 4, 5]. This function becomes particularly critical in sports such as soccer, where unilateral loading patterns and limb-specific tasks are highly prevalent [6]. In such contexts, postural control strategies may vary depending on task demands and limb-specific characteristics [4].

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Postural control is achieved through different motor strategies depending on task requirements [5, 6, 7]. Among these, the ankle, hip, and stepping strategies are the most commonly described. The ankle strategy plays a dominant role in controlling small-amplitude postural oscillations. The effectiveness of this strategy is closely related to the morphological characteristics of the foot–ankle complex and the quality of somatosensory input derived from the plantar surface [8, 9, 10]. Accordingly, the mechanical and sensory interactions between the plantar surface and the ground can be considered key determinants in the organization of postural control.

Foot arch structure represents a fundamental morphological feature that directly influences plantar contact area and pressure distribution [11, 12]. The height of the medial longitudinal arch determines the extent of plantar surface contact. It thereby modulates both mechanical stability and the intensity of sensory input transmitted to the central nervous system via plantar mechanoreceptors [10, 11, 12]. Although foot arch structure is generally considered a static morphological characteristic, it may indirectly influence the organization of ankle strategy during single-leg postural tasks. In this regard, the effects of foot arch profiles on postural control may become more pronounced in tasks where the ankle strategy predominates.

Most studies evaluating postural control in soccer players have relied on static stance assessments or non-sport-specific balance protocols [13, 14, 15]. However, given the nature of soccer, which frequently involves single-leg stance and unilateral loading tasks [14, 16], postural control should be assessed within a limb-specific and task-relevant framework. In addition, these approaches often fail to capture the dynamic and feedback-dependent nature of postural regulation during sport-specific activities. The relationship between foot arch profiles and single-leg postural control in task-specific and limb-specific contexts requires further clarification [10, 11, 17].

Furthermore, although foot arch structure is typically characterized using static measurements, its functional implications during dynamic single-leg postural control tasks have not yet been fully elucidated [12, 18, 19]. In particular, the role of foot arch profiles in the organization of postural control strategies during tasks requiring controlled postural sway remains a subject of ongoing debate. Moreover, it remains unclear whether different foot arch profiles lead to distinct directional control strategies under dynamic conditions. Therefore, the aim of the present study was to investigate the relationship between foot arch profiles and single-leg dynamic postural control in soccer players. Athletes with normal arch profiles were expected to demonstrate superior postural control performance. High and low arch profiles were expected to be associated with distinct and less efficient control strategies.

Materials and Methods

Participants

The study was conducted using a convenience sampling approach. Male university-level licensed soccer players were voluntarily recruited from university teams competing in regional leagues during the 2025–2026 season. Foot arch profiles were determined after all measurements. Participants were subsequently categorized into three groups: high arch, normal arch, and low arch. To ensure numerical balance, a random selection procedure was applied to overrepresented groups. A computer-based randomization method (random number generator) was used, resulting in 16 participants in each group (total N = 48). All participants were actively training and competing soccer players. They were identified as right-foot dominant based on self-report. Dominance was defined as the preferred foot used for kicking a ball. Inclusion criteria included the absence of orthopedic or neurological conditions affecting the lower extremities. Participants also had no history of injury or medical treatment within the previous year that could influence performance. An a priori power analysis (G*Power 3.1) indicated that a minimum sample size of 42 participants was required to detect a large effect size (f = 0.50) with 80% power at $\alpha = 0.05$. Therefore, the sample size used in this study (N = 48) was considered sufficient.

The anthropometric characteristics of the participants are presented in Table 1.

Table 1. Anthropometric Characteristics of Participants (Mean ± SD)

Variable	High Arch (n = 16)	Normal Arch (n = 16)	Low Arch (n = 16)
Age (years)	19.51 ± 1.21	18.87 ± 1.13	19.23 ± 1.49
Height (cm)	182.0 ± 6.59	178.11 ± 6.28	175.6 ± 6.80
Body mass (kg)	74.83 ± 7.23	72.63 ± 6.73	75.9 ± 7.57
BMI (kg/m^2)	22.67 ± 1.78	22.91 ± 1.66	24.6 ± 1.91

The study protocol was approved by the Non-Interventional Clinical Research Ethics Committee of Düzce University (Approval No: 206/116; Date: 27 February 2026). All procedures were carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to data collection.

Research Design

This study was designed as a cross-sectional investigation to examine the relationship between foot arch profiles and single-leg dynamic postural control in soccer players. All measurements were conducted in a single session for each participant under standardized laboratory conditions. These conditions included identical flooring, equipment, and testing instructions. Testing was performed in a quiet indoor laboratory environment under consistent lighting conditions. All measurements were conducted at similar times of day to minimize circadian effects.

Anthropometric Measurements

Anthropometric assessments were conducted at the beginning of the measurement session, prior to any procedures that could induce fatigue. These assessments were performed in accordance with the standards of the International Society for the Advancement of Kinanthropometry (ISAK) (Olds, 2006). Body height was measured without shoes and in an upright standing position using a portable stadiometer (SECA 213, SECA GmbH, Germany). Body mass was recorded with participants wearing light sports clothing and no shoes, using a calibrated digital scale (SECA 813, SECA GmbH, Germany). Body mass index (BMI) was calculated as body mass divided by the square of height (kg/m^2).

Determination of Foot Arch Profiles

Foot arch profiles were determined based on plantar pressure distribution measurements. Plantar pressure data were collected using the Footscan® 7 Platform System (RSscan International, Olen, Belgium), which records data at a sampling frequency of 300 Hz. Measurements were conducted with participants standing barefoot in a relaxed upright posture. Participants performed three 10-second standing trials. The first two trials were used for familiarization. The third trial was recorded for analysis. A 30-second rest interval was provided between trials. Foot placement was standardized using visual markers. Participants stood barefoot in a relaxed upright posture with their feet positioned naturally at shoulder width. Foot arch profiles were classified using the Chippaux–Smirak Index (CSI). It was defined as the ratio of the narrowest width of the midfoot region to the widest width of the forefoot. Based on CSI values, participants were categorized as high arch ($\leqslant 0.29$), normal arch (0.30–0.39), and low arch ($\geqslant 0.40$). Only dominant foot (right foot) values were used for analysis.

Single-Leg Dynamic Postural Control Assessment

Single-leg postural control was assessed using a wireless portable balance system (Sigma System Cosmo Gamma, Cosmo). Participants stood barefoot on their dominant foot, while the non-supporting foot was lifted off the ground. They were instructed to maintain their center of mass within a visual target zone for 30 seconds using real-time feedback. Prior to data collection, participants performed two familiarization trials to ensure adequate understanding of the task and the visual feedback system. The third trial was used for analysis. A 60-second rest interval was provided between trials. The system was calibrated individually for each participant according to the manufacturer's guidelines before testing. The target zone was defined as a circular area centered on the participant's baseline center of pressure position obtained during calibration. Visual feedback was provided continuously via a monitor positioned at eye level approximately 1.5 m in front of the participant. Directional postural sway (medial, lateral, anterior, posterior) and the percentage of time spent within the target zone were recorded. These variables were used as indicators of dynamic postural control performance.

Statistical Analysis

Statistical analyses were performed using GraphPad Prism (version 10.3.1; GraphPad Software, San Diego, CA, USA). Descriptive statistics were expressed as mean ± standard deviation ($\bar{x} \pm SD$). The normality of data distribution was assessed using skewness and kurtosis coefficients (acceptable range: ±2). In addition, normality was visually examined using Q–Q plots. Differences between foot arch groups were analyzed using one-way analysis of variance (ANOVA). The homogeneity of variances was evaluated using the Brown–Forsythe and Bartlett tests. The results of these tests confirmed that the assumption of homogeneity of variances was satisfied. When significant differences were found, Holm–Šídák-corrected post hoc tests were applied. Effect sizes were reported using eta squared (η^2). Statistical significance was set at $p < 0.05$.

Results

Descriptive statistics and between-group comparisons of single-leg dynamic postural control parameters obtained from the dominant foot, according to foot arch profiles, are presented in Table 2. The results of pairwise post hoc comparisons are illustrated in the corresponding figures.

As shown in Table 2, significant differences were observed between foot arch profile groups across all postural control variables, with large effect sizes ($\eta^2 = 0.81–0.90$). The most pronounced difference was found in time spent in the target zone. The normal arch group demonstrated substantially higher values compared with both the high and low arch groups ($F(2,45) = 158.50$, $p < 0.0001$, $\eta^2 = 0.88$). Regarding directional postural sway, distinct patterns emerged across groups. The high arch group exhibited reduced right-directed sway but increased left and posterior sway. The low arch group demonstrated markedly higher anterior sway values ($F(2,45) = 204.50$, $p < 0.0001$, $\eta^2 = 0.90$). In contrast, the normal

Table 2. Single-leg dynamic postural control parameters of the dominant foot according to foot arch profiles

Parameter	High arch (n = 16)	Normal arch (n = 16)	Low arch (n = 16)	F (2,45)	p	η^2
Right-directed postural sway (%)	42.00 ± 2.42	48.63 ± 1.09	49.44 ± 1.09	96.89	<0.0001	0.81
Left-directed postural sway (%)	58.00 ± 2.42	51.38 ± 1.09	50.56 ± 1.09	96.89	<0.0001	0.81
Anterior postural sway (%)	47.63 ± 1.59	49.06 ± 0.85	57.88 ± 2.00	204.50	<0.0001	0.90
Posterior postural sway (%)	52.38 ± 1.59	50.94 ± 0.85	42.13 ± 2.00	204.50	<0.0001	0.90
Time spent in target zone (%)	71.69 ± 3.95	90.75 ± 2.30	77.31 ± 2.87	158.50	<0.0001	0.88

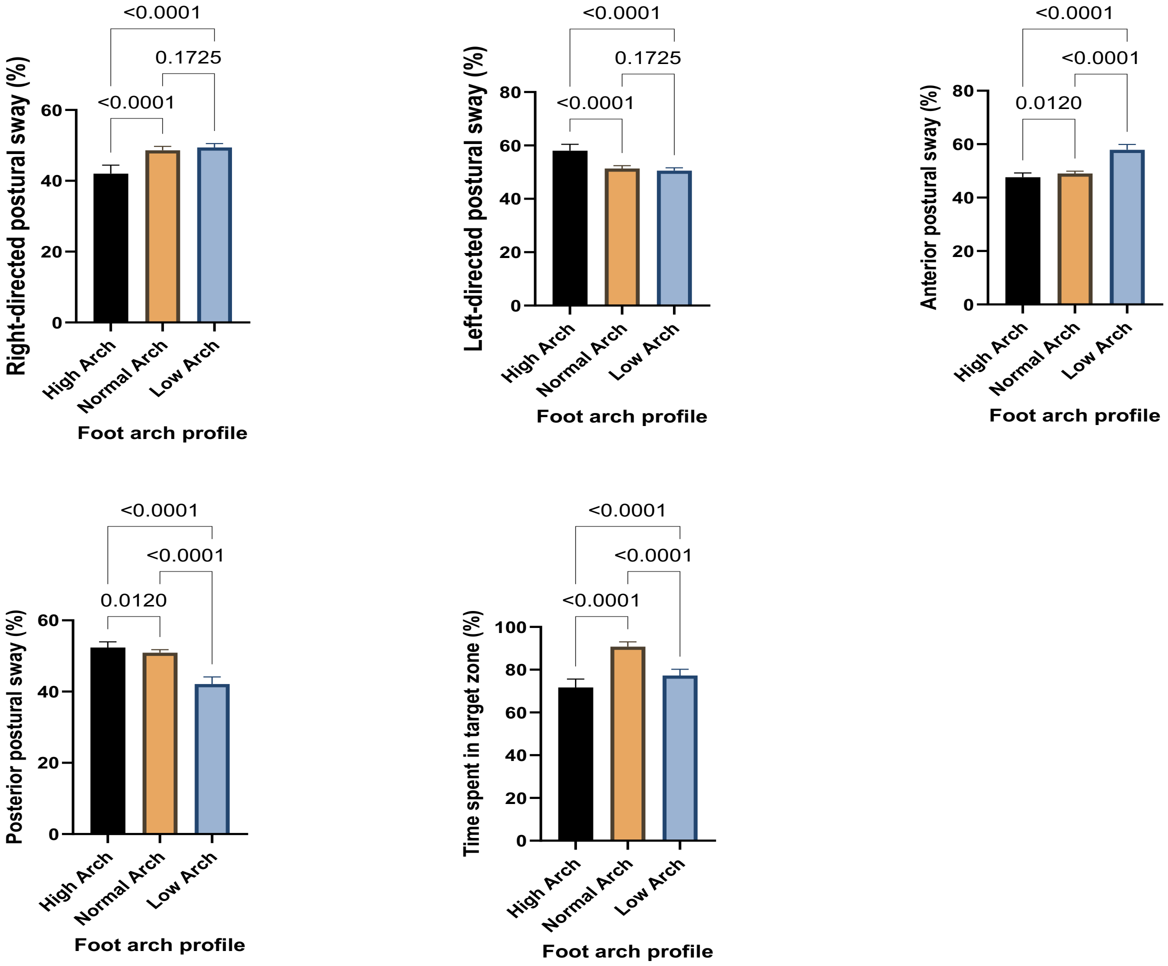

Figure 1. Post hoc comparisons of single-leg dynamic postural control parameters across foot arch profiles

arch group showed a more balanced distribution of sway across directions. This was accompanied by superior performance in maintaining position within the target zone.

The results of post hoc comparisons are presented in Figure 1.

As shown in Figure 1, post hoc analyses revealed that participants with a high arch profile exhibited significantly lower right-directed postural sway compared with both the normal arch ($p < 0.0001$) and low arch groups ($p < 0.0001$). No significant difference was observed between the normal and low arch groups ($p = 0.1725$). For left-directed postural sway, the high arch group demonstrated significantly greater sway than both the normal arch ($p < 0.0001$) and low arch groups ($p < 0.0001$). No significant difference was observed between the normal and low arch groups ($p = 0.1725$). In terms of anterior postural sway, values were significantly higher in the low arch group compared with both the normal arch ($p < 0.0001$) and high arch groups ($p < 0.0001$). In addition, the normal arch group exhibited significantly greater anterior sway than the high arch group ($p = 0.0120$). Regarding posterior postural sway, the high arch group showed significantly greater sway than both the normal arch ($p = 0.0120$) and low arch groups ($p < 0.0001$). Furthermore, posterior sway was significantly higher in the normal arch group compared with the low arch group ($p < 0.0001$). For time spent in the target zone, the normal arch group demonstrated significantly higher values than both the low arch ($p < 0.0001$) and high arch groups ($p < 0.0001$). In addition, the low arch group showed significantly greater time in the target zone compared with the high arch group ($p < 0.0001$).

Discussion

The aim of the present study was to investigate the relationship between foot arch profiles and single-leg dynamic postural control in soccer players. The findings demonstrated that foot arch structure significantly influences single-leg postural control performance. Large effect sizes were observed across all directional sway parameters and time spent in the target zone. These results support the notion that foot morphology plays a critical role in the organization of postural control mechanisms. They are generally consistent with previous research emphasizing the role of plantar sensory input and foot structure in balance regulation [9, 10].

One of the findings was that participants with a normal arch profile exhibited superior performance in terms of time spent within the target zone. This suggests that an optimal medial longitudinal arch height may provide advantages in both mechanical stability and plantar somatosensory feedback. Previous studies have highlighted the importance of plantar contact area and mechanoreceptor activation in the fine regulation of postural control [9, 10]. A normal arch structure may facilitate an optimal balance between rigidity and flexibility. This may enhance sensorimotor integration. However, these mechanisms were not directly measured in the present study. They are therefore interpreted based on existing theoretical frameworks. In contrast, the postural sway distribution observed in the high arch group indicated a more asymmetrical control strategy. The combination of reduced right-directed sway and increased left and posterior sway suggests that individuals with a high arch may rely on a more rigid foot structure. This may result in load transfer through a relatively limited contact area. It may lead to a more heterogeneous plantar pressure distribution and reduced quality of somatosensory input [11]. From the perspective of ankle strategy effectiveness, a high arch structure may therefore impose constraints on fine postural adjustments. These findings may reflect a shift in directional control strategy rather than a uniform reduction in stability.

The low arch group, on the other hand, exhibited increased anterior postural sway, indicating a different control pattern. Although a lower medial longitudinal arch increases plantar contact area, this broader contact does not necessarily translate into improved stability. Instead, it may reduce the precision of postural control. The increased sway in the anterior–posterior plane may reflect greater reliance on compensatory muscular and passive structures around the ankle joint. This may result in a more reactive control strategy. Previous studies have reported that alterations in plantar contact characteristics and pressure distribution may influence postural control [12, 17]. This may be related to the patterns observed in the present study. When directional postural sway parameters are considered collectively, the findings suggest that foot arch profiles influence not only the level of postural stability but also the organization of postural control strategies. A more rigid and constrained strategy appears to characterize the high arch group. The low arch group demonstrates a wider but less controlled sway pattern. In contrast, the normal arch group exhibits a more balanced and optimized control strategy. These findings support the notion that the effectiveness of the ankle strategy is sensitive to foot morphology, particularly in single-leg tasks where ankle-based control predominates [7, 8]. Importantly, this suggests that foot morphology may influence how postural adjustments are distributed across movement directions. It does not only affect overall stability magnitude.

The present study contributes to the literature by moving beyond traditional static balance assessments and employing a dynamic task involving visual feedback. This approach more closely reflects the functional demands of soccer, where unilateral loading conditions are frequently encountered. Accordingly, the findings provide a more ecologically valid perspective on the role of foot arch morphology in sport-specific postural control. Previous studies in soccer players have predominantly relied on static or non-specific balance assessments [13, 14]. These approaches may not fully capture task-dependent postural strategies. However, it remains unclear whether the observed differences represent fundamentally distinct control mechanisms or task-specific adaptations. This warrants further investigation. From an applied perspective, these results highlight the importance of including foot arch assessment in athlete screening protocols. Furthermore, for athletes with high or low arch profiles, targeted interventions such as proprioceptive training, balance exercises, and individualized conditioning programs may be beneficial for performance optimization and injury risk reduction. More specifically, interventions may be tailored according to direction-specific deficits, such as anterior–posterior control in low arch profiles and symmetry and load distribution in high arch profiles.

Limitations of the Study and Future Research Directions

Several limitations of this study should be acknowledged. Due to the cross-sectional design, causal relationships between foot arch profiles and postural control cannot be established. The sample consisted exclusively of male university-level soccer players. This may limit the generalizability of the findings to other populations, including female athletes, different age groups, and other sports disciplines. Foot arch profiles were determined using static plantar pressure measurements. Potential changes in arch behavior under dynamic loading conditions were not assessed. This limitation may have restricted the ability to fully capture functional foot behavior during dynamic tasks. Postural control was evaluated using a single task and only on the dominant limb. This may limit the generalizability of the findings across different task conditions and bilateral performance. No direct biomechanical or neuromuscular measurements were included. Therefore, mechanistic interpretations should be considered with caution.

Future research should consider incorporating multiple task conditions, bilateral assessments, and longitudinal or experimental designs to further elucidate the relationship between foot arch structure and postural control. Expanding the sample to include different populations may also provide deeper insight into the underlying mechanisms. Integrating biomechanical and neuromuscular analyses may further enhance this understanding. In particular, combining plantar pressure, kinematic, and electromyographic analyses may allow for a more direct examination of the mechanisms underlying arch-related differences in postural control.

Conclusions

This study demonstrated that foot arch profiles have a significant impact on single-leg dynamic postural control in soccer players. Athletes with a normal arch profile exhibited superior postural control performance. High and low arch profiles were associated with distinct postural control strategies. These findings indicate that foot arch morphology is an important factor influencing the organization of postural control, particularly in tasks where the ankle strategy predominates. The findings suggest that foot arch structure influences not only the magnitude of postural stability but also the directional characteristics of postural control. Accordingly, the assessment of foot arch structure and the implementation of individualized training programs based on morphological characteristics may play a key role in optimizing performance and reducing injury risk in athletes. Integrating arch-specific assessments into performance evaluation may further enhance individualized training approaches.

Conflict of Interest

The authors declare no conflict of interest.

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PHYSICAL EDUCATION OF STUDENTS

ORIGINAL ARTICLE

An ergogenic approach to enhancing performance in archery: the acute effects of caffeine

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Abstract

Background and Study Aim Ergogenic aids are widely used to enhance exercise performance and training adaptations. Among these, caffeine is recognized for its stimulatory effects on the central nervous system and neuromuscular function. Despite their widespread use, the relative effectiveness of such aids in improving performance in precision-based target sports such as archery remains a matter of practical interest. This study aimed to examine the effects of acute caffeine supplementation on shooting performance in university-level archers.

Material and Methods A total of 12 licensed university archers (mean age: 22.92 ± 2.11 years) participated in this study. A single-group pretest–posttest experimental design was employed. Participants completed two laboratory sessions separated by 72 hours under standardized conditions. In each session, anthropometric and hearing assessments were conducted. This was followed by the ingestion of 200 mg of caffeine. After a 60-minute absorption period, archers performed shooting tests at 18 meters. The protocol included practice trials and 10 sets of scoring shots. Data were analyzed using paired-samples t-tests and repeated-measures ANOVA. These methods accounted for within-subject variability across sets. Statistical significance was set at $p < .05$.

Results Posttest scores were consistently higher than pretest scores across most sets. Statistically significant improvements were observed in Sets 2, 3, 4, 6, 8, 9, and 10 ($p < .05$). Sets 1, 5, and 7 showed non-significant differences. Overall performance increased significantly from 6.61 ± 1.20 to 8.33 ± 0.39 ($p < .001$), with a large effect size (Cohen's $d = 1.90$; $\eta^2 = .50$). Repeated-measures ANOVA revealed a significant main effect of condition ($p < .001$). No significant set or interaction effects were found. This indicates that performance improvements were consistent across shooting sets.

Conclusions Acute caffeine supplementation was associated with improved shooting performance in university-level archers. The findings suggest that caffeine may have potential as an ergogenic aid in precision-oriented sports requiring sustained attention and performance consistency. However, the results should be interpreted with caution due to methodological limitations. These include the absence of a control condition and the small sample size. Further randomized placebo-controlled studies are needed to confirm and extend these findings.

Keywords: acute effects, archery performance, attention and concentration, caffeine supplementation, cognitive performance

Introduction

Performance optimization in sport involves the integration of physiological, cognitive, and technical factors that collectively influence competitive outcomes. In precision-based disciplines such as archery, success depends not only on physical stability but also on sustained attention, fine motor control, and the ability to regulate arousal under competitive conditions. The interaction between neuromuscular function and cognitive processes plays a critical role in maintaining shooting accuracy across repeated attempts. In this context, interventions that influence central nervous system activity and alertness may affect both execution quality and performance consistency.

Ergogenic aids are defined as psychological techniques, mechanical devices, nutritional supplements, or pharmacological approaches aimed at enhancing training adaptations or improving exercise performance capacity [1]. Among these, nutritional ergogenic aids refer to orally administered substances containing dietary components intended to support sports performance. In addition to performance-related effects, such products may contribute to the prevention of conditions including excessive fatigue, dehydration, and reduced physical capacity [2]. The use of dietary supplements is widespread among athletes [3].

The American College of Sports Medicine (ACSM), the International Olympic Committee (IOC), and

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the International Society of Sports Nutrition (ISSN) classify ergogenic aids into three primary categories: sports foods, medical supplements, and performance-enhancing supplements [4]. Within the category of performance-enhancing supplements, caffeine is one of the most widely used ergogenic aids due to its stimulant properties and its ability to improve exercise efficiency [5]. Caffeine has been shown to exert effects in endurance-based sports requiring prolonged effort. It also demonstrates stimulatory effects during short-duration and repeated high-intensity activities [1].

In aerobic exercise, the ergogenic effects of caffeine are primarily attributed to increased catecholamine release and enhanced fat metabolism, which contribute to glycogen sparing. In contrast, during anaerobic exercise, caffeine exerts more direct effects on the muscular system [6]. For instance, it may enhance neuromuscular transmission and excitation–contraction coupling by increasing intracellular calcium availability [7]. Furthermore, caffeine is involved in several physiological mechanisms. These include the inhibition of adenosine receptors, increased activity of the sodium–potassium ATPase enzyme, and more efficient mobilization of intracellular calcium [8]. In addition to these physiological effects, caffeine may reduce perceived exertion and muscle pain. This may contribute to improved overall exercise performance [9].

Evidence indicates that caffeine influences physical performance parameters such as gross motor skills and endurance capacity. It also affects cognitive functions, including attention, focus, and motivation. This has contributed to a growing body of research examining the relationship between caffeine and performance [10]. Caffeine is recognized as an ergogenic aid with stimulatory effects on the central nervous system (CNS). The primary mechanism underlying its effects on cognitive performance is explained by its antagonistic action on adenosine receptors in the brain [11]. Under normal physiological conditions, adenosine contributes to fatigue and sleepiness by suppressing neural activity. Caffeine binds to adenosine receptors and blocks this inhibitory effect. This leads to increased central nervous system activity. As a result, the release of excitatory neurotransmitters such as dopamine, norepinephrine, and acetylcholine increases [12]. Consequently, improvements may be observed in cognitive functions, including alertness, attention, information processing speed, and psychomotor performance (David McLellan et al., 2016). Caffeine is widely used as an ergogenic stimulant affecting both physical and cognitive aspects of performance [5].

The neuromuscular and muscular effects of caffeine are related to its pharmacokinetic profile. Peak plasma concentrations are typically reached approximately one hour after ingestion. Consuming caffeine about 60 minutes prior to training or competition is considered appropriate [13]. This timing is linked to its absorption characteristics. Caffeine is a moderately water-soluble compound. It is absorbed through the gastrointestinal tract within approximately 15 to 45 minutes following ingestion. It is then distributed throughout body tissues over time [14].

When consumed during the warm-up phase, plasma caffeine levels may be maintained during the competition [8]. Caffeine intake in the range of 3–9 $mg \cdot kg^{-1}$, consumed 30–90 minutes prior to exercise, is considered an ergogenic strategy for influencing exercise performance [8, 9, 13]. Due to its effects on motor functions and the central nervous system (CNS), caffeine may be a relevant factor in sports where attention and focus are important, such as archery [9, 11].

Achieving successful shooting performance in archery requires the development of a range of physical and technical skills. Archery is a predominantly static sport that emphasizes the strength and endurance of the shoulder musculature. It also requires high levels of attention and concentration [15]. It is an Olympic sport that requires sustained attentional focus, precise mental control, and the use of cognitive abilities during shot execution [16].

Caffeine supplementation may help maintain these parameters in target-based sports such as archery, where attention and focus are important determinants of performance [17]. A number of studies have reported that caffeine supplementation influences cognitive performance parameters. These include attention, memory, concentration, focus, and psychomotor performance [18, 19, 20, 21].

Caffeine supplementation has been shown to influence cognitive and performance-related parameters in archery. Evidence indicates improvements in attention, focus, and shooting accuracy under controlled conditions. Experimental and randomized studies show that moderate caffeine intake may influence archery performance outcomes. These effects are associated with its action on the central nervous system and related cognitive functions, particularly in athletes with low habitual caffeine consumption [22, 23, 24].

Analysis of research findings has shown that caffeine influences both physiological and cognitive components of performance, including neuromuscular function, attention, and psychomotor processes. Researchers emphasize that in precision-based sports such as archery, performance outcomes depend on the interaction between physical stability, cognitive control, and sustained attentional focus. At the same time, variability in individual responses, differences in supplementation protocols, and the specificity of task demands complicate the interpretation of these effects within applied settings. These aspects continue to limit the consistent application of caffeine supplementation strategies in precision-oriented sports contexts.

Considering the available evidence, the effects of acute caffeine supplementation on shooting performance in archery require further clarification within applied sport settings. Variability in study designs, performance metrics, and supplementation protocols complicates the interpretation of outcomes related to precision-based tasks. These aspects indicate the need for structured evaluation of shooting performance under controlled and repeatable conditions.

The present study aimed to investigate the effects of acute caffeine supplementation on the shooting performance of actively competing, licensed university-level archers. It was also intended to examine changes in performance outcomes under standardized conditions and to quantify the magnitude of the observed effects. Based on existing evidence, it was hypothesized that acute caffeine supplementation would be associated with an improvement in shooting performance compared to baseline measurements.

Materials and Methods

Participants

The study included 12 volunteer university-level archers (2 females and 10 males) with a mean age of 22.92 ± 2.11 years, a mean sport experience of 6.50 ± 1.78 years, a mean height of 175.83 ± 7.46 cm, and a mean body mass of 74.58 ± 7.22 kg. All participants were actively training archers who regularly engaged in structured training routines. Regarding visual and motor dominance, 83.3% (n = 10) used the right eye and right drawing arm, while 16.7% (n = 2) used the left side. Inclusion criteria required participants to be free from musculoskeletal injuries, cardiovascular conditions, metabolic diseases, recent surgical procedures, and adverse reactions to caffeine. Participants were instructed to abstain from caffeine for at least 24 hours prior to each session and to maintain consistent sleep and dietary habits; compliance was not objectively verified.

Sample Size Estimation. A priori sample size estimation was conducted using G*Power 3.1 for a paired-samples t-test. Assuming a two-tailed test, $\alpha = .05$, statistical power $(1-\beta) = .80$, and a large effect size (dz = 0.80), the required minimum sample size was calculated as 15 participants. The final sample consisted of 12 participants, which is considered a limitation; therefore, the findings should be interpreted with caution in relation to the observed effect size.

Ethical Considerations. Ethical approval for this study was obtained from the Ethics Committee of the Faculty of Sport Sciences at Atatürk University (Decision No: E-70400699-050.02.04-2600019255; Date: 20 January 2026). All procedures were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and its subsequent amendments. Data were collected, analyzed, and reported in accordance with established ethical principles.

Research Design

A single-group pretest–posttest experimental design was employed. Participants completed two laboratory sessions separated by 72 hours under standardized conditions. Anthropometric and hearing assessments were conducted prior to testing. Pure tone audiometry was used to confirm normal hearing thresholds within the range of −10 to 25 dB HL across frequencies from 500 to 8000 Hz. Testing conditions were controlled in accordance with established audiometric standards. Participants were instructed to maintain their usual training routines and to avoid intense physical activity prior to testing; compliance was not objectively monitored.

The design was used to evaluate the effects of acute caffeine supplementation on shooting performance in university-level archers. The independent variable was applied to the sample group, and measurements were obtained before (pretest) and after (posttest) the intervention [26, 27]. The study was conducted under standardized procedures reflecting typical training conditions.

Study Organization

Participants visited the laboratory on two separate occasions. During the first visit, participants were informed about the study procedures and signed an informed consent form. Anthropometric measurements were then obtained. Body height was measured using a stadiometer (Holtain, UK) with a precision of ±0.01 mm. Body mass was assessed using a Tanita BC-418 A (Japan) device with a precision of ±0.1 kg. Measurements were conducted with participants wearing standard sports clothing and without shoes. Hearing thresholds were assessed using a clinical audiometer.

Following these assessments, participants consumed a standardized breakfast at 09:00. No caffeine was administered during the first session. At 12:00, archers performed shooting trials from a distance of 18 meters. Participants used their personal recurve bows (66″–70″; draw weight: #34–#42 lbs). They first completed three sets of practice shots with three arrows per set. After adjustments, participants performed 10 sets of scoring shots, each consisting of three arrows (total: 30 arrows; maximum score: 300 points).

The second session was conducted 72 hours later and followed the same protocol. Participants consumed a standardized breakfast at 09:00 and ingested 200 mg of caffeine at 11:00. This dose corresponded to approximately 3 mg·kg^{-1} based on average body mass. After a 60-minute period, participants completed a 10-minute general warm-up followed by sport-specific warm-up activities. The same shooting protocol was then repeated.

All sessions were conducted under standardized conditions. Equipment, shooting distance, and environmental settings were kept constant. Shooting procedures followed World Archery guidelines. Each set consisted of three arrows and was completed within 2 minutes. A total of 10 sets were performed. Trials were conducted in an indoor range with consistent lighting and no external distractions. Auditory signals were used to regulate the shooting process.

Short transition intervals were allowed between sets to maintain a consistent sequence. Scoring was performed using official target faces, and results were recorded after each set using a consistent procedure. All data were entered into IBM SPSS (version 27) for analysis (Figure 1). No randomization

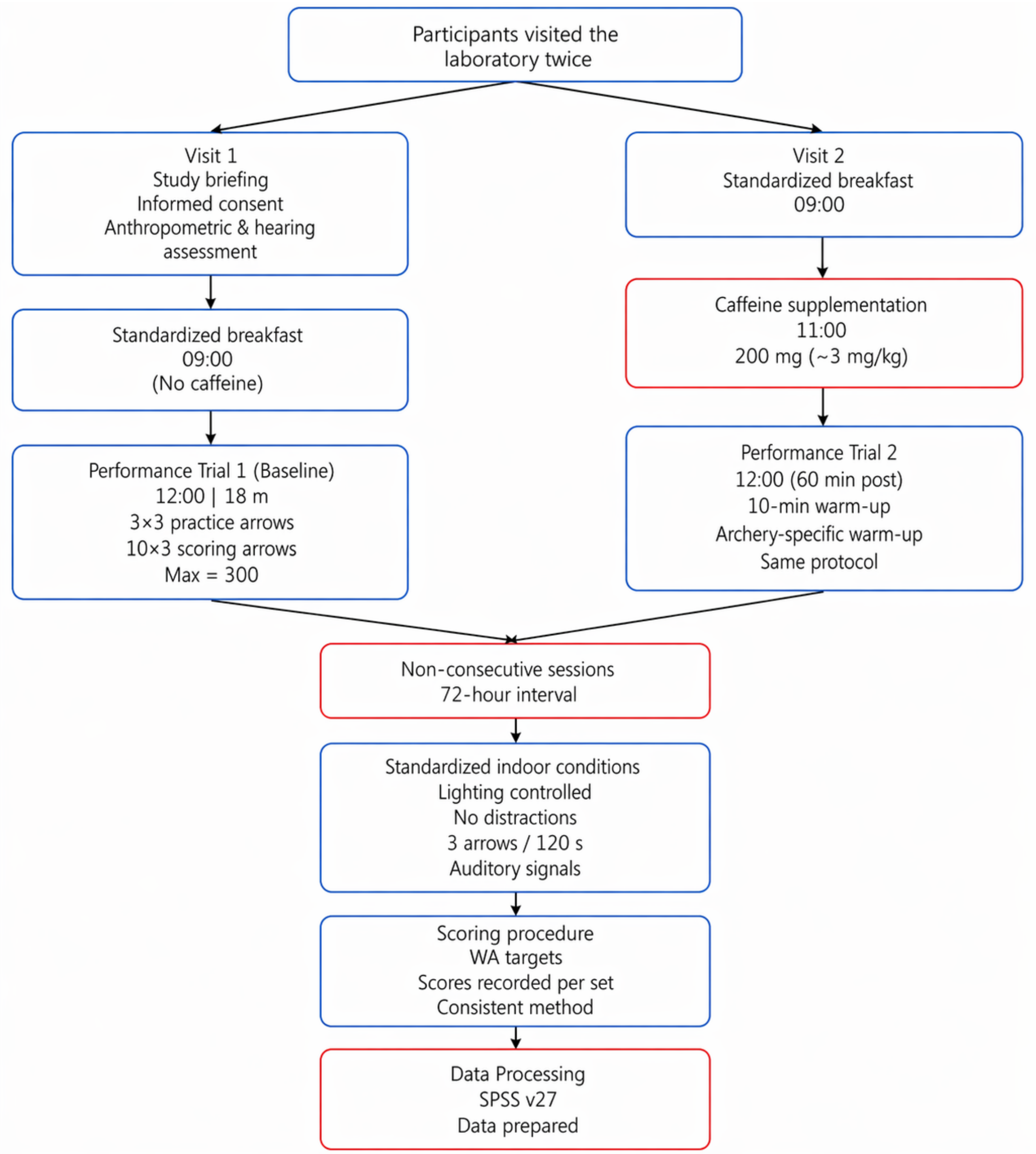

Figure 1. Flowchart of the Experimental Design and Data Collection Procedure

or counterbalancing procedure was implemented, which may have introduced order effects.

Instruments

Anthropometric Measurements. Body height was measured using a stadiometer (Holtain, UK), a portable device with a precision scale providing measurements with millimetric accuracy. Body mass was assessed using a Tanita BC-418 A (Japan) analyzer. Measurements were conducted with participants wearing standard sports clothing and without shoes.

Hearing Assessment. Hearing thresholds were evaluated using a clinical audiometer (Interacoustics AC40, Denmark).

Caffeine Supplementation. Caffeine was administered in the form of a commercially available supplement (Nature's Supreme, 200 mg). Each participant consumed one capsule, corresponding approximately to the caffeine content of two cups of coffee. The supplement contained pharmaceutical-grade caffeine produced under standardized manufacturing conditions and approved by relevant regulatory authorities.

Archery Equipment and Testing Protocol. During the trials, participants used their personal competition equipment. Recurve bows (HOYT) with lengths ranging from 66″ to 70″ and draw weights between #34 and #42 lbs were used. Arrows (Easton X10) were selected according to individual anthropometric characteristics, particularly arm length. Shooting performance was assessed in accordance with World Archery standards using indoor target faces (3-spot, 5-ring targets for recurve bow).

Statistical Analysis

All statistical procedures were performed using IBM SPSS Statistics (version 27) following standard analytical practices. The normality of the data distribution was assessed using the Shapiro–Wilk test [28]. Skewness and kurtosis values were also evaluated [29]. Given that the sample size was fewer than 50 participants, the Shapiro–Wilk test was used as the primary criterion for normality assessment, with the level of significance set at $p = .05$ [30]. Skewness and kurtosis values within the range of ±1.5 were accepted as indicative of normal distribution [29]. Data were screened for potential outliers using standardized z-scores. No extreme values (±3 SD) were detected. Based on the study design and sample size, paired-samples t-tests were used to compare pretest and posttest measurements. A repeated-measures analysis of variance (ANOVA) was also conducted to account for within-subject variability across multiple sets and to reduce the risk of Type I error. The assumptions of normality and sphericity were evaluated prior to analysis. Appropriate corrections were applied when necessary. Effect sizes were calculated to assess the magnitude of differences. Cohen's d was interpreted according to conventional thresholds (small: 0.20, medium: 0.50, large: 0.80) [31]. The level of statistical significance for all analyses was set at $p < .05$.

Results

To ensure analytical coherence, a repeated-measures ANOVA was used as the primary statistical approach to evaluate overall performance changes across conditions and sets. Paired-samples t-tests were used as supplementary analyses to examine set-by-set differences. Pretest and posttest performance scores were compared. Descriptive statistics and inferential results are reported, taking into account statistical significance and effect size estimates.

The comparison of shooting performance across test conditions is presented in Table 1.

The comparison of pretest and posttest scores across the 10 sets is presented in Table 1. Posttest scores were generally higher than pretest scores, indicating an overall improvement in shooting performance.

Statistical analysis showed that differences were not significant in several sets, while significant differences were observed in others. The direction of the differences indicated higher posttest values. As illustrated in Figure 2, this pattern was generally consistent across sets, with some variability in the magnitude of change.

The analysis of total mean scores is presented in Table 2. Posttest values were higher than pretest values, indicating an improvement in shooting performance under the caffeine condition. A statistically significant main effect was observed. The reduction in variability in the posttest condition suggests a more consistent performance pattern following caffeine ingestion. Effect size estimates indicate a substantial magnitude of change.

A repeated-measures ANOVA was conducted to examine the effects of condition (pretest vs posttest) and set (1–10) on shooting performance. A significant main effect of condition was observed, indicating improved performance following caffeine supplementation. The main effect of set was not significant after Greenhouse–Geisser correction, suggesting that performance remained relatively stable across sets. The condition × set interaction was also not significant (Table 3). This indicates that the improvement in performance was consistent across sets and not dependent on specific shooting phases.

Table 1. Comparison of shooting performance across test conditions

Shooting Sets	Test	Mean ± SD	Md.	r	t	p
Set 1	Pre	6.33 ± 2.28	-1.41	.296	-2.120	.058
	Post	7.75 ± 1.45				
Set 2	Pre	5.50 ± 2.21	-2.01	.167	-2.923	.014
	Post	7.50 ± 1.28				
Set 3	Pre	6.01 ± 2.83	-2.52	-.422	-2.682	.021
	Post	8.52 ± 0.81				
Set 4	Pre	6.63 ± 1.79	-1.80	.219	-3.541	.005
	Post	8.44 ± 0.62				
Set 5	Pre	7.13 ± 1.68	-1.19	-.007	-2.149	.055
	Post	8.33 ± 0.92				
Set 6	Pre	7.11 ± 1.64	-1.38	.099	-2.694	.021
	Post	8.50 ± 0.87				
Set 7	Pre	7.16 ± 2.10	-1.13	.058	-1.809	.098
	Post	8.30 ± 0.70				
Set 8	Pre	7.02 ± 1.45	-1.72	.008	-3.488	.005
	Post	8.72 ± 0.90				
Set 9	Pre	6.55 ± 2.08	-2.05	.085	-3.326	.007
	Post	8.61 ± 0.70				
Set 10	Pre	6.75 ± 2.23	-1.91	-.189	-2.728	.020
	Post	8.66 ± 0.61				
Average score (10 sets)	Pre	6.61 ± 1.20	-1.71	.481	-5.557	< .001
	Post	8.33 ± 0.39				
Total score (10 sets)	Pre	198.58 ± 36.09	-51.50			
	Post	250.08 ± 11.96				

Note. SD – standard deviation; Md. – mean difference; r – effect size (correlation coefficient); t – t-value from paired-samples t-test; p – significance level. Pre – pretest; Post – posttest. Statistical significance was set at p < .05.

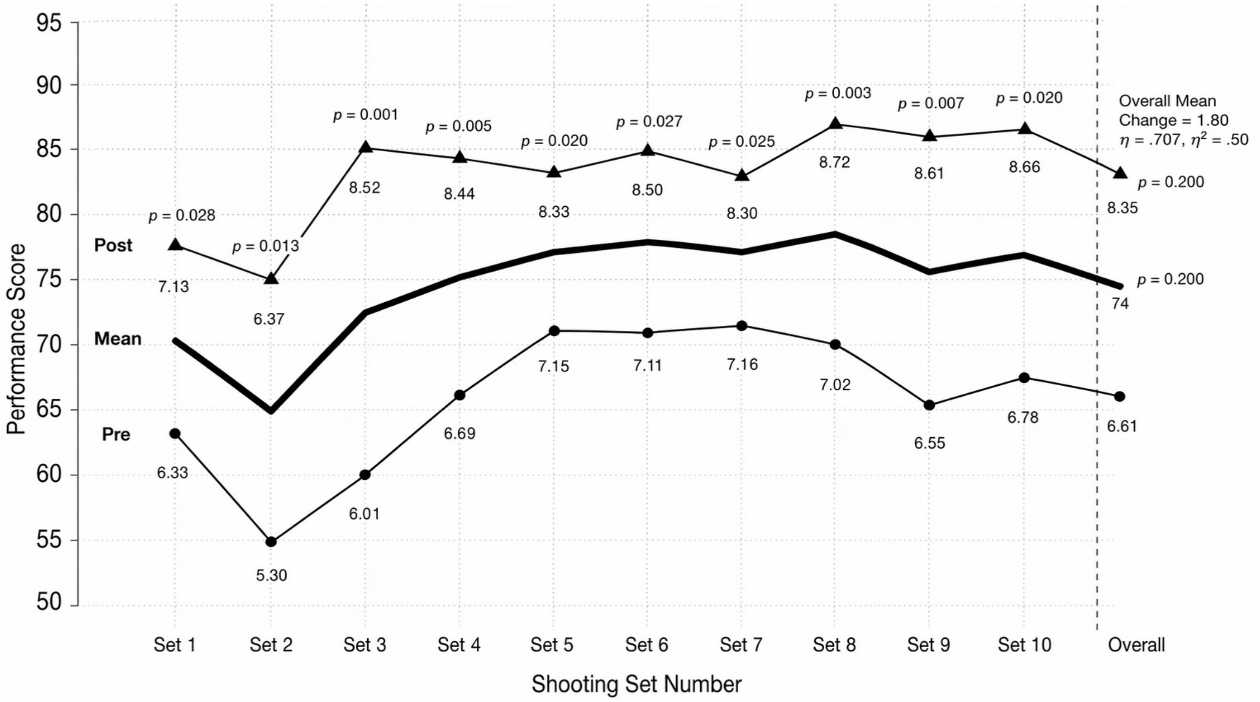

Figure 2. Effects of acute caffeine supplementation on archery performance: a set-by-set pre–post analysis

Table 2. Pre–post differences in shooting performance and associated effect sizes in archery

Test	n	Mean ± SD	F	p	η	η^2	Cohen's d
Pre	12	6.61 ± 1.20	22.01	< .001	.707	.50	1.90
Post		8.33 ± 0.39					

Note. SD – standard deviation; F – F-value from repeated-measures ANOVA; p – significance level; η – effect size (eta); η^2 – eta squared; Cohen's d – standardized effect size. Pre – pretest (caffeine-free); Post – posttest (caffeine condition). Statistical significance was set at p < .05.

Table 3. Descriptive statistics and repeated-measures ANOVA results for shooting performance

Variable	Pretest (Mean ± SD)	Posttest (Mean ± SD)	F (df)	p	Partial η^2
Condition	6.62 ± 1.20	8.33 ± 0.39	30.88 (1, 11)	< .001	.737
Set (1–10)			2.44 (4.41, 48.51)*	.054	.182
Condition × Set			0.53 (5.71, 62.80)*	.773	.046

Note. SD – standard deviation; F – F-value from repeated-measures ANOVA; df – degrees of freedom; p – significance level; Partial η^2 – effect size. *Greenhouse–Geisser correction applied. Statistical significance was set at p < .05.

Discussion

In this study, the effects of acute caffeine supplementation on shooting performance in university-level archers were evaluated. The findings indicated higher performance scores under the caffeine condition in both set-based averages and total shooting scores. Effect size estimates indicated a large magnitude of difference [31]. Repeated-measures ANOVA showed a significant main effect of condition, indicating an overall increase in performance. The non-significant condition × set interaction indicates that this effect was consistent across sets.

A review of the literature reveals studies with designs comparable to the present research. Aghadewa and Sumartiningsih investigated the acute effects of coffee containing 2 g/100 mL caffeine at different temperatures on archery shooting performance and concentration. Improvements were reported in both variables regardless of beverage temperature [22]. In contrast, a study examining the effects of 300 mg of caffeine on shooting performance and reaction time in traditional archery found no statistically significant effects of supplementation on either variable [24].

Similarly, in precision-based sports such as rifle shooting, caffeine supplementation at doses of 2 mg/kg and 4 mg/kg did not produce significant changes in shooting performance or reaction time among elite athletes. No significant differences were observed between low-dose caffeine, high-dose caffeine, and placebo conditions (p > .05) [32]. In contrast, a study conducted on female athletes reported that caffeine intake at doses of 3 mg/kg and 6 mg/kg improved reaction time and attention performance. The largest effect was observed at the 3 mg/kg dose. No improvements were observed at a dose of 9 mg/kg, which was associated with a higher incidence of side effects [23].

These differences may be related to variations in caffeine dosage, participant characteristics, and the cognitive–motor demands of the sport. In precision-based disciplines such as archery, which require fine motor control and sustained attention, the effects of caffeine may differ from those observed in strength- or endurance-based activities.

The potential effects of caffeine on performance are often explained by its action on the central nervous system. As an adenosine receptor antagonist, caffeine may increase neural activation and the release of excitatory neurotransmitters. This may contribute to changes in cognitive processes such as attention and reaction time [5, 11]. However, these mechanisms were not directly measured in the present study. Therefore, their contribution to the observed performance outcomes should be interpreted with caution.

In a study conducted by Doyle et al. [35] with university-level fencers, caffeine ingestion at doses of 4.5–6.0 mg/kg improved reaction time and overall performance. At a dose of 7.5 mg/kg, performance declined. These findings are consistent with a dose-dependent pattern described as an "inverted U-shaped" model. Similarly, Karaalp and Taşkıran [36] reported that supplementation with Turkish coffee providing 7 mg/kg of caffeine over a 6-week period improved anaerobic power, agility, and coordination in male athletes.

In another study, the consumption of 200 mg of caffeine influenced cognitive processing by suppressing EEG delta wave activity following central fatigue. No changes were observed in Taekwondo-specific physical performance [37]. In contrast, Toktaş et al. [38] found that caffeine administered via mouth rinsing did not produce differences in attention or hand–eye coordination.

These findings indicate that the effects of caffeine on sports performance depend on multiple factors. These include the mode of administration, dosage, individual tolerance, sport-specific skill requirements, and the physiological or fatigue state of the athlete.

These findings should be considered in relation to existing literature on caffeine, which has primarily examined endurance and strength-based performance outcomes. The results indicate that caffeine may also be associated with performance changes in precision-oriented sports such as archery, where performance depends on both physical execution and attentional control. The use of a fixed-dose protocol provides an applied perspective, suggesting that moderate caffeine intake may produce consistent effects across repeated trials. Individual variability related to body mass and caffeine sensitivity may influence responses. These aspects contribute to the interpretation of sport-specific effects of caffeine and the role of cognitive and motor factors in performance.

Limitations and Future Research Directions

The study sample consisted of university-level archers, representing a relatively homogeneous group in terms of training background and performance level. This may limit the generalizability of the findings. Subgroup analyses, including sex differences, training experience, and habitual caffeine consumption, were not conducted. The study design did not include a placebo or control condition, randomization, or blinding. These factors may increase susceptibility to learning, repetition, and expectancy effects. The relatively small sample size and the assessment of only acute effects also limit the strength of the conclusions.

Additional factors were not controlled, including habitual caffeine intake, individual tolerance, prior dietary intake, hydration status, and sleep patterns. These variables may have influenced performance outcomes. The use of a fixed caffeine dose does not account for differences in body mass. Participants were limited to recurve archers, which restricts generalization to other archery disciplines. Cognitive and neuromuscular mechanisms were not directly measured, and interpretations related to these factors should be made with caution.

Future studies should include larger and more diverse samples to improve generalizability. Randomized placebo-controlled designs are required to strengthen internal validity. Individualized caffeine dosing strategies based on body mass should be considered. Subgroup analyses based on sex, training experience, and caffeine habituation are needed. Direct assessment of cognitive and neuromuscular variables would allow a more precise interpretation of underlying mechanisms. These approaches would improve the evaluation of caffeine effects in precision-based sports contexts.

Conclusions

The findings of the present study indicate that caffeine supplementation is associated with improved shooting performance in university-level archers under the tested conditions. Paired comparisons and repeated-measures ANOVA demonstrated an overall increase in performance following caffeine ingestion. Improvements were observed across multiple sets, indicating a consistent effect throughout the shooting series.

These results support the view that caffeine may have a role as an ergogenic aid in precision-oriented target sports that require sustained attention and performance consistency. The findings should be interpreted with caution due to methodological limitations, including the absence of a control condition, lack of randomization, and the relatively small sample size. Cognitive and neuromuscular mechanisms were not directly assessed, and interpretations regarding underlying processes remain indirect.

The present findings should be considered as preliminary evidence rather than confirmation of causality.

Practical Applications

The findings of the present study indicate that caffeine supplementation may be associated with improved shooting performance in archery when consumed approximately 60 minutes prior to activity. These results should be interpreted with caution due to methodological limitations, including the absence of a control condition. Moderate doses (e.g., ~3–6 $mg \cdot kg^{-1}$ or ~200 mg) may represent a practical intake range. Individual responses may vary. Athletes and coaches are encouraged to evaluate caffeine use in training settings and to consider factors such as individual tolerance, nutritional status, and potential side effects.

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Conflicts of Interest

The authors declare no conflict of interest.

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ORIGINAL ARTICLE

A canonical analysis of the general variability and interrelationships among parameters of speed-strength fitness, circumferential, and longitudinal body dimensions in highly skilled wrestlers

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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 Speed-strength fitness and body dimensions are components of athletic performance in combat sports. The interaction between speed-strength fitness parameters and anthropometric characteristics influences physical capabilities and competitive outcomes in wrestlers. Despite the application of various approaches to assessing these parameters, their interrelationships and general variability remain of practical interest. The aim of the study is to perform a canonical analysis of the general variability and interrelationships among parameters of speed-strength fitness (SSF), circumferential, and longitudinal body dimensions in highly skilled wrestlers.

Material and Methods The research was conducted on 44 combat athletes aged 18–31 who were members of the Ukrainian national teams in Greco-Roman wrestling, freestyle wrestling, and judo. The assessment of SSF was based on the results of motor tests that characterize the manifestation of anaerobic alactate work capacity, explosive strength, and speed-strength endurance in athletes. Circumferential (CBD) and longitudinal (LBD) body dimensions were considered indicators of physical development (PD). Canonical correlation, regression, and correlation analysis methods were used to process the research data.

Results The analysis of general variability and interrelationships between the canonical variables of PD and SSF in combat athletes revealed a high level of mutual influence ($R = 0.981$, $p = 0.0000$). Increases in CBD and LBD are accompanied by increases in SSF, and increases in SSF are associated with increases in CBD and LBD. The interaction between SSF and CBD parameters demonstrates approximately equal mutual influence (redundancy: 53.9% and 53.4%). In the relationships between LBD and CBD, a stronger influence of LBD parameters on CBD is observed (redundancy: 66.88% vs. 57.5%). CBD values are more dependent on changes in SSF parameters than on the group of LBD indicators (39.53% vs. 24.79%). The SSF level of athletes shows greater dependence on the group of CBD indicators than on that of LBD indicators (43.71% vs. 44.83% of total variability contribution across significant roots). LBD values are less dependent on CBD values and SSF level than CBD parameters are on LBD values and SSF level.

Conclusions The findings indicate that speed-strength fitness parameters are functionally related to circumferential and longitudinal body dimensions in highly skilled wrestlers. The structure of these relationships reflects the role of specific anthropometric characteristics in the manifestation of different forms of physical work capacity. The intergroup interactions between circumferential and longitudinal body dimensions form a structural basis associated with the development of speed-strength fitness. The identified patterns characterize the integration of morphofunctional and performance-related parameters within the physical state of combat athletes.

Keywords: wrestlers, physical development, physical fitness, work capacity, canonical analysis, interrelationships.

Introduction

Athletic performance in combat sports is determined by a combination of functional capacities and morphological characteristics. In wrestlers, speed-strength fitness is associated with the ability to generate force rapidly under conditions of short-term, high-intensity effort. At the same time, circumferential and longitudinal body dimensions reflect structural features that influence movement mechanics and load distribution during

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competitive activity. The relationships between these functional and morphological parameters form a complex system of interdependencies that affect the manifestation of physical qualities in highly skilled athletes.

In the process of long-term adaptation to training and competitive loads, a specific structure of physical state (PS) is formed in the bodies of combat athletes. It is characterized by a certain level of development, as well as by the ratios and interrelationships among parameters of physical development (PD), functional, physical, psychological, and technico-tactical fitness, and special physical work capacity (SPWC). The dynamics of changes in these parameters during long-term adaptation to strenuous muscular activity reflect the process of forming a specific profile of highly skilled athletes [1, 2, 3, 4].

The factors determining the morphofunctional profile of elite athletes include both individual and integral parameters of physical development, physical, functional, and psychological fitness, as well as special physical work capacity. The long-term process of adaptation to physical loads in combat athletes is characterized not only by morphofunctional and metabolic changes in the leading body systems, but also by changes in their ratios and interrelationships within the morphofunctional structure of fitness in highly skilled athletes [5]. However, most publications are dominated by a one-sided characterization of the morphofunctional profile of athletes.

Most authors describe the structure of the morphofunctional profile primarily according to individual criteria:

- anthropometric parameters [2, 6, 7];
- parameters of physical development (PD) [8, 9, 10];
- parameters of physical fitness (PF) [8, 11, 12];
- parameters of functional state [1, 11, 13, 14, 15];
- parameters of special physical work capacity (SPWC) [2, 5, 16, 17, 18].

Fewer studies have been devoted to the formation of the structural profile of combat athletes from a systems perspective, that is, from the standpoint of a comprehensive analysis of the relationships and interconnections among PS parameters during adaptation to specific training and competitive loads [5].

The level of development, as well as the ratios and interrelationships of PS parameters in combat athletes, are determined by the specificity of training loads and the nature of motor activity during a bout. These include the speed of response to an opponent's actions, the time required to perform single movements and series of movements of varying structure, their number and intensity, and the total duration of the bout. The variable character and intensity of a wrestling bout determine the activation of different energy systems: anaerobic alactate, anaerobic lactate, and aerobic. The degree of involvement and the balance among these energy systems are determined by the duration and intensity of both the bout as a whole and its individual segments [11, 19].

To assess the PS structure of combat athletes, a set of individual and integral parameters of PD, physical (PF), functional, psychological, and technico-tactical fitness is typically used.

The following are considered integral parameters of the PS structure in athletes: a) integral parameters of functional state: efficiency, stability, mobility of functional manifestations, aerobic and anaerobic power, and the general level of functional fitness [20, 21, 22, 23, 24]; b) integral parameters of PD: Quetelet index, volume of muscle, fat, and bone tissue, body surface area, body water content, and other parameters [8, 25]; c) integral parameters of PF: the level of development of motor qualities, as well as different forms of SPWC, including aerobic, anaerobic, speed, strength, and speed-strength [12, 16, 17, 19, 26].

One of the issues in systems physiology is the elucidation of the morphofunctional and metabolic mechanisms underlying the support of the SPWC of combat athletes from the standpoint of the relationships and interactions between both individual and integral parameters of the PS structure of wrestlers, including PD, PF, and functional state. Among the insufficiently studied aspects of the formation of the profile of highly skilled combat athletes are the mechanisms of interaction and integration of various components of the athletes' PS. These include the level of development, as well as the relationships and interconnections of individual and integral, intra- and intergroup parameters of the PS of combat athletes [5, 22]. Intra- and intergroup pairwise relationships of PS parameters in combat athletes are widely represented in the specialized literature [26, 27, 28, 29]. However, intergroup interactions among sets of interrelated variables belonging to different subsets of the PS structure of highly skilled combat athletes have been addressed to a lesser extent [5].

To analyze the structure of the PS and the morphofunctional profile of combat athletes, a number of authors have examined the interrelationships among parameters of PD, PF, functional state, and SPWC [30, 31, 32]. Several studies present evidence indicating the dependence of the SPWC level and wrestlers' endurance on anthropometric factors [26, 27, 29, 33], as well as on the level of development of motor abilities [17, 28, 33]. However, most publications are devoted to the analysis of pairwise relationships between parameters of the PS structure of athletes. These include relationships between body composition and aerobic work capacity, recovery after training loads [34, 35], body composition and anaerobic work capacity [29, 33], and body composition and the level of development of motor abilities [27, 28].

The diversity of factors, parameters, and mechanisms determining the morphofunctional and metabolic profile of combat athletes provides a basis for studying them from the standpoint of integrated and systems approaches. The methodological principles of the systems approach necessitate the use of comprehensive methods for the recording, processing, and analysis of various parameters of the PS of combat athletes. They also require the investigation of their relationships and interconnections, which collectively determine the morphofunctional and metabolic profile of elite athletes.

From a systems perspective, the level of special work capacity of combat athletes is a system-forming factor that determines the level of development, the partial contribution, and the relationships and interconnections among parameters of different components of the PS structure of athletes, including PD, PF, and functional state. At the same time, publications by various authors indicate that the partial role and influence of individual PS indicators on the level of SPWC in highly skilled combat athletes are determined both by the level of development and interrelationships of intragroup indicators and by intergroup relationships among parameters belonging to different subsets of the athletes' PS, including PD, PF, SPWC, and functional state.

Intra- and intergroup relationships among parameters of various PS components play a role in shaping the structure of the morphofunctional and metabolic profile of highly skilled combat athletes. However, most researchers have characterized this profile through the analysis of pairwise interactions among different PS components, using methods of pairwise correlation and regression [29, 33, 34, 35]. Multiple correlation and regression coefficients, reflecting the dependence of individual parameters on several determining variables, have been calculated to a lesser extent [5, 22].

Among the insufficiently explored aspects of the formation of the morphofunctional and metabolic profile of highly skilled combat athletes are the intergroup interactions of integral components of the PS. In this regard, one of the least studied areas of relationships among components of the PS structure in combat athletes is the combined intergroup mutual influence of parameters of PD, functional state, PF, SPWC, and others. Only a limited number of studies [28, 36] have addressed the intergroup interactions among PS parameters in highly skilled combat athletes. These studies served as a basis for developing regression models describing the dependence of wrestlers' SPWC level on a set of leading parameters from the studied PS groups. However, in analyzing intergroup interactions, researchers have primarily focused on the dependence of individual outcome PS variables on a set of determining factors.

In biological research, the method of canonical analysis, based on constructing linear combinations in two specified sets of variables, has been used less frequently to determine relationships between two sets of variables [37, 38, 39]. A number of authors have noted that the method of canonical correlations makes it possible to identify the maximum correlation between several outcome variables and several determining factors [38, 39]. However, the potential of this method for studying intergroup interactions among parameters belonging to different sets of the PS of highly skilled athletes has been insufficiently reflected in biological research.

Analysis of research findings has shown that the morphofunctional profile of combat athletes is determined by a combination of physical development, functional state, physical fitness, and special work capacity, as well as by the relationships among these parameters. Researchers emphasize that both individual indicators and their interconnections contribute to the structure of physical state in highly skilled athletes. At the same time, the complexity of intergroup interactions among different components of the PS structure complicates their comprehensive assessment within a unified analytical framework. This limitation constrains the interpretation of integrated relationships among parameters belonging to different subsets of the PS of combat athletes.

Given the limited coverage of intergroup interactions among parameters of the PS structure in highly skilled combat athletes, as well as its relevance for the theory and practice of wrestling, the aim of the present study was defined as follows: to perform a canonical analysis of the general variability and interrelationships among parameters of speed-strength fitness and circumferential and longitudinal body dimensions in highly skilled wrestlers.

Materials and Methods

Participants

The studies were conducted on members of the national teams of Ukraine in Greco-Roman wrestling, freestyle wrestling, and judo. A total of 44 combat athletes aged 18–31 years were examined. Among them were 10 Candidates for Master of Sport, 14 Masters of Sport, 17 Masters of Sport of International Class, and 3 Honored Masters of Sport. Most of them were students of higher education institutions in Ukraine.

The study protocol was approved by the Ethics Committee of the university. The research was conducted in compliance with the WMA Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects [40].

Research Design

As parameters of PD and PF in highly skilled combat athletes at the stage of maximal realization of individual capacities, indicators of circumferential (CBD) and longitudinal (LBD) body dimensions and speed-strength fitness (SSF), including special physical work capacity (SPWC), were recorded.

Circumferential body dimension indicators in combat athletes included neck circumference (NC), chest circumference (CC), abdominal circumference (AC), relaxed shoulder circumference (ShC), forearm circumference (FC), calf circumference (CaC), and thigh circumference (TC).

Longitudinal body dimension indicators included the longitudinal dimensions of the trunk (LTD), upper extremity (LDUE), shoulder (LShD), forearm (LFD), lower extremity (LDLE), thigh (LThD), and calf (LCaD).

The SSF level of athletes was assessed according to the time of 30 m running (R30m), the time required to perform 15 partner throws of equal weight at maximal tempo (T15T), the standing long jump result (SLJ), the maximum number of pull-ups on a horizontal bar performed within 10 seconds (PU10s), and push-ups in a prone support position performed within 10 seconds (PPU10s).

The results of the studied motor tests reflect the level of development of motor abilities: speed (R30m), explosive strength (SLJ), and speed-strength endurance (PU10s, PPU10s, T15T). In addition, they reflect the power of the anaerobic alactate (creatine phosphate) system as one of the energy systems ensuring special physical work capacity in combat athletes.

The acyclic nature of a sporting bout is characterized by the execution of movements that vary in structure and intensity. These include accelerations, pushes, single throws, and series of throws of different types, performed during wrestling matches at varying speeds and durations and under conditions of opponent resistance. Such a character of a competitive bout indicates the manifestation of different forms of physical work capacity in wrestling.

If one proceeds from the criteria of energy supply for muscular activity, the following types of work capacity are manifested in a combat sports bout: anaerobic alactate (creatine phosphate), anaerobic lactate (glycolytic), and aerobic. Based on the criteria of manifestation of leading motor qualities, the following types of physical work capacity are distinguished: speed, strength, and speed-strength. From the standpoint of the mode of muscle contraction, both static and dynamic forms of physical work capacity are manifested during a bout.

The result of performing 15 throws of a partner of equal weight at maximal tempo (T15T) reflects the power of one of the forms of SPWC in combat athletes, namely the anaerobic alactate (creatine phosphate) type.

From these perspectives, the speed-strength motor tests performed by the athletes in this study characterize the manifestation of anaerobic alactate (creatine phosphate) work capacity in combat athletes, including speed, strength, and speed-strength forms of physical work capacity. These tests include a 30 m maximal run (R30m), the standing long jump (SLJ), the maximum number of pull-ups on a horizontal bar within 10 seconds (PU10s), push-ups in a prone support position within 10 seconds (PPU10s), and the time required to perform 15 throws of an equal-weight partner at maximal tempo (T15T).

Statistical Analysis

To determine intra- and intergroup relationships within the structure of the PS of combat athletes, methods of correlation, regression, and canonical analysis were employed. The processing of the experimental data was carried out using the STATISTICA 13.5 software package [41]. Pairwise and multiple coefficients of correlation and determination, multiple stepwise regression, and canonical analysis were calculated. In canonical analysis, linear combinations (referred to as canonical variables) are computed for each set of variables, which maximize the correlation between the two sets [37, 38]. The method of canonical correlations was applied to identify latent relationships between two sets of variables, determine maximal correlation links, as well as the partial and total mutual influence of indicators belonging to different groups of the PS of combat athletes. In particular, relationships were examined between the following pairs of variable sets: (1) CBD (7 indicators) and SSF (5 indicators); (2) LBD (7 indicators) and SSF (5 indicators); (3) LBD (7 indicators) and CBD (7 indicators).

Results

Table 1 presents the canonical correlation coefficients, extracted variance, and total variance, which characterize the degree of interaction and mutual variability between two sets of wrestlers' PS variables: five speed-strength indicators of PF and seven indicators of PD.

The results presented in Table 1 reflect different degrees of mutual variability between speed-strength indicators of PF and CBD in the group of highly skilled combat athletes.

An eigenvalue analysis of the PD and PF indicators identified five canonical roots, which account for 100% of the extracted variance in the PF indicator group and 90.9% in the PD indicator group. However, statistically significant mutual influences between the two sets of physical state variables are manifested in each group of subjects only for three of the five canonical roots. Therefore,

Table 1. Results of the canonical correlation analysis of the mutual influence of speed-strength indicators and indicators of body circumferential dimensions in highly skilled wrestlers.

Parameters	Speed-strength indicators	Body circumferential dimensions
Canonical correlation (R), χ^2	0.981, χ^2 (35) = 145.3, p = 0.0000	
Extracted variance	100.0%	90.88%
Total variability (redundancy)	53.896%	53.359%

further analysis was conducted using only these three statistically significant roots.

The values of total variability (redundancy) indicate (Table 1) that 53.9% ($p < 0.0000$) of the PF indicators in combat athletes are explained by the influence of the group of interrelated PD indicators, while 53.4% ($p < 0.0000$) of the variability in PD indicators is explained by the influence of the weighted PF variables.

The total contribution of the three statistically significant roots to the total variability of PF indicators amounted to 43.71% and to PD indicators 44.83%. This corresponds to 81.1% of the total contribution of all five roots to the overall variance of PF indicators and 84.02% for PD indicators.

These results, presented in Table 1, reflect an approximately equal mutual influence between SSF and CBD variables in the studied group of highly skilled combat athletes. An increase in CBD contributes to an increase in SSF level. Conversely, an increase in SSF in wrestlers contributes to an increase in CBD.

The analysis of the factor structure allowed determining the partial variability of individual CBD and SSF indicators within the overall variability of each set under the influence of the group of canonical variables from the other set.

As a result, it was found that across the three statistically significant canonical roots, the highest partial weight in the overall variability of SSF parameters belongs to indicators of explosive strength (PU10s – 14.41%), speed-strength endurance (PPU10s – 10.67%), and anaerobic alactate work capacity (T15T – 9.50%).

Their combined contribution to the total variability (redundancy) of SSF across the three statistically significant roots amounts to 34.57%. This constitutes 79.1% of the total contribution of all studied variables to the overall variability of SSF parameters.

The largest specific weight in the overall variability of PD variables (CBD) in combat athletes belongs to the indicators of chest circumference (CC – 7.12%), shoulder circumference (ShC – 7.28%), and calf circumference (CaC – 10.93%). Their combined contribution to the total variability of PD parameters across the three statistically significant roots is 44.8%. This contribution of the three PD indicators accounts for 84.02% of the total contribution of all studied variables to the overall variability of the CBD indicator group.

This also indicates that CC, ShC, and CaC indicators are the most variable parameters under the influence of the SSF group of indicators in combat athletes. Conversely, indicators of explosive strength (PU10s), speed-strength endurance (PPU10s), and anaerobic alactate work capacity (T15T) are the most variable under the influence of the CBD group of indicators.

Correlation analysis made it possible to determine the magnitude and direction of intra- and intergroup relationships between SSF and CBD indicators. The analysis of pairwise correlation coefficients showed that intragroup relationships among CBD indicators are higher than those within the SSF group and the intergroup relationships between CBD and SSF. Specifically, the mean correlation coefficient among CBD indicators was 0.617 ± 0.07 ($p < 0.001$), within the speed-strength group 0.256 ± 0.06 ($p < 0.05$), and for intergroup relationships 0.224 ± 0.03 ($p < 0.05$).

The averaged pairwise correlation coefficients indicate that among CBD indicators, the strongest relationships with other variables in the set are demonstrated by TC (0.750 ± 0.12), FC (0.738 ± 0.13), CC (0.729 ± 0.14), and NC (0.712 ± 0.11).

Among the individual indicators of SSF, the strongest pairwise relationships with other variables in the complex are demonstrated by two indicators: PPU10s ($r = 0.329 \pm 0.10$) and SLJ ($r = 0.365 \pm 0.10$).

Among intergroup pairwise interactions, the strongest relationships were identified between the indicator of anaerobic alactate work capacity (T15T) and the indicators of CBD. The average value of the pairwise correlation coefficients between T15T and all examined CBD indicators was −0.410 ± 0.09.

However, pairwise intergroup correlations reflect only the relationships between individual pairs of PD and SSF indicators in combat athletes, as well as their averaged intergroup values.

In this regard, to reveal the dependence of individual key indicators in each set (CBD and SSF) on the combined influence of a group of key indicators from the other set, multiple correlation analysis and stepwise multiple regression analysis were performed (Table 2).

Table 2 presents the equations of stepwise multiple regression, as well as the coefficients of multiple correlation and determination. They reflect statistically significant effects of the group of CBD indicators on individual SSF indicators and of

Table 2. Model characteristics of the dependence of individual SSF indicators on the combined influence of a number of key PD indicators (Y_1–Y_5), and of individual PD indicators on the influence of key SSF indicators in wrestlers (Y_5–Y_9).

Regression equations*	r	d	F	p
$Y_1 = (16.36 + 1.144x_1 + 0.115x_2 + 0.337x_3 - 0.216x_4 - 0.244x_5 - 0.765x_6) \pm 0.98$	0.834	0.696	11.07	< 0.00000
$Y_2 = (5.54 + 0.0927x_7 + 0.040x_8 - 0.013x_5 - 0.121x_6 - 0.004x_5 - 0.011x_1) \pm 0.18$	0.634	0.402	4.14	< 0.003
$Y_3 = (3.83 + 0.3495x_6 + 0.1124x_4 - 0.1422x_5) \pm 0.92$	0.572	0.327	6.45	< 0.001
$Y_4 = (47.81 + 2.68x_6 + 0.61x_5 + 1.005x_7 - 2.71x_9 - 0.91x_8 - 0.31x_3) \pm 3.99$	0.642	0.412	5.03	< 0.0006
$Y_5 = (129.98 + 0.02x_{10} - 0.760x_{11} - 0.720x_{12}) \pm 7.22$	0.423	0.179	3.26	< 0.029
$Y_6 = (52.05 - 0.23x_{12} - 0.50x_{13}) \pm 2.74$	0.400	0.160	4.18	< 0.02
$Y_7 = (46.59 - 0.242x_{12} - 0.730x_{13}) \pm 2.74$	0.377	0.142	3.8	< 0.03
$Y_8 = (50.46 - 0.305x_{12} - 0.678x_{13}) \pm 3.4$	0.424	0.180	3.4	< 0.01
$Y_9 = (112.51 + 0.045x_{10} - 0.521x_{12} - 11.24x_{14} - 1.11x_{11}) \pm 8.7$	0.750	0.562	8.7	< 0.0002

* where: Y_1 – PPU10s; Y_2 – R30m; Y_3 – PU10s; Y_4 – T15T; Y_5 – CC; Y_6 – NC; Y_7 – TC; Y_8 – ShC; Y_9 – tense shoulder circumference; x_1 – chest excursion, cm; x_2 – AC, cm; x_3 – CC, cm; x_4 – CaC, cm; x_5 – TC, cm; x_6 – FC, cm; x_7 – ShC, cm; x_8 – NC, cm; x_9 – tense shoulder circumference, cm; x_{10} – SLJ, cm; x_{11} – PPU10s, number; x_{12} – BR15s, s; x_{13} – PU10s, s; x_{14} – R30m, s.; ** r – correlation coefficient; d – determination coefficient; F – Fisher's coefficient.

the SSF group on individual CBD indicators.

The coefficients of determination reflect a stronger influence of the group of leading CBD indicators on individual SSF indicators than the influence of SSF indicators on individual CBD parameters.

In the regression models describing the dependence of individual SSF indicators on the group of CBD indicators, the CBD variables that entered the models with the highest correlation and determination coefficients included CC, TC, CaC, FC, ShC, and NC (Table 2, Y_1–Y_4). Different combinations of PD indicators exert varying degrees of influence on the manifestation of speed, strength, and speed-strength (anaerobic alactate) work capacity in wrestlers during motor tests.

It was found that among the individual parameters of SSF, the strongest dependence on the group of CBD parameters is demonstrated by the indicator of speed-strength (anaerobic alactate) work capacity, PPU10s (Table 2, Y_1). High coefficients of multiple correlation ($r = 0.834$, $p = 0.0000$) and determination ($d = 0.696$, $p = 0.0000$) reflect a strong dependence of the speed-strength work capacity parameter on the group of interrelated PD indicators: AC, CC, CaC, TC, FC, and chest excursion.

The parameters of the first model (Y_1) indicate that with an increase in chest circumference, its excursion, and abdominal circumference, the maximum number of push-ups from the prone support position (PPU10s) increases, that is, the level of speed-strength anaerobic work capacity increases. Conversely, with an increase in the circumference of the calf, thigh, and forearm, the number of push-ups decreases. This reflects a decrease in the level of speed-strength anaerobic work capacity.

The signs of the coefficients in regression model Y_4 indicate that with an increase in neck circumference, tensed shoulder circumference, and chest circumference at rest, the time required to complete the test involving throws of a partner of equal weight (T15T) decreases. That is, the level of special work capacity increases. Conversely, with an increase in thigh, forearm, and relaxed shoulder circumferences, the time required to complete the special test (T15T) increases. This indicates a decrease in the level of special work capacity.

Among the individual parameters of CBD, the strongest dependence on the SSF group is demonstrated by shoulder circumference in a flexed (contracted) state ($r = 0.750$, $p = 0.0000$, $d = 0.696$, $p = 0.0000$). The coefficients of multiple correlation and determination indicate a high dependence of shoulder circumference in a flexed state on the following group of SSF indicators: SLJ, PPU10s, T15T, and R30m.

The model equations indicate that the provision of athletes' anaerobic physical work capacity may be based on different combinations within a complex of PD variables. Stepwise analysis selected a set of variables for the regression models. Their combination provides the best prediction of the result characterizing the level of wrestlers' SPWC.

The values of the canonical factor loadings indicate that among SSF indicators, the strongest relationship with the canonical variable of the first root is shown by the parameter PU10s (−0.732), of the second root by T15T (−0.739), and of the third root by PPU10s (0.807). Among CBD indicators, the strongest relationship with the canonical variable of the first root is shown by CaC (−0.769), of the second root by CC (0.570), and of the third root by FC (−0.711).

The values of the canonical weights of SSF indicators indicate that the greatest contribution to the formation of the canonical variable of the first root is made by the PU10s parameter (−1.201), of the second root by T15T (−0.878), and of the third root by PPU10s (1.103).

The values of the canonical weights of PD variables indicate that the greatest contribution to the first canonical variable is made by FC (2.913), to the second canonical variable by TC (−2.632), and to the third by FC (−3.239).

The magnitudes of the canonical factor loadings and canonical weights indicate that among SSF indicators, the PU10s parameter, having the strongest relationship with the canonical variable, makes the greatest contribution to the formation of the canonical variable of the first root. Among CBD indicators, the strongest relationship with the canonical variable is demonstrated by the CaC parameter; however, the greatest contribution to the formation of the canonical variable of the first root is made by FC and ShC.

Canonical weights were used to construct multiple regression equations. These equations reflect the contribution of each of the PD (CBD) and PF (SSF) indicators to the formation of the canonical variable values.

Thus, the regression equations reflecting the contribution of individual PD (CBD) and PF (SSF) variables of combat athletes to the formation of the canonical variable of the first root (Equations 1–2) are presented below:

$$\text{Root } 1_{PD} = 0.191CC_1 + 0.705AC_2 + 2.913FC_3 - 1.047NC_4 - 1.442ShC_5 - 1.327CaC_6 - 0.404TC_7 \quad (1)$$

$$\text{Root } 1_{PF} = 0.843PPU10s + 0.139T15T - 0.014R30m - 1.002SLJ - 1.201PU10s \quad (2)$$

The results reflect different patterns of mutual variability between the indicators of PD (CBD) and PF (SSF) in the group of highly skilled combat athletes.

Graphical and generalized regression models, as well as the coefficients of correlation and determination reflecting the relationships between the canonical variables of SSF and CBD for root 1, are presented in Figure 1.

The scatter plot of canonical variables for the first root reflects the linear relationship between the weighted sums of variables from two canonical sets, CBD and SSF. Each point on the graph represents an integral parameter of the weighted sums of the initial variables of SSF (five variables) and CBD (seven variables) for each subject. The X-axis corresponds to the scale of weighted sums of CBD, while the Y-axis corresponds to the scale of weighted sums of SSF indicators.

A strong positive linear relationship between the canonical variables of SSF and CBD for the first root ($r = 0.981$, $p < 0.0000$) indicates that an increase in CBD in combat athletes is accompanied by an increase in SSF parameters, including speed-strength work capacity, and vice versa. The distribution of

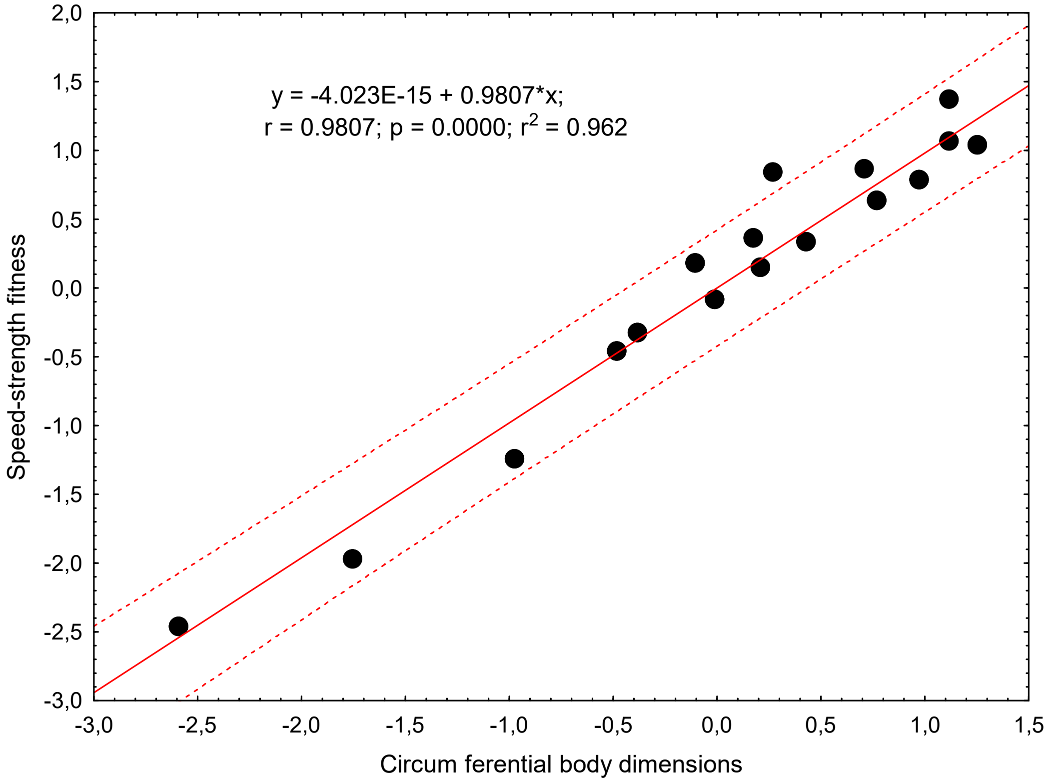

Figure 1. Graphical and regression models of the relationships between the weighted variables of PD (CBD) and the indicators of SSF for the first canonical root.

individual points on the graph, as well as the values of the correlation and determination coefficients, indicate that variables from one group are predicted by variables from the other group.

Below are presented the results of the canonical analysis of the interaction between variables of speed-strength fitness (five variables: R30m, SLJ, PU10s, PPU10s, T15T) and variables of longitudinal body dimensions (seven variables: LTrD, LDUE, LShD, LDLE, LTD, LCaD) (Table 3).

The results of the canonical analysis presented in Table 3 indicate a high level of canonical correlation between the two sets of variables, SSF and LBD ($R = 0.900$, $p = 0.0000$). The chi-square values ($\chi^2 = 82.75$, $p = 0.00001$) reflect a statistically significant interdependence between the set of canonical variables of SSF and the set of variables of LBD (Table 3).

The indicators of total variability (redundancy) demonstrate different mutual influences between the two analyzed groups of variables. Specifically, 39.53% of the variability of the canonical SSF variables is determined by the influence of the canonical LBD variables of combat athletes, while 24.79% of the total variability of the LBD group is explained by the influence of the SSF indicators.

The analysis of the factor structure and redundancy made it possible to determine the loadings of canonical factors for variables in both groups, the proportion of extracted variance explained by the corresponding root for each set, as well as the values of total variability of individual parameters across all roots.

Canonical factor loadings indicate that five roots account for 100% of the total variance of SSF indicators and 70.5% of the variance in the LBD group. Since only two out of the five roots were statistically significant, further analysis was conducted primarily based on these roots.

The analysis of intra- and intergroup relationships between canonical variables of SSF and LBD showed that the strongest relationships are the intragroup correlations among LBD indicators ($r = 0.470 \pm 0.04$). The relationships among speed-strength indicators (SSF) are lower ($r = 0.159 \pm 0.02$). The average level of intergroup relationships between canonical variables of SSF and LBD is also low ($r = 0.199 \pm 0.04$).

Among the LBD variables, the strongest intragroup relationships with all indicators in the set are demonstrated by two variables: LDUE ($r = 0.546 \pm 0.06$) and LDLE ($r = 0.638 \pm 0.05$).

Among the variables of the SSF group, the strongest intragroup relationships with all variables in this group are shown by the indicators SLJ ($r = 0.234 \pm 0.02$) and PU10s ($r = -0.218 \pm 0.05$).

Among variables from different sets, the strongest intergroup relationships are observed between indicators of PU10s and LDUE ($r = -0.453$, $p < 0.05$), as well as between PPU10s and LDUE ($r = -0.456$, $p < 0.05$).

To identify the dependence of individual indicators of each set (LBD and SSF) on the group of leading indicators of the other set, multiple correlation and stepwise multiple regression analyses were performed.

Table 4 presents the dependencies of individual SSF indicators (Y_1–Y_6) on the combined influence of the leading LBD variables.

The parameters of the regression equations, as well as the coefficients of multiple correlation and determination, reflect the combined influence of the group of leading LBD indicators on individual SSF indicators (Table 4, Y_1–Y_6). The coefficients of determination indicate that the degree of influence of different combinations of LBD parameters on individual SSF parameters in wrestlers ranges from 29.2% (result in the SLJ, equation Y_3) to 53.6% (result in the PPU10s, equation Y_2).

Table 5 presents the dependencies of individual LBD indicators (Y_1–Y_5) on the combined influence of the leading SSF variables.

The parameters of the regression equations, along with the coefficients of multiple correlation and determination, indicate that the degree of variability of individual LBD indicators in response to changes in SSF parameters in wrestlers ranges from 18.1% ($p < 0.004$; equation Y_3) to 44.1% ($p < 0.004$; LDUE, equation Y_2) (Table 5). Statistically significant regression coefficients reflect the magnitude, proportion, and interaction of various SSF parameters influencing the values of individual LBD indicators.

The results suggest that in the process of long-term adaptation, a model of speed-strength indicators is formed, associated with a specific number and ratio of LBD parameters. Each LBD parameter is determined by the level, proportion,

Table 3. Results of the canonical correlation analysis of the mutual influence between speed-strength fitness parameters and longitudinal body dimensions in highly skilled wrestlers (N = 35).

Parameters	Indicators of speed-strength fitness	Indicators of longitudinal body dimensions
Canonical correlation (R), χ^2	0.900, χ^2 (35) = 82.75, p = 0.00001	
Extracted variance	100.0%	70.5%
Total variability (redundancy)	39.53%	24.79%

Table 4. Model characteristics of the dependence of individual SSF indicators on the leading LBD variables (Y_1–Y_6).

Regression equations*	**r**	**d**	**F**	**p**
$Y_1 = (18.73 + 0.194x_1 - 0.120x_2) \pm 1.37$	0.628	0.395	11.09	< 0.0002
$Y_2 = (15.20 + 0.235x_1 + 0.136x_3 - 0.125x_2 - 0.294x_4) \pm 1.23$	0.733	0.536	9.23	< 0.00004
$Y_3 = (7.77x_1 + 13.09x_5 - 4.17x_3 - 135.2) \pm 89.6$	0.541	0.292	4.55	< 0.009
$Y_4 = (47.16 + 0.945x_4 + 0.236x_6 - 0.640x_3) \pm 4.2$	0.578	0.334	5.36	< 0.004
$Y_5 = (5.012 + 0.009x_7 + 0.012x_1 - 0.036x_4 - 0.021x_5) \pm 0.14$	0.578	0.335	3.65	< 0.015
$Y_6 = (9.75 + 0.093x_8 - 0.088x_7 - 0.044x_1) \pm 0.88$	0.560	0.313	5.01	< 0.006

* where: Y_1–Y_2 – PPU10s, number; Y_3 – SLJ, cm; Y_4 – T15T, s; Y_5 – R30m, s; Y_6 – PU10s; x_1 – LTD, cm; x_2 – LDUE, cm; x_3 – LTrD, cm; x_4 – LShD, cm; x_5 – LFD, cm; x_6 – LCaD, cm; x_7 – LDUE, cm; x_8 – LDLE, cm.; ** r – correlation coefficient; d – determination coefficient; F – Fisher's coefficient.

Table 5. Model characteristics of the dependence of individual LBD indicators on the combined influence of the leading SSF variables (Y_1–Y_5) in wrestlers.

Regression equations*	**r**	**d**	**F**	**p**
$Y_1 = (261.5 + 0.979x_1 - 0.637x_2 - 27.63x_3 - 3.85x_4 - 3.39x_5) \pm 6.1$	0.629	0.396	3.7	< 0.01
$Y_2 = (165.3 + 0.039x_6 - 2.51x_1 - 3.23x_5 - 0.331x_2 - 1.996x_4) \pm 7.2$	0.664	0.441	4.41	< 0.004
$Y_3 = (48.41 + 0.012x_6 + 0.662x_1 - 1.11x_5 - 0.17x_2) \pm 4.0$	0.426	0.181	4.29	< 0.004
$Y_4 = (34.2 + 0.016x_6 - 0.467x_1 - 0.135x_2) \pm 2.45$	0.463	0.214	3.3	< 0.06
$Y_5 = (94.59 + 0.013x_6 - 1.446x_1 - 2.2x_4 - 5.37x_3) \pm 4.48$	0.534	0.285	2.88	< 0.04

* where: Y_1 – LBD, cm; Y_2 – LDUE, cm; Y_3 – LTD, cm; Y_4 – LFD, cm; Y_5 – LCaD, cm; x_1 – PPU10s, number; x_2 – T15T, s; x_3 – R30m, s; x_4 – 4 m rope climb time, s; x_5 – PU10s, s; x_6 – SLJ, cm.; ** r – correlation coefficient; d – determination coefficient; F – Fisher's coefficient.

and interrelationships of certain SSF parameters within each regression model.

The analysis of variability across two statistically significant roots demonstrated that the greatest variability in the SSF group under the influence of canonical LBD variables is observed in the parameters PPU10s (52.8% of the total variance of root 1 indicators) and R30m (28.7% of the total variance of root 2 indicators). At the same time, the greatest variability in the LBD group under the influence of SSF is observed in the parameters LDUE (33.04%, root 1) and LShD (24.73%, root 2).

The analysis of canonical weights of normalized variables in each set showed that within the SSF group, the greatest contribution to the first canonical variable is made by the 10 s maximal anaerobic power test (–0.785), while the second canonical variable is primarily determined by the 30 m sprint (–0.982).

In the LBD parameter group, the greatest contribution to the first canonical variable is made by the LTrD variable (–1.338), and to the second canonical variable by LShD (1.626).

The canonical weights of root 1 individual indicators were used to construct regression equations reflecting the partial and combined contributions of SSF and LBD indicators to the formation of the values of the first canonical variable (Equations 3, 4):

$$\text{Root } 1_{SSF} = 0.092\text{R30m} + 0.070\text{SLJ} + 0.434\text{T15T} - 0.275\text{PU10s} - 0.785\text{PPU10s} \qquad (3)$$

$$\text{Root } 1_{LBD} = 0.827\text{LDUE} + 1.014\text{LShD} + 0.071\text{LFD} + 0.781\text{LDLE} - 0.992\text{LTD} - 0.744\text{LCaD} - 1.338\text{LTrD} \qquad (4)$$

Figure 2 presents graphical and regression models of the relationship between the canonical variables of LBD and SSF for the first canonical root in highly skilled combat athletes.

The squared correlation (r^2) of the canonical variable pairs indicates that 81.1% ($p = 0.0000$) of the variation in the weighted LBD and SSF variables for the first canonical root is explained by their mutual influence. The magnitude and direction of the correlation and determination coefficients indicate a strong positive linear relationship between the weighted variables of LBD and SSF.

Table 6 presents an analysis of the relationships between two sets of PD variables, longitudinal (LBD) and circumferential (CBD) body dimensions.

The first set of PD variables, presented in Table 6, consists of seven indicators of LBD: the longitudinal dimensions of the upper extremity (LDUE), lower extremity (LDLE), trunk (LTrD), shoulder (LShD), forearm (LFD), thigh (LTD), and calf (LCaD). The second group of PD variables, also presented in Table 6, includes seven indicators of CBD: neck circumference (NC), chest circumference (CC), shoulder circumference (ShC), forearm circumference (FC), abdominal circumference (AC),

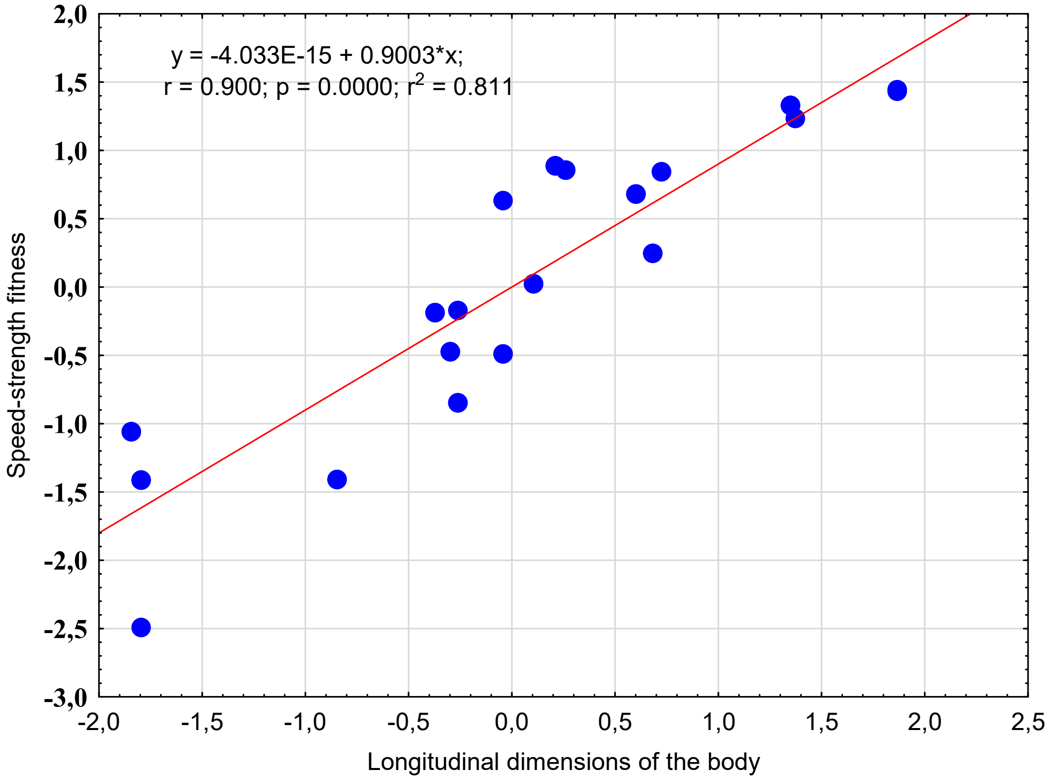

Figure 2. Graphical and regression models of the relationships between the weighted variables of LBD and SSF for the first canonical root.

Table 6. Results of the canonical correlation analysis of the mutual influence between the group of longitudinal body dimensions and the group of circumferential body dimensions (N = 35).

Statistical parameters	Longitudinal body dimensions	Circumferential body dimensions
Canonical correlation (R), χ^2	R = 0.968, χ^2 (49) = 163.9, p = 0.0000	
Extracted variance	100.0%	100.0%
Total variability (redundancy)	57.61%	66.877%

calf circumference (CaC), and thigh circumference (TC).

A high level of canonical correlation was found between the examined groups of variables (Table 6: R = 0.969, p = 0.0000). Its value and that of the chi-square (χ^2 = 163.9, df = 49, p = 0.0000) reflect a strong interdependence between the first canonical variables of the two PD groups, LBD and CBD.

The canonical analysis of eigenvalues revealed seven canonical roots explaining 100% of the extracted variance in the LBD group and 100% in the CBD group. Of the seven roots, the first four are statistically significant.

The results of total variance across all seven roots, presented in Table 6, indicate that 57.5% of the extracted variance in LBD indicators is due to the influence of the CBD canonical variables in combat athletes, while 66.88% of the total variance in CBD indicators is explained by the influence of the LBD variable group.

Redundancy analysis for the four statistically significant roots showed that 54.84% of the total variance in LBD indicators is determined by the influence of the CBD canonical variables, while 65.23% of the total variance in CBD indicators is determined by the influence of the LBD variable group. Relative to the combined effect of all variables across the seven roots, these values amount to 95.2% for LBD indicators and 97.5% for CBD indicators.

High values of the canonical correlation coefficient (R = 0.969, p = 0.0000) and the coefficient of determination (d = 0.938, p = 0.0000) for the first root indicate a strong relationship and mutual influence between the two sets of PD variables: an increase in LBD in combat athletes is accompanied by an increase in CBD, and conversely, an increase in CBD is associated with an increase in LBD. The variability of LBD indicators under the influence of CBD is less pronounced than the variability of CBD indicators under the influence of LBD.

Analysis of the factor structure of the four statistically significant roots made it possible to determine the proportional variability of individual CBD and LBD indicators in the total variability of their respective sets under the influence of the canonical variables of the other set. As a result, it was found that the greatest partial weight in the total variability of CBD indicators belongs to chest circumference (CC – 11.01%), neck circumference (NC – 11.51%), forearm circumference (FC – 10.62%), and thigh circumference (TC – 10.95%). Their combined weight in the total variability of CBD parameters across the four statistically significant roots constitutes 67.6%. This contribution of these four PD indicators accounts for 69.3% of the total contribution of all studied variables to the overall variability of the CBD group under the influence of the LBD canonical variables.

The greatest partial contribution to the total variability of LBD indicators across the four canonical roots belongs to indicators of LTrD (11.25%), LDLE (10.01%), LFD (9.2%), and LShD (9.04%). Their combined contribution to the total variability of LBD parameters across the four roots is 72.0%. This corresponds to 75.6% of the total contribution of all studied variables to the overall variability of the LBD group.

The findings indicate that the most variable CBD indicators under the influence of LBD in combat athletes are chest circumference (CC), neck circumference (NC), forearm circumference (FC), and thigh circumference (TC). The most variable LBD indicators under the influence of CBD are the longitudinal dimensions of the trunk (LTrD), lower extremity (LDLE), forearm (LFD), and shoulder (LShD).

Analysis of the canonical weights of standardized variables for each set showed that within the CBD parameter group, the greatest contribution to the value of the first canonical variable is made by the TC variable (−1.114); to the second canonical variable by CC (3.088); to the third by ShC (1.678); and to the fourth by FC (3.219).

In the LBD parameter group, the greatest contribution to the value of the first canonical variable is made by LFD (−0.721); to the second canonical variable by LTrD (1.28); to the third by LDLE (1.614); and to the fourth by ShC (1.2).

Canonical weights were used to construct regression equations reflecting the contribution of each CBD and LBD indicator to the formation of the canonical variables of the first root (Equations 5–6):

$$\text{Root } 1_{LBD} = 0.371LDUE + 0.232LTD - 0.237LTrD - 0.491LShD - 0.721LFD - 0.058LDLE - 0.271LTrD \quad (5)$$

$$\text{Root } 1_{CBD} = 0.632CC + 0.149AC + 0.132ShC + 0.537FC - 1.114TC - 0.41CaC - 0.915NC \quad (6)$$

Figure 3 presents graphical and regression models of the relationships between the weighted CBD and LBD variables for the first canonical root.

The squared canonical correlation (r^2), presented in Figure 3, indicates that 93.8% of the variance in the weighted LBD and CBD variables for the first canonical root is explained by their mutual influence.

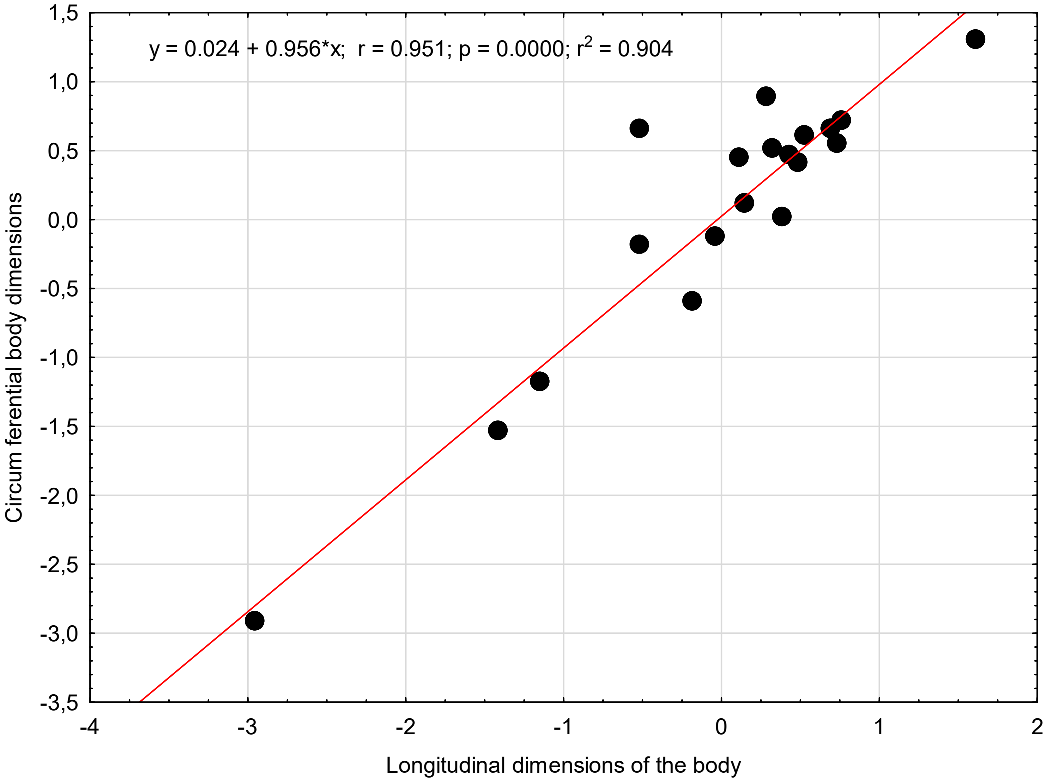

Figure 3. Graphical and mathematical models of the relationships between the weighted LBD and CBD variables for the first canonical root.

Discussion

The aim of the study was to perform a canonical analysis of the general variability and interrelationships among parameters of speed-strength fitness, as well as circumferential and longitudinal body dimensions in highly skilled wrestlers. The results showed the presence of statistically significant interrelationships between the studied groups of variables, reflecting their mutual influence. The analysis demonstrated that changes in speed-strength fitness parameters are associated with changes in circumferential and longitudinal body dimensions. It was also found that the degree of influence differs depending on the specific group of indicators and their combinations.

Long-term adaptation of combat athletes to physical loads is characterized by the formation of a complex of morphological, functional, and metabolic rearrangements. These reflect the structure of physical state (PS) and the reserve capacities of athletes.

The level of development, ratios, and interrelationships among parameters of PD, physical, functional, psychological, and technico-tactical fitness, as well as SPWC, determine the multilevel, hierarchically organized structure of the PS of combat athletes. They also determine their specific profile and the effectiveness of competitive activity [18, 24, 42, 43].

The complex and interconnected nature of adaptive changes in the bodies of combat athletes necessitates comprehensive studies of the level of development, proportions, and interrelationships of PS parameters. These depend on various determinants such as age, weight category, qualification, sex, training period, and the orientation of the training process.

The methodological principles of the systems approach form the basis for studying complex adaptive transformations in hierarchically organized biological systems during long-term adaptation to physical loads.

The principles of the systems approach necessitate conducting synchronous investigations of the level of development, proportions, and interrelationships among various PS components of combat athletes. They also involve identifying the most informative indicators and their partial contribution to the overall variability of the group of interacting parameters.

Systemic and comprehensive approaches also require the use of an appropriate set of statistical programs to determine the specificity of interrelationships and mutual influences, as well as the degree of integration of parameters representing different components of the PS of combat athletes. This applies both to the process of improving athletic mastery and shaping the morphofunctional and metabolic profile, and to the development of various forms of SPWC, including anaerobic, aerobic, mixed, strength, speed, speed-strength, static, and dynamic.

In accordance with the main aim and objectives of the present study, the processing of experimental data was carried out using methods of correlation, regression, and canonical analysis [41].

An analysis of scientific publications has shown that the method of canonical analysis is still insufficiently used for assessing the morphological, psychological, metabolic, functional, and technico-tactical profiles of athletes. At the same time, the specific profile and effectiveness of competitive activity are largely determined by intergroup interactions among various components of the PS structure of athletes [5]. The method of canonical correlation is one of the appropriate tools for studying such intergroup interactions [37, 44].

Only a limited number of studies [8, 37, 39], as well as our previous works [5, 45], have demonstrated that the canonical correlation method is one of the suitable methods for:

a) identifying latent relationships between groups of interacting parameters;

b) determining the maximum correlation between several output (resultant) indicators and a large number of input (determinant) factors;

c) assessing the partial role of individual parameters in the overall variability of the canonical variables of each group under the influence of the canonical variables of another group;

d) identifying the most variable output (resultant) indicators and the most variable input (determinant) factors.

However, the use of the canonical correlation method to assess intergroup interactions and mutual influences among indicators from different sets of the PS of combat athletes is insufficiently represented in the specialized literature.

The experimental material presented in our previous studies confirms the effectiveness of this method for identifying maximum relationships and the specific nature of mutual influences among parameters of different PS sets in combat athletes, including functional state, SSF, integral indicators of functional fitness, CBD, skinfold thickness (SFT), and other sets [5, 45].

In the present study, the canonical correlation method was used to evaluate both the combined and partial mutual influence of indicators from the following PS sets in combat athletes: CBD and SSF; LBD and SSF; CBD and LBD.

The SSF parameter group included indicators of speed and speed-strength work capacity, strength endurance, and explosive strength. The intensity and duration of the tests performed indicated the predominance of the anaerobic alactate (creatine phosphate) mechanism in the energy supply of

SPWC in combat athletes, along with contributions from anaerobic glycolytic (lactate) or aerobic mechanisms [46].

The assessment of other forms of SPWC manifestation, in which anaerobic (glycolytic) or aerobic energy systems play a significant role, was not within the scope of the present study.

The results obtained in this study confirm and extend the findings of our previous research devoted to the application of the canonical correlation method for evaluating interactions among parameters of different PS sets in combat athletes [45, 47].

While our previous studies analyzed intra- and intergroup correlations of CBD parameters, SFT, and integral functional parameters with a set of SSF parameters in combat athletes [45, 47], the present study examined intra- and intergroup relationships between CBD and SSF parameters, CBD and LBD, and LBD and SSF.

The results of the present study confirm the findings of our earlier research, which indicate close intergroup correlations between CBD and SSF parameters in combat athletes [45].

However, while our previous studies analyzed the correlations between CBD parameters and SSF test results, in which the anaerobic lactate mechanism played a role in energy supply, the present study analyzed the correlations between CBD and SSF test results, in which the anaerobic alactate (creatine phosphate) mechanism played a role in energy supply [20, 24, 46].

This methodological approach made it possible to obtain results that complement our previous studies conducted in this area [45].

The novelty of the present study lies in the fact that in highly skilled combat athletes, canonical analysis revealed latent intergroup interactions among the sets of variables of SSF, CBD, and LBD. The partial role of individual parameters in the mutual influence of the studied sets of the athletes' PS was also determined.

The analysis of intergroup interactions showed that increases in CBD and LBD contribute to increases in SSF, while increases in SSF parameters are accompanied by increases in CBD and LBD. In the interaction between SSF and CBD variables, an approximately equal mutual influence was identified. In contrast, in the interaction between CBD and LBD variables, a more pronounced influence of LBD variables on CBD was observed than the reverse effect of CBD parameters on LBD. It was also found that CBD parameters exert a stronger influence on the level of SSF in combat athletes than LBD parameters. Moreover, CBD parameters are more dependent on the level of SSF than on LBD.

The analysis of pairwise intragroup relationships revealed a higher degree of integration among CBD parameters than the intragroup integration of SSF and LBD parameters. The weakest intragroup integration was observed among SSF parameters.

Among the individual CBD variables, the strongest intragroup relationships with all variables in the set are exhibited by the circumferential dimensions of the neck, forearm, and chest. Among the individual LBD variables, the strongest intragroup relationships with all indicators in the set are shown by the longitudinal dimensions of the upper and lower extremities. Among the SSF variables, the strongest intragroup relationships with all other indicators of the analyzed group are demonstrated by the standing long jump and the number of pull-ups on the bar performed within 10 seconds.

The analysis of pairwise intergroup relationships showed that the strongest associations between SSF and CBD indicators are observed between the parameter of anaerobic alactate work capacity (T15T) and all indicators of the CBD group.

Among the intergroup interactions between SSF and LBD parameters, the strongest relationships were identified between the indicator of speed-strength work capacity (PPU10s) and all LBD indicators.

The analysis of the factor structure and canonical weights made it possible to determine the shared variability of individual indicators in the overall variability of each set (CBD and LBD, SSF) under the influence of the group of canonical variables from the other set.

The redundancy analysis revealed that among CBD indicators, the most variable under the influence of LBD in combat athletes are the circumferential dimensions of the neck, chest, forearm, and thigh. Among LBD indicators, the most variable under the influence of CBD are the longitudinal dimensions of the trunk, lower extremity, forearm, and shoulder. Among SSF indicators, the most variable under the influence of the canonical variables of LBD are the maximum number of push-ups performed in the prone support position within 10 seconds and the result in 30 m running.

The greatest variability within the LBD group under the influence of SSF is observed in the parameters of the longitudinal dimensions of the upper extremity and the shoulder. The most variable SSF parameters under the influence of CBD variables are indicators of speed-strength endurance, anaerobic alactate work capacity, and explosive strength. The highest degree of variability within the CBD group under the influence of SSF is observed in the circumferential dimensions of the calf, shoulder, and chest.

The canonical regression equations reflect the partial contribution of the leading indicators of the wrestlers' PS to the formation of the values of the first canonical root variables for each of the studied sets (Equations 1–6).

High values of canonical correlations, coefficients of determination, and χ^2 between the three interacting groups of PS parameters in combat athletes indicate a strong interdependence of the parameters of the studied sets. They also show that the variables of one group of indicators are predicted by the variables of another group.

The results of the stepwise multiple regression analysis showed that the level of speed-strength work capacity in combat athletes can be provided by different combinations and interactions of variables from two groups of PD parameters (CBD and LBD). The calculated models indicate that the total influence of the leading CBD indicators of wrestlers on individual SSF parameters ranges from 32.7% to 69.6%. The total influence of different combinations of leading SSF indicators on individual CBD parameters ranges from 14.2% to 56.2%. The total influence of different combinations of leading LBD indicators on individual SSF parameters ranges from 29.2% to 53.6%. The total influence of different combinations of leading SSF indicators on individual LBD parameters ranges from 8.2% to 44.02%.

The coefficients of canonical correlation, multiple regression, and determination indicate a stronger influence of the CBD parameter group on individual SSF parameters than the reverse influence of the SSF indicators on individual CBD parameters.

The regression models also showed that an increase in chest, neck, and tensed shoulder circumference is associated with an increase in the level of special (anaerobic alactate) work capacity. An increase in chest circumference, chest excursion, and abdominal circumference is associated with an increase in speed-strength anaerobic endurance. At the same time, an increase in the circumferential dimensions of the thigh, forearm, and shoulder is associated with a decrease in special anaerobic (alactate) work capacity. It should be noted that the values of TC, FC, and ShC are higher in combat athletes of heavier weight categories. These athletes also demonstrate a lower level of SPWC than athletes in middle and lightweight categories [22]. Therefore, for an adequate interpretation of the obtained results, it is necessary to take into account the weight categories of combat athletes.

Limitations and Future Research Directions

The present study has several limitations that should be considered when interpreting the findings. The analysis was based on a selected set of morphofunctional and performance indicators corresponding to the study aim, which defines the scope of the obtained results and limits their extension to other components of physical state. The assessment of speed-strength fitness was focused on motor tests reflecting predominantly anaerobic alactate work capacity, which determines the specificity of the identified relationships among the studied parameters. The cross-sectional design of the study does not allow establishing the direction of causal relationships between variables and does not reflect potential changes in their interactions over time. In addition, the applied multivariate statistical methods, including canonical analysis, are based on the structure of the selected variables and their linear relationships, which should be considered when interpreting the identified patterns of intergroup interaction.

Future research may focus on examining the relationships among PS parameters in more homogeneous groups with respect to sport specialization, qualification level, and weight categories in order to уточнить структуру выявленных взаимодействий. It is also appropriate to analyze the dynamics of these relationships at different stages of training and competitive activity using longitudinal designs. Further studies may expand the set of analyzed indicators within the framework of the studied components of physical state to уточнить характер межгрупповых взаимосвязей.

Conclusions

As a result of the canonical analysis of the interaction between physical development parameters and speed-strength fitness of combat athletes, the following were determined: a) the leading parameters of the overall variability of the indicators of the interacting groups; b) the partial role of individual indicators in the mutual influence of the parameters of the studied sets; c) the specifics of mutual influences among the sets of variables of speed-strength fitness and circumferential and longitudinal body dimensions; d) the most variable determining indicators and the most variable outcome indicators; e) latent intra- and intergroup relationships among the parameters of the physical state of combat athletes.

The indicators of overall variability of the canonical variables of physical development and speed-strength fitness of combat athletes, as well as the values of canonical correlations, coefficients of determination, and χ^2, reflect a high level of interdependence among the parameters of the studied sets. Increases in circumferential and longitudinal body dimensions contribute to increases in speed-strength fitness, while increases in speed-strength fitness are associated with increases in circumferential and longitudinal body dimensions of athletes. The strongest intergroup relationships are observed between the indicators of circumferential and longitudinal body dimensions, whereas the strongest intragroup relationships are found among the indicators of circumferential body dimensions.

In the interaction between circumferential and longitudinal body dimensions, a stronger influence of longitudinal dimensions on circumferential ones is observed. In the interaction between circumferential body dimensions and speed-strength fitness variables, their mutual influence is approximately equal. In the interaction between longitudinal body dimensions and speed-strength fitness variables, a stronger influence of longitudinal dimensions is observed. The level of speed-strength fitness in combat athletes is more dependent on circumferential than on longitudinal body dimensions. Variables of circumferential body dimensions demonstrate a greater dependence on speed-strength fitness variables than on longitudinal body dimension variables.

The speed-strength fitness parameters most dependent on circumferential body dimensions are indicators of explosive strength, speed-strength endurance, and anaerobic alactate work capacity. The circumferential body dimension parameters most dependent on the level of speed-strength fitness in combat athletes are the circumferences of the chest, shoulder, and calf. The speed-strength fitness parameters most dependent on longitudinal body dimensions are indicators of anaerobic alactate work capacity and speed-strength endurance. The longitudinal body dimension parameters most dependent on the level of speed-strength fitness are the longitudinal dimensions of the upper extremity and the shoulder. The circumferential body dimension parameters most dependent on changes in longitudinal body dimensions are the circumferences of the chest, neck, forearm, and thigh. The longitudinal body dimension parameters most dependent on changes in circumferential body dimensions are the longitudinal dimensions of the trunk, shoulder, forearm, and lower extremity.

The results of the multiple regression analysis indicate that the total influence of different combinations of leading indicators of wrestlers' circumferential body dimensions on individual parameters of longitudinal body dimensions ranges from 8.2% to 44.02%, and on individual parameters of speed-strength fitness from 32.7% to 69.6%. The total influence of different combinations of leading indicators of longitudinal body dimensions on individual parameters of circumferential body dimensions ranges from 14.2% to 56.2%, and on individual parameters of speed-strength fitness ranges from 29.2% to 53.6%. The total influence of different combinations of speed-strength fitness indicators on individual parameters of circumferential body dimensions ranges from 14.2% to 56.2%, and on individual parameters of longitudinal body dimensions ranges from 8.2% to 44.02%.

An increase in the circumference of the neck, tensed shoulder, chest, and abdomen is associated with an increase in the level of special work capacity and speed-strength endurance in combat athletes. Conversely, an increase in the circumferential dimensions of the thigh, calf, forearm, and shoulder, in parallel with an increase in athletes' weight categories, is associated with a decrease in the level of anaerobic work capacity.

Conflict of interest

The authors declare that there is no conflict of interest.

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