

Research article

Effects of Quadriceps Strengthening Exercise with Blood Flow Restriction on Knee Angular Velocity, Strength, and Balance in Fencers

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Abstract

The purpose of this study was to investigate the effects of low-load blood flow restriction (BFR) training on lower limb kinematics during the fencing lunge, quadriceps strength, and balance in collegiate fencers. Sixteen collegiate sabre and epee fencers were randomly assigned to either a BFR group ($n = 8$) or a general leg extension (GLE) group ($n = 8$). Both groups performed 6 weeks of leg extension training. The BFR group trained at 30% of 1 repetition maximum (1RM) and the GLE group at 70% of 1RM. Due to dropouts, data from 14 participants were included in the final analysis. Primary outcomes were lower limb kinematics during three defined phases of the fencing lunge, quadriceps isometric strength, and static balance, assessed before and after the intervention. Between-group comparisons of change scores (Δ) were evaluated using effect sizes (Rank-biserial r) with 95% confidence intervals (CIs). Between-group Δ comparisons revealed small-to-large effect sizes favoring BFR across rear leg kinematic variables in all fencing lunge phases ($r = 0.24 - 0.52$). The largest effect was observed in rear leg hip flexion angle during Phase 3 ($r = 0.52$, 95% CI: -0.01 to 0.83). Significant between-group differences were found in front leg knee flexion angle during Phase 2 ($p = .043$) and rear leg hip extension angular velocity during Phase 3 ($p = .029$). Both groups showed significant increases in rear leg quadriceps strength ($p < .05$), with no meaningful changes in static balance. These kinematic improvements are functionally relevant, as greater rear leg hip flexion and faster angular velocity during the fencing lunge are associated with increased propulsive force and more effective lunge execution in competitive fencing. Preliminary evidence suggests that low-load BFR training may produce small-to-large effects on rear leg kinematics during the fencing lunge and may enhance quadriceps strength, providing a safe and practical alternative to high-load training for improving fencing performance.

Key words: Occlusion training, lower limb kinematics, IMU, isometric strength, postural balance.

Introduction

Fencing is one of the four events included in the modern Olympic Games, and South Korean athletes have achieved notable international success, contributing to the sport's growing popularity domestically (Park and Byung, 2017). Among the various fencing techniques, the fencing lunge (fente)—the most fundamental offensive action involving extension of the weapon arm, propulsion from the rear leg, and forward landing of the front leg—is a fundamental movement essential for rapid offensive and defensive actions during competition (Turner et al., 2013; Chida et al., 2023). This movement is characterized by a distinct functional asymmetry: the rear leg generates explosive forward

propulsion through concentric contraction, while the front leg performs an eccentric braking action via the knee extensors to ensure stability and safe foot contact upon landing (Kim and Kim, 2014). Therefore, successful performance of the fencing lunge requires both concentric force production for propulsion and eccentric control for knee stability, highlighting the critical role of the knee extensors in both limbs (Kim and Kim, 2014). Accordingly, effective execution of the fencing lunge depends largely on lower limb strength, speed, and agility (Chida et al., 2023). Therefore, targeted strengthening of the quadriceps is vital for enhancing both the propulsive power and the stability required for an effective lunge (Guan et al., 2018).

Biomechanical analysis of fencing has traditionally employed three-dimensional optical motion capture systems (OMC), which provide high spatial accuracy (Topley and Richards, 2020). However, OMC systems are limited by high costs, complex setup, and dependence on an unobstructed line of sight, restricting their use to controlled laboratory environments (van der Kruk and Reijne, 2018). Alternative approaches have been explored to address these constraints. Two-dimensional video-based analysis has been applied to fencing lunge movements due to its accessibility (Chida et al., 2023); however, conventional video systems may lack the sampling frequency required to capture the high angular velocities characteristic of elite fencing gestures (Delgado Garcia et al., 2021). Wearable inertial measurement units (IMUs) have emerged as a practical alternative, offering portability, ease of use, and high sampling rates suitable for analyzing fast, multidirectional fencing movements in field-based settings (Weygers et al., 2020; Delgado Garcia et al., 2021).

Another critical factor influencing the fencing lunge is balance, which works in tandem with muscular strength to support rapid directional changes (Cingoz et al., 2023). Enhancing quadriceps strength not only improves power output but also contributes to better knee proprioception, leading to greater postural stability and a reduced risk of injury (Wang et al., 2016; Li et al., 2025). In particular, BFR combined with low-intensity resistance training has been shown to enhance knee joint position sense accuracy through increased proprioceptor excitability and sensitivity (Li et al., 2025). Therefore, the concurrent development of strength and balance is essential for improving performance in fencers (Ludwig et al., 2020).

While high-load resistance training is commonly used to improve muscle strength, it can impose substantial mechanical stress and increase the risk of overuse injuries (American College of Sports Medicine, 2009; Fahs et al.,

2015). As a safer and effective alternative, blood flow restriction (BFR) training has been proposed. BFR uses external pressure to restrict venous blood flow, creating a hypoxic environment in the muscle that stimulates hypertrophy and strength gains even at low training intensities (Wortman et al., 2020; Shinohara et al., 1998; DePhillipo et al., 2018). Studies have shown that BFR training can produce comparable or superior outcomes to traditional high-load training while minimizing joint stress (Korkmaz et al., 2022). Given these advantages, BFR is particularly promising for fencers seeking to enhance lower limb strength and balance simultaneously (Li et al., 2025).

Despite extensive research on the biomechanics of the fencing lunge, little is known about how specific training interventions such as BFR affect its components. Specifically, there is a lack of evidence regarding how BFR-mediated improvements in muscle strength translate into changes in the complex kinematics of the fencing lunge, particularly concerning the rear leg, which is the primary determinant of lunge velocity. Therefore, this study aims to investigate the effects of quadriceps strengthening exercises combined with BFR on lower limb kinematics during the fencing lunge, quadriceps strength, and balance in fencers. The findings may offer new insights into effective, low-risk training strategies for performance enhancement and injury prevention. We hypothesized that;

- (1) both the BFR and GLE groups would show significant improvements in knee angular velocity, muscle strength, and balance after the 6-week intervention,
- (2) the BFR group would demonstrate significantly greater improvements in these variables compared to the GLE group.

Methods

Study Design

This study employed a single-blind, randomized controlled

trial with a two-group pretest-posttest design to assess and compare the primary outcomes. To minimize bias, a single-blind approach was used when the outcome assessor was blinded to the group assignments throughout the data collection and evaluation process. The primary outcomes included lower limb kinematics, isometric quadriceps strength, and static balance. The intervention spanned six weeks, with sessions occurring three times per week. A total of 16 participants were recruited and randomly assigned to either the blood flow restriction group (BFR, $n = 8$) or the general leg extension group (GLE, $n = 8$) using a random sequence generated by a web-based program (<https://www.randomizer.org/>). To ensure allocation concealment, the group assignments were placed in sequentially numbered, opaque, sealed envelopes, which were opened only after the baseline measurements were completed. Statistical analyses were conducted on a per-protocol basis. During the study, two participants from the GLE group dropped out due to retirement and injury (GLE group, $n = 2$) (Figure 1).

Participants

Participants were recruited from the D University fencing team. The inclusion criteria were active athletes specializing in sabre or epee. Foil was not represented in the available team roster; furthermore, sabre and epee share comparable fencing lunge mechanics, which supported kinematic comparability across participants. Participants included both right- and left-handed athletes; therefore, outcomes were expressed as front leg and rear leg rather than dominant and non-dominant limb to reflect the functional role of each limb during the fencing lunge. Exclusion criteria were a history of deep vein thrombosis or varicose veins, open wounds or dermatological conditions on the proximal thigh, or reduced or altered sensation in the lower extremities. The purpose and methods of the study were explained to the participants, and informed consent was obtained.

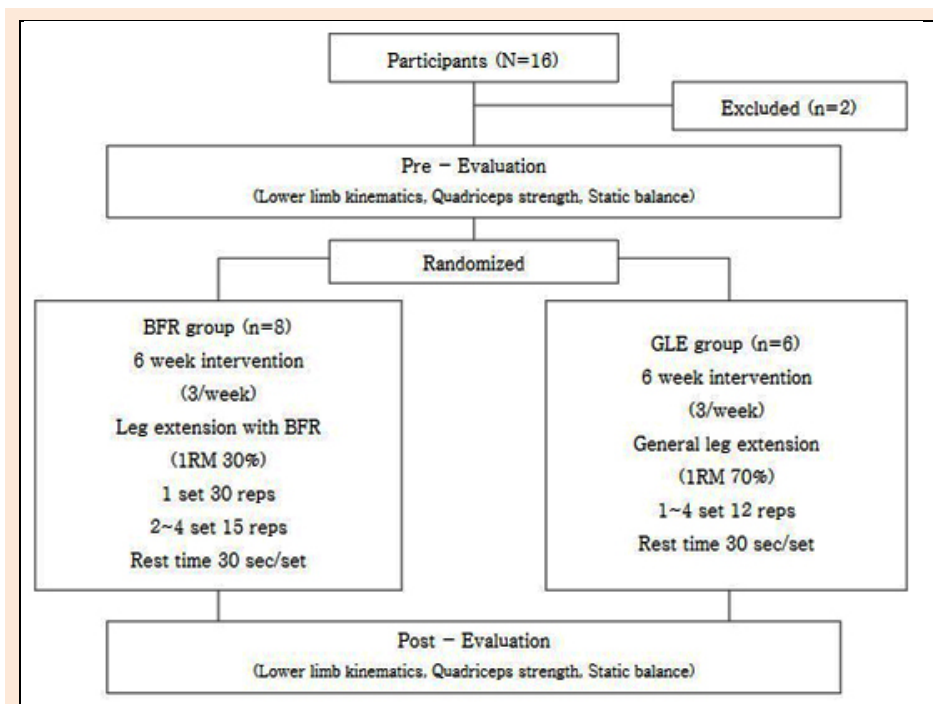


Figure 1. Study design.

This study was approved by the Ethics Committee of Daejeon University (IRB 1040647-202408-HR-001-03) and was registered with the Clinical Research Information Service (CRIS, KCT0010239). G*Power software (G*Power 3.1.9.4, University of Kiel, Germany) was used to calculate the appropriate sample size. The required sample size was estimated to be at least fourteen participants with an effect size of 1.47, a significance level (α) of 0.05, and a power ($1-\beta$) of 0.80. The effect size of 1.47 was derived from lower body muscular strength adaptations reported in a previous study examining the effects of BFR training in collegiate athletes (Yamanaka et al., 2012). In addition, a dropout rate of 10% was expected; therefore, sixteen participants were recruited.

Outcome Measures

Lower limb kinematics

Joint angle and angular velocity were measured during the fencing lunge using a motion analysis system (ISEN, STT, Spain). Seven inertial measurement unit (IMU) sensors were attached to participants' bodies at specific locations: both dorsum of the foot, shins, thighs, and the sacrum (Figure 2). The sensors were wirelessly connected via Wi-Fi and securely fixed to the participants' bodies using adhesive bands. Data from the ISEN sensors were sampled at 100 Hz, and extraction and conversion were performed directly using the ISEN software (Piche et al., 2022).

Joint angle and angular velocity were extracted and analyzed for each phase of the fencing lunge movement, which was divided into three sequential phases: Phase 1, from the en garde position with both feet on the ground to the point of maximum rear knee flexion (Figure 3, A-B); Phase 2, from maximum flexion to maximum extension of the rear knee during forward propulsion (Figure 3, B-C); Phase 3, from maximum rear knee extension to ground contact and maximum front knee flexion (Figure 3, C-D) (Guan et al., 2018).

For each phase, the maximum values of angle and angular velocity during flexion and extension of the hip and knee were recorded from three fencing lunge trials. A 30-second rest period was provided between trials to minimize the effects of fatigue (Chida et al., 2023).

Subsequently, average values for each joint's angles and angular velocities were calculated across the trials. The test-retest reliability (ICC) of the measure has been reported as 0.95 - 0.99 (Piche et al., 2022).

Quadriceps strength

Quadriceps isometric strength was measured bilaterally with a handheld dynamometer (Active force 2, Active body, USA). Participants were seated at 105° hip flexion. Measurements were taken at 60° of knee flexion, where quadriceps strength is known to be near maximal. The dynamometer was positioned above the participants' ankle and secured to the chair using straps to standardize testing conditions (Figure 4). Participants were instructed to exert maximal knee extension force for 5 seconds. Measurements were conducted alternately for the front and rear legs, with each leg measured three times. A rest interval of 30 seconds was provided between measurements (Giles et al., 2017). The average of the three measurements was used for analysis. The test-retest reliability (ICC) of the measure has been reported as 0.95 - 0.99 (Karagiannopoulos et al., 2022).



Figure 2. Marker attachment location.

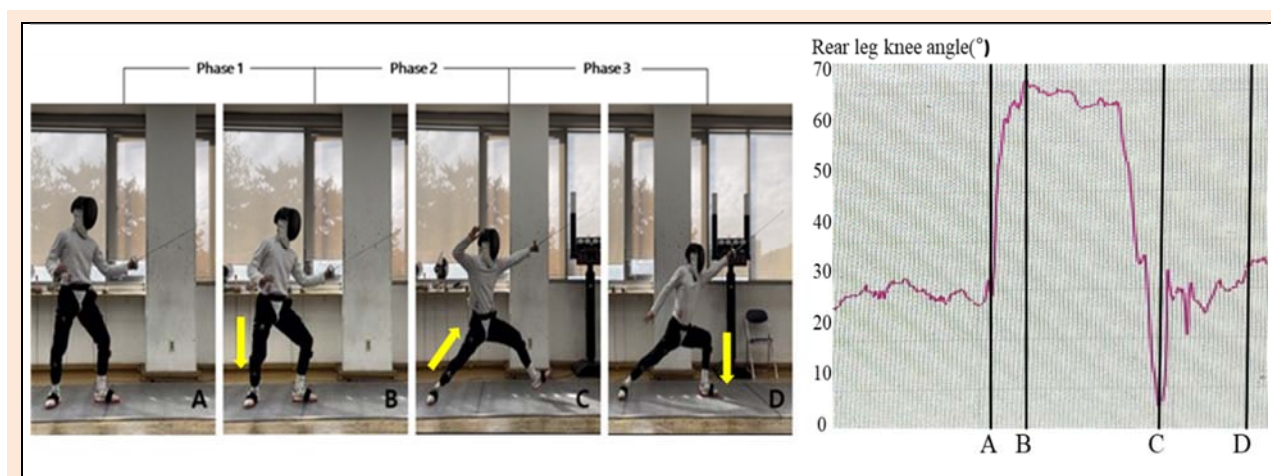


Figure 3. Fencing lunge Phase in fencing. A: En garde position(starting Point), B: Rear knee at maximum flexion, C: Rear knee at maximum extension while lunging forward, D: Landing position with front knee at maximum flexion.



Figure 4. Measurement of quadriceps strength.

Static Balance

Static balance was measured with a force plate (Wii balance board, Nintendo, Japan). Participants stood on the center of the device on one leg, keeping their knee extended and arms crossed over their chest (Figure 5). The measurement was performed by maintaining balance on one leg with eyes open for 30 seconds, alternated between the front and rear legs, with each leg measured three times. A rest interval of one minute was provided between trials (Citaker et al., 2011). The average of the three measurements was used for analysis. The test-retest reliability (ICC) of the measure has been reported as 0.66 - 0.94 (Kim et al., 2022).

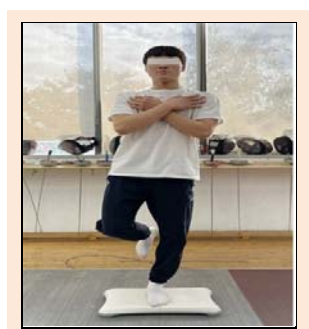


Figure 5. Single leg stance for static balance.

Interventions

BFR training

The BFR group trained using the EDGE Restriction System cuffs (The EDGE Mobility System, USA; length: 29¼ inches, width: 3 inches) placed on the proximal thighs, which were inflated to the target pressure while participants were in a resting position before starting the exercises (Figure 6). The exercises were conducted at around 30% of each participant's 1RM, consistent with the low-load BFR range (20 - 30% 1RM) commonly employed in previous research with athletic populations (Yamanaka et al., 2012), with the cuffs inflated. Participants completed an initial set of 30 repetitions followed by three sets of 15 repetitions. During the 30-second rest periods between sets, the cuffs remained inflated and were removed only after completing the exercise session (Giles et al., 2017). BFR pressure was set at 130% of resting systolic blood pressure (Takano et al., 2005). This pressure level was selected as prior research has demonstrated no significant difference in skeletal muscle metabolic stress between moderate (130% of resting SBP) and higher absolute pressures during BFR

exercise (Suga et al., 2010), suggesting that increasing BFR pressure beyond this level does not confer additional physiological benefit while ensuring participant safety. Adherence was monitored by the supervising researcher during every session, and no adverse events were reported throughout the intervention period.

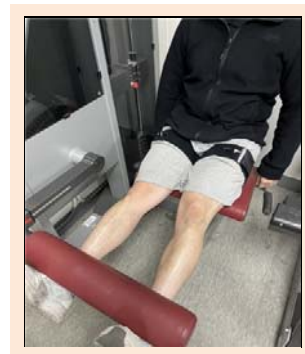


Figure 6. Leg extension with blood flow restriction.

General leg extension training

The GLE group performed four sets of 12 repetitions at 70% of their 1RM, with 30 seconds of rest between sets (Figure 7) (American College of Sports Medicine, 2009). Each participant's 1RM was determined through a pre-assessment, and the 1RM determined at baseline was used to prescribe training loads throughout the six-week intervention. The researcher closely monitored the exercises in real time to ensure proper execution and provided feedback as needed.

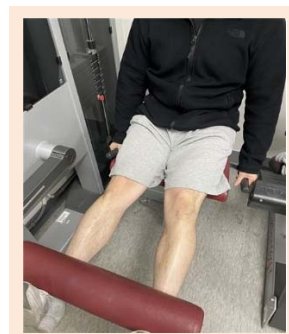


Figure 7. General leg extension.

Statistical analysis

The collected data were analyzed using IBM SPSS Statistics version 21.0 (IBM Corp., Chicago, IL, USA). The general characteristics of the participants were expressed as means and standard deviations using descriptive statistics. Homogeneity was confirmed using the Mann–Whitney U test. Normality tests for all variables were performed using the Shapiro–Wilk test, which indicated that the data did not follow a normal distribution. Therefore, the Wilcoxon signed-rank test was used to analyze within-group differences, and the Mann–Whitney U test was applied for between-group comparisons of change scores ($\Delta = \text{post} - \text{pre}$). Rank-biserial correlation (r) was calculated as the Mann-Whitney U test statistic divided by the square root of the total sample size ($r = Z / \sqrt{N}$), with 95% confidence intervals derived using Fisher's Z transformation. Effect sizes were interpreted as small ($r = 0.1$), medium ($r = 0.3$),

and large ($r \geq 0.5$). The statistical significance level (α) was set at 0.05.

Results

General characteristics of participants

The general characteristics of the participants showed no statistically significant differences between groups (Table 1).

Lower limb kinematics

Between-group comparisons of change scores (Δ = post - pre) with effect sizes (Rank-biserial r) and 95% confidence intervals are presented in Tables 2 - 4. Effect sizes were interpreted as small ($r = 0.1$), medium ($r = 0.3$), and large ($r \geq 0.5$) according to Cohen's conventions.

Phase 1 in fencing lunge

In Phase 1, between-group comparisons of Δ revealed several medium-to-large effects favoring the BFR group (Table 2). The largest between-group difference was observed in front leg hip flexion angular velocity ($r = 0.41$, 95% CI: -0.15 to 0.77), indicating a substantially greater increase in the BFR group ($\Delta = 3.66 \pm 23.97^\circ/s$) compared to a decrease in the GLE group ($\Delta = -32.41 \pm 46.75^\circ/s$). Medium-to-large effects were also found in rear leg hip flexion angular velocity ($r = 0.45$, 95% CI: -0.11 to 0.79) and front leg knee flexion angle ($r = 0.35$, 95% CI: -0.23 to 0.74). Small-to-medium effects were observed in rear leg knee flexion angle ($r = 0.28$) and rear leg knee extension angular velocity ($r = 0.31$). None of these between-group differences reached statistical significance (all $p > .05$), likely reflecting the limited statistical power of the sample size.

Phase 2 in fencing lunge

In Phase 2, a statistically significant between-group difference was found in front leg knee flexion angle ($\Delta BFR = 17.71 \pm 19.75^\circ$ vs. $\Delta GLE = 5.59 \pm 22.65^\circ$; $r = 0.55$, 95% CI: 0.03 to 0.84; $p = .043$) (Table 3). Additionally, several variables demonstrated medium between-group effects: front leg hip flexion angular velocity ($r = 0.38$), rear leg knee flexion angle ($r = 0.28$), and front leg hip flexion angle ($r = 0.28$). These consistently positive effect sizes suggest a systematic trend of BFR training in enhancing both hip and knee flexion during the propulsion phase, even where individual comparisons did not reach significance.

Phase 3 in fencing lunge

Phase 3 yielded the most pronounced between-group effects (Table 4). The change in rear leg hip flexion angle showed a large effect ($r = 0.52$, 95% CI: -0.01 to 0.83), with the BFR group demonstrating a substantial increase ($\Delta = 8.66 \pm 9.93^\circ$) compared to a decrease in the GLE group ($\Delta = -6.41 \pm 10.82^\circ$). Notably, this was the only kinematic variable whose 95% CI excluded zero, providing the strongest evidence for a differential training effect. A significant

between-group difference was also observed in rear leg hip extension angular velocity ($r = -0.59$, 95% CI: -0.85 to -0.08; $p = .029$). Medium effects were further observed in rear leg knee flexion angle ($r = 0.38$) and rear leg knee extension angular velocity ($r = -0.31$).

Quadriceps strength

Both groups showed significant within-group increases in rear leg isometric quadriceps strength (BFR: $p = .012$; GLE: $p = .028$) (Table 5). The between-group comparison of Δ in front leg strength yielded a small-to-medium effect favoring BFR ($r = 0.28$, 95% CI: -0.30 to 0.70; $\Delta BFR = 3.13 \pm 7.66$ kg vs. $\Delta GLE = -4.30 \pm 11.93$ kg), although this did not reach significance ($p = .345$). The between-group difference in rear leg strength was smaller ($r = 0.21$, 95% CI: -0.36 to 0.66; $p = .491$), as both groups demonstrated comparable gains.

Static balance

No significant within-group or between-group differences were observed in any static balance variable (all $p > .05$) (Table 6). Effect sizes for between-group comparisons were small and consistently negative, ranging from $r = -0.17$ (95% CI: -0.64 to 0.39) to $r = -0.28$ (95% CI: -0.70 to 0.30), indicating no meaningful advantage of BFR training over GLE training for static balance.

Discussion

The purpose of this study was to compare the effects of low-load BFR training and traditional high-load GLE training on lower limb kinematics during the fencing lunge, quadriceps strength, and balance in collegiate fencers. The primary analysis focused on between-group comparisons of change scores (Δ), with effect sizes (Rank-biserial r) and 95% CIs used as the principal measures of treatment effect. This approach was adopted because conventional significance testing is highly sensitive to sample size, and the present study, while adequately powered for large effects ($r = 0.52$), was underpowered to detect the medium-to-large effects ($r = 0.3 - 0.5$) observed across many outcome variables.

The training protocols differed in intensity and volume. The BFR group followed a low-load regimen (30% of 1RM) using a 30/15/15/15 repetition scheme consistent with established BFR protocols (Patterson et al., 2019), designed to maximize intramuscular metabolic stress and thereby enhance protein synthesis and muscle fiber recruitment (Scott et al., 2016). In contrast, the GLE group performed traditional high-load training (70% of 1RM). Previous meta-analyses have suggested that low-load BFR training produces comparable hypertrophic effects to conventional high-load training (Loenneke et al., 2012; De Queiros et al., 2024), while imposing substantially less mechanical stress on the joints.

Table 1. General characteristics.

Variables	BFR (n = 8)	GLE (n = 6)	Z (p)
Age (year)	21.38 \pm 1.06	20.83 \pm 1.33	.954 (.414)
Height (cm)	180.50 \pm 4.66	180.67 \pm 2.81	.261 (.852)
Weight (kg)	75.13 \pm 4.12	75.50 \pm 4.76	.587 (.573)
Athletic experience (year)	7.63 \pm 1.06	7.67 \pm 1.51	.287 (.852)

Table 2. Hip and knee joint angles and angular velocities in Phase 1.

Variables		BFR (n = 8)	GLE (n = 6)	Z (p)	Effect size r (95%CI)
Front Leg Hip Flexion Angle (°)	Pre	53.75 ± 10.19	67.88 ± 12.21	1.936 (.059)	
	Post	57.74 ± 4.31	58.15 ± 12.46	.000 (1.000)	
	Z (p)	.420 (.674)	1.153 (.249)		
	Diff (Δ)	3.99 ± 9.92	-9.73 ± 16.87	1.162 (.282)	-.31 (-.72~.26)
Front Leg Hip Flexion Velocity (°/s)	Pre	123.86 ± 37.11	143.07 ± 40.51	.904 (.414)	
	Post	127.52 ± 37.27	110.66 ± 16.96	1.162 (.282)	
	Z (p)	.560 (.575)	1.782 (.075)		
	Diff (Δ)	3.66 ± 23.97	-32.41 ± 46.75	1.549 (.142)	.41 (-.15~.77)
Front Leg Hip Extension Velocity (°/s)	Pre	-19.03 ± 13.36	-11.94 ± 35.78	.000 (1.000)	
	Post	-9.43 ± 18.55	-19.49 ± 9.60	.904 (.414)	
	Z (p)	1.400 (.161)	.105 (.917)		
	Diff (Δ)	9.60 ± 20.20	-7.55 ± 41.18	.775 (.491)	.21 (-.36~.66)
Front Leg Knee Flexion Angle (°)	Pre	70.21 ± 17.15	79.43 ± 22.69	.775 (.491)	
	Post	85.69 ± 9.90	79.60 ± 20.77	.516 (.662)	
	Z (p)	1.960 (.050)*	.105 (.917)		
	Diff (Δ)	15.47 ± 17.55	.17 ± 21.24	1.291 (.228)	.35 (-.23~.74)
Front Leg Knee Flexion Velocity (°/s)	Pre	146.85 ± 50.53	171.68 ± 123.54	.516 (.662)	
	Post	196.70 ± 55.96	157.02 ± 46.01	1.291 (.228)	
	Z (p)	1.680 (.093)	.314 (.753)		
	Diff (Δ)	49.85 ± 66.17	-14.66 ± 139.32	1.033 (.345)	.28 (-.30~.70)
Front Leg Knee Extension Velocity (°/s)	Pre	51.84 ± 98.52	76.09 ± 89.07	.645 (.573)	
	Post	47.03 ± 96.72	76.00 ± 112.16	.387 (.755)	
	Z (p)	.280 (.779)	.314 (.753)		
	Diff (Δ)	-4.81 ± 43.91	-.09 ± 132.32	.258 (.852)	-.07 (-.58~.48)
Rear Leg Hip Flexion Angle (°)	Pre	14.54 ± 9.92	12.67 ± 5.99	.387 (.755)	
	Post	19.51 ± 7.11	14.94 ± 8.78	.904 (.414)	
	Z (p)	1.680 (.093)	1.153 (.249)		
	Diff (Δ)	4.97 ± 6.08	2.27 ± 4.62	.904 (.414)	.24 (-.33~.68)
Rear Leg Hip Flexion Velocity (°/s)	Pre	41.49 ± 30.40	43.58 ± 20.87	.129 (.950)	
	Post	87.02 ± 43.15	58.88 ± 27.62	1.291 (.228)	
	Z (p)	2.100 (.036)*	1.572 (.116)		
	Diff (Δ)	45.53 ± 45.53	15.30 ± 22.58	1.678 (.108)	.45 (-.11~.79)
Rear Leg Hip Extension Velocity (°/s)	Pre	78.21 ± 34.98	92.38 ± 76.81	.387 (.755)	
	Post	91.77 ± 28.74	98.14 ± 19.84	1.033 (.345)	
	Z (p)	.700 (.484)	.105 (.917)		
	Diff (Δ)	13.56 ± 39.41	5.75 ± 59.42	.516 (.662)	.14 (-.42~.62)
Rear Leg Knee Flexion Angle (°)	Pre	55.76 ± 9.78	56.54 ± 4.67	.904 (.414)	
	Post	60.84 ± 7.48	55.19 ± 10.79	.516 (.662)	
	Z (p)	2.100 (.036)*	.105 (.917)		
	Diff (Δ)	5.07 ± 5.70	-.35 ± 10.02	1.033 (.345)	.28 (-.30~.70)
Rear Leg Knee Flexion Velocity (°/s)	Pre	90.05 ± 22.05	90.69 ± 38.48	.387 (.755)	
	Post	150.77 ± 40.60	135.38 ± 50.81	.775 (.491)	
	Z (p)	2.521 (.012)*	1.572 (.116)		
	Diff (Δ)	60.72 ± 32.05	44.70 ± 62.61	1.162 (.282)	.31 (-.26~.72)
Rear Leg Knee Extension Velocity (°/s)	Pre	.77 ± 4.31	1.01 ± 7.99	.904 (.414)	
	Post	9.56 ± 5.53	5.04 ± 9.35	1.033 (.345)	
	Z (p)	2.521 (.012)*	1.153 (.249)		
	Diff (Δ)	8.79 ± 6.10	4.03 ± 7.87	1.162 (.282)	.31 (-.26~.72)

All values are presented as Mean ± SD; BFR: Blood Flow Restriction; GLE: General Leg Extension; *p < 0.05.

The most salient finding of this study was the consistent pattern of medium-to-large effect sizes favoring BFR across rear leg kinematic variables in all three phases of the fencing lunge. While only two between-group comparisons reached statistical significance (front leg knee flexion angle in Phase 2, $p = .043$; rear leg hip extension angular velocity in Phase 3, $p = .029$), the majority of kinematic variables suggested effect sizes of $r \geq 0.3$ with CIs

predominantly shifted toward favoring BFR. However, given that most CIs crossed zero and statistical significance was not reached, these findings should be interpreted as exploratory and preliminary, and cannot be taken as definitive evidence of systematic benefits.

In Phase 1, the between-group Δ comparison revealed medium-to-large effects in front leg hip flexion angular velocity ($r = 0.41$) and rear leg hip flexion angular

velocity ($r = 0.45$) and a medium effect in front leg knee flexion angle ($r = 0.35$). Phase 1 involves the generation of propulsion through eccentric contraction of the quadriceps as the rear knee flexes (Kim et al., 2011). The medium-to-large effect sizes observed in this phase indicate that BFR training may enhance the preparatory loading mechanism

of the rear leg more effectively than traditional high-load training. The concurrent increase in rear leg knee extension angular velocity ($r = 0.31$) further suggests that BFR training facilitates a more rapid and powerful extension, which is critical for generating propulsion during the fencing lunge.

Table 3. Hip and knee joint angles and angular velocities in Phase 2.

Variables		BFR (n = 8)	GLE (n = 6)	Z (p)	Effect size r (95%CI)
Front Leg Hip Flexion Angle (°)	Pre	67.06 ± 11.75	74.48 ± 17.17	.516 (.662)	
	Post	73.91 ± 9.76	72.47 ± 23.89	.645 (.573)	
	Z (p)	1.260 (.208)	.105 (.917)		
	Diff (Δ)	6.83 ± 12.93	-2.01 ± 17.57	1.033 (.345)	.28 (-.30~.70)
Front Leg Hip Flexion Velocity (°/s)	Pre	157.09 ± 61.90	200.79 ± 111.99	.516 (.662)	
	Post	193.65 ± 53.22	177.49 ± 114.64	.258 (.852)	
	Z (p)	1.120 (.263)	.943 (.345)		
	Diff (Δ)	36.56 ± 82.95	-23.31 ± 58.53	1.420 (.181)	.38 (-.19~.76)
Front Leg Hip Extension Velocity (°/s)	Pre	114.81 ± 73.48	66.82 ± 88.26	1.291 (.228)	
	Post	98.31 ± 85.84	71.52 ± 95.32	.645 (.573)	
	Z (p)	.420 (.674)	.314 (.753)		
	Diff (Δ)	-16.50 ± 75.04	4.70 ± 65.92	.645 (.573)	-.17 (-.64~.39)
Front Leg Knee Flexion Angle (°)	Pre	66.44 ± 22.31	70.01 ± 27.79	.258 (.852)	
	Post	84.15 ± 12.95	75.61 ± 25.46	.387 (.755)	
	Z (p)	2.100 (.036)*	.943 (.345)		
	Diff (Δ)	17.71 ± 19.75	5.59 ± 22.65	2.066 (.043)*	.55 (.03~.84)
Front Leg Knee Flexion Velocity (°/s)	Pre	173.50 ± 109.21	252.08 ± 206.94	.387 (.755)	
	Post	228.34 ± 102.92	246.29 ± 139.21	.387 (.755)	
	Z (p)	1.400 (.161)	.105 (.917)		
	Diff (Δ)	54.84 ± 116.34	-5.79 ± 125.27	.904 (.414)	.24 (-.33~.68)
Front Leg Knee Extension Velocity (°/s)	Pre	382.79 ± 151.44	424.24 ± 284.14	.129 (.950)	
	Post	483.08 ± 169.19	459.82 ± 222.73	.258 (.852)	
	Z (p)	1.680 (.093)	.734 (.463)		
	Diff (Δ)	100.30 ± 116.35	35.58 ± 108.82	1.291 (.228)	.35 (-.23~.74)
Rear Leg Hip Flexion Angle (°)	Pre	10.09 ± 10.40	11.84 ± 8.96	.387 (.755)	
	Post	14.65 ± 8.63	11.19 ± 8.06	.645 (.573)	
	Z (p)	1.400 (.161)	.105 (.917)		
	Diff (Δ)	4.55 ± 8.12	-.65 ± 9.22	1.162 (.282)	.31 (-.26~.72)
Rear Leg Hip Flexion Velocity (°/s)	Pre	59.66 ± 51.30	58.51 ± 21.33	.129 (.950)	
	Post	59.48 ± 30.09	62.42 ± 37.60	.387 (.755)	
	Z (p)	.000 (1.000)	.314 (.753)		
	Diff (Δ)	-.17 ± 40.72	3.91 ± 36.03	.258 (.852)	-.07 (-.58~.48)
Rear Leg Hip Extension Velocity (°/s)	Pre	187.47 ± 48.8	218.81 ± 16.86	1.936 (.059)	
	Post	179.83 ± 41.90	200.61 ± 28.56	1.033 (.345)	
	Z (p)	1.120 (.263)	1.153 (.249)		
	Diff (Δ)	-7.64 ± 24.20	-18.19 ± 27.94	.645 (.573)	.17 (-.39~.64)
Rear Leg Knee Flexion Angle (°)	Pre	55.66 ± 9.79	57.34 ± 5.43	1.033 (.345)	
	Post	60.67 ± 7.53	56.19 ± 10.53	.516 (.662)	
	Z (p)	2.100 (.036)*	.105 (.917)		
	Diff (Δ)	5.01 ± 5.63	-1.15 ± 11.69	1.033 (.345)	.28 (-.30~.70)
Rear Leg Knee Flexion Velocity (°/s)	Pre	-2.76 ± 3.73	-3.28 ± 3.78	.129 (.950)	
	Post	-2.38 ± 5.33	2.56 ± 7.13	1.291 (.228)	
	Z (p)	.000 (1.000)	.943 (.345)		
	Diff (Δ)	.38 ± 5.05	5.84 ± 9.74	1.033 (.345)	-.28 (-.70~.30)
Rear Leg Knee Extension Velocity (°/s)	Pre	368.61 ± 88.02	373.61 ± 45.02	.516 (.662)	
	Post	368.36 ± 77.38	387.67 ± 68.05	.387 (.755)	
	Z (p)	.420 (.674)	.105 (.917)		
	Diff (Δ)	-.25 ± 43.98	14.06 ± 61.22	.516 (.662)	-.14 (-.62~.42)

All values are presented as Mean ± SD; BFR: Blood Flow Restriction; GLE: General Leg Extension; *p < 0.05.

Table 4. Hip and knee joint angles and angular velocities in Phase 3.

Variables		BFR (n = 8)	GLE (n = 6)	Z (p)	Effect size r (95%CI)
Front Leg Hip Flexion Angle (°)	Pre	95.45 ± 23.49	113.25 ± 18.55	1.291 (.228)	
	Post	103.37 ± 11.47	111.04 ± 17.56	1.291 (.228)	
	Z (p)	1.120 (.263)	.524 (.600)		
	Diff (Δ)	7.93 ± 17.85	-2.20 ± 14.05	1.033 (.345)	.28 (-.30~.70)
Front Leg Hip Flexion Velocity (°/s)	Pre	271.99 ± 90.28	297.42 ± 96.99	.516 (.662)	
	Post	296.72 ± 39.34	296.56 ± 105.43	.645 (.573)	
	Z (p)	.840 (.401)	.105 (.917)		
	Diff (Δ)	24.73 ± 78.10	-.86 ± 73.76	.516 (.662)	.14 (-.42~.62)
Front Leg Hip Extension Velocity (°/s)	Pre	35.92 ± 39.45	34.26 ± 16.71	.258 (.852)	
	Post	31.79 ± 20.45	25.62 ± 24.49	.775 (.491)	
	Z (p)	.560 (.575)	.734 (.463)		
	Diff (Δ)	-4.13 ± 38.01	-8.64 ± 30.43	.129 (.950)	.03 (-.51~.55)
Front Leg Knee Flexion Angle (°)	Pre	-3.76 ± 10.16	4.57 ± 12.01	1.291 (.228)	
	Post	4.90 ± 7.52	-1.84 ± 9.58	1.420 (.181)	
	Z (p)	2.100 (.036)*	1.363 (.173)		
	Diff (Δ)	8.66 ± 9.93	-6.41 ± 10.82	1.963 (.059)	.52 (-.01~.83)
Front Leg Knee Flexion Velocity (°/s)	Pre	41.79 ± 20.76	52.89 ± 37.19	.000 (1.000)	
	Post	76.47 ± 38.13	78.05 ± 44.90	.000 (1.000)	
	Z (p)	2.100 (.036)*	1.363 (.173)		
	Diff (Δ)	34.67 ± 32.87	25.17 ± 48.86	.645 (.573)	.17 (-.39~.64)
Front Leg Knee Extension Velocity (°/s)	Pre	52.49 ± 26.51	29.83 ± 38.65	1.291 (.228)	
	Post	31.47 ± 29.66	38.22 ± 35.91	.516 (.662)	
	Z (p)	1.540 (.123)	.105 (.917)		
	Diff (Δ)	-21.03 ± 30.79	8.40 ± 29.49	2.195 (.029)*	-.59 (-.85~-.08)
Rear Leg Hip Flexion Angle (°)	Pre	87.43 ± 17.57	95.76 ± 19.39	.387 (.755)	
	Post	90.29 ± 18.77	95.06 ± 10.28	.387 (.755)	
	Z (p)	.140 (.889)	.734 (.463)		
	Diff (Δ)	2.86 ± 18.09	-.70 ± 17.14	.516 (.662)	.14 (-.42~.62)
Rear Leg Hip Flexion Velocity (°/s)	Pre	415.40 ± 62.87	439.74 ± 84.43	.387 (.755)	
	Post	447.68 ± 46.26	454.36 ± 73.30	.516 (.662)	
	Z (p)	1.400 (.161)	.105 (.917)		
	Diff (Δ)	32.29 ± 79.37	14.62 ± 138.72	.258 (.852)	.07 (-.48~.58)
Rear Leg Hip Extension Velocity (°/s)	Pre	-1.30 ± 2.65	.65 ± 4.46	1.291 (.228)	
	Post	-.86 ± 3.45	.87 ± 2.61	.775 (.491)	
	Z (p)	.280 (.779)	.734 (.463)		
	Diff (Δ)	.44 ± 4.96	.22 ± 5.41	.129 (.950)	.03 (-.51~.55)
Rear Leg Knee Flexion Angle (°)	Pre	11.64 ± 11.64	14.04 ± 12.61	.258 (.852)	
	Post	26.75 ± 14.62	19.07 ± 13.49	.258 (.852)	
	Z (p)	2.521 (.012)*	.943 (.345)		
	Diff (Δ)	15.11 ± 9.14	5.03 ± 15.01	1.420 (.181)	.38 (-.19~.76)
Rear Leg Knee Flexion Velocity (°/s)	Pre	75.18 ± 59.11	86.90 ± 62.78	.387 (.755)	
	Post	153.54 ± 99.13	152.31 ± 81.17	.129 (.950)	
	Z (p)	2.380 (.017)*	1.572 (.116)		
	Diff (Δ)	78.36 ± 59.71	65.41 ± 96.62	.387 (.755)	.10 (-.45~.60)
Rear Leg Knee Extension Velocity (°/s)	Pre	10.02 ± 12.27	2.69 ± 16.26	1.162 (.282)	
	Post	-6.59 ± 19.33	3.56 ± 16.02	1.162 (.282)	
	Z (p)	1.960 (.050)*	.105 (.917)		
	Diff (Δ)	-16.60 ± 19.13	.87 ± 23.11	1.162 (.282)	-.31 (-.72~.26)

All values are presented as Mean ± SD; BFR: Blood Flow Restriction; GLE: General Leg Extension; *p < 0.05.

In Phase 2, the only statistically significant between-group difference was observed in front leg knee flexion angle ($r = 0.55$, $p = .043$). This finding is consistent with previous biomechanical analyses of the fencing lunge (Gholipour et al., 2008), in which greater front knee flexion during the thrust phase serves as a preparatory motion for powerful extension and facilitates quadriceps stretching. The BFR group also suggested medium effects in front leg

hip flexion angular velocity ($r = 0.38$) and rear leg knee flexion angle ($r = 0.28$), suggesting a broader pattern of improved joint excursion during the propulsion phase.

Phase 3 yielded the strongest evidence for differential training effects. The between-group difference in rear leg hip flexion angle produced the largest effect observed in this study ($r = 0.52$, 95% CI: -0.01 to 0.83), and was the only kinematic variable for which the 95% CI excluded

Table 5. Isometric quadriceps strength.

Variables		BFR (n = 8)	GLE (n = 6)	Z (p)	Effect size r (95%CI)
Front Leg (kg)	Pre	38.58 ± 6.51	44.93 ± 11.92	1.033 (.345)	
	Post	41.71 ± 8.16	40.64 ± 7.39	.258 (.852)	
	Z (p)	1.120 (.263)	.524 (.600)		
	Diff (Δ)	3.13 ± 7.66	-4.30 ± 11.93	1.033 (.345)	.28 (-.30~.70)
Rear Leg (kg)	Pre	33.83 ± 7.22	35.60 ± 13.40	.129 (.950)	
	Post	44.59 ± 5.43	43.60 ± 10.33	.775 (.491)	
	Z (p)	2.521 (.012)*	2.201 (.028)*		
	Diff (Δ)	10.76 ± 7.34	8.00 ± 6.36	.775 (.491)	.21 (-.36~.66)

All values are presented as Mean ± SD; BFR: Blood Flow Restriction; GLE: General Leg Extension; *p < 0.05.

zero. This finding indicates that BFR training substantially enhanced hip flexion during the landing phase, which is functionally important for decelerating the body and retracting the rear leg after the lunge. The large negative effect in rear leg hip extension angular velocity ($r = -0.59$, $p = .029$) further supports this interpretation, as the reduction in extension velocity likely reflects a shift toward greater flexion-dominant movement patterns. Previous studies have suggested that hamstring activation during landing aids in body stabilization through rapid leg retraction (Guilhem et al., 2014; Li et al., 2023), and the present findings suggest that BFR training may enhance this capacity. Additional medium effects were observed in rear leg knee flexion angle ($r = 0.38$) and knee extension angular velocity ($r = -0.31$), forming a coherent pattern of enhanced rear leg flexion control during the landing phase.

Both groups exhibited significant within-group improvements in rear leg quadriceps strength, with the BFR group showing a slightly larger gain ($\Delta = 10.76 \pm 7.34$ kg vs. $\Delta_{GLE} = 8.00 \pm 6.36$ kg; $r = 0.21$). Of particular interest was the between-group effect on front leg strength ($r = 0.28$, 95% CI: -0.30 to 0.70), where the BFR group gained 3.13 kg while the GLE group lost 4.30 kg. Although this difference was not statistically significant ($p = .345$), the small-to-medium effect size suggests a possible protective or enhancing effect of BFR training on the front leg. The preferential rear leg strength gains in both groups are consistent with the rear leg's primary role in generating propulsion during the fencing lunge (Turner et al., 2013) and with findings that BFR has greater effects on muscles subjected to high metabolic demand (Abe et al., 2005). This divergence in front leg strength likely stems from the inter-

vention's timing and mechanical load. Post-season accumulated fatigue may have rendered the GLE group high-load training (70% of 1RM) an excessive stressor, leading to non-functional overreaching.

No meaningful improvements were observed in static balance, with small negative effect sizes ($r = -0.17$ to -0.28) indicating no advantage for either training conditions. Several factors may explain this null finding. First, the leg extension exercise is an open kinetic chain movement that provides limited proprioceptive challenge (Kwon et al., 2013). Second, BFR preferentially recruits fast-twitch muscle fibers (Scott et al., 2015), which contribute less to the fine postural adjustments required for balance. Third, collegiate fencers likely possess well-developed baseline balance due to years of sport-specific conditioning, which may create a ceiling effect that reduces the sensitivity of static balance assessments (Miller et al., 2015; Paillard, 2014). This aligns with the understanding that elite athletes, who already maintain postural stability within optimal clinical ranges despite the asymmetric demands of their sport, find it increasingly difficult to achieve further performance gains through training (Cieslinski et al., 2024).

Taken together, these findings indicate that low-load BFR training produces medium-to-large effects on rear leg kinematics during the fencing lunge and quadriceps strength that are comparable to or exceed those of traditional high-load training. From a practical standpoint, BFR training may offer particular advantages for fencers during in-season periods or rehabilitation, when minimizing joint loading is a priority (Scott et al., 2016).

Table 6. Static balance.

Variables		BFR (n = 8)	GLE (n = 6)	Z (p)	Effect size r (95%CI)	
Velocity Average (cm/s)	Front Leg	Pre	4.24 ± .96	4.79 ± .96	1.162 (.282)	
		Post	4.51 ± 1.03	5.23 ± 1.38	.775 (.491)	
		Z (p)	.700 (.484)	1.363 (.173)		
		Diff (Δ)	.26 ± .85	.44 ± .70	.645 (.573)	-.17 (-.64~.39)
	Rear Leg	Pre	4.73 ± .96	5.14 ± .96	.904 (.414)	
		Post	4.59 ± 1.11	5.17 ± 1.44	.775 (.491)	
		Z (p)	.140 (.889)	.524 (.600)		
		Diff (Δ)	-.14 ± .71	.03 ± .77	.775 (.491)	-.21 (-.66~.36)
Path Length (cm)	Front Leg	Pre	128.31 ± 27.66	141.22 ± 28.44	1.162 (.282)	
		Post	135.27 ± 30.88	156.83 ± 41.36	.645 (.573)	
		Z (p)	.700 (.484)	1.572 (.116)		
		Diff (Δ)	6.96 ± 22.99	15.61 ± 17.36	.645 (.573)	-.17 (-.64~.39)
	Rear Leg	Pre	141.94 ± 28.91	148.83 ± 26.30	.904 (.414)	
		Post	137.66 ± 33.37	155.05 ± 43.29	.645 (.573)	
		Z (p)	.140 (.889)	.943 (.345)		
		Diff (Δ)	-4.27 ± 21.34	6.22 ± 25.66	1.033 (.345)	-.28 (-.70~.30)

All values are presented as Mean ± SD; BFR: Blood Flow Restriction; GLE: General Leg Extension.

From a practical perspective, the observed changes in rear leg kinematics may have meaningful implications for fencing-specific movement patterns. Previous biomechanical studies have demonstrated that rear leg joint function, particularly knee extensor capacity and joint excursion, is closely associated with lunge velocity and horizontal propulsion (Guan et al., 2018). In this context, the kinematic adaptations observed in the present study may reflect movement patterns that support more effective force generation during the fencing lunge. This optimization of force production is likely facilitated by the efficient transfer of localized strength gains into the functional movement pattern. However, the transfer of strength gains to complex, multi-joint movements such as the fencing lunge requires the precisely coordinated action of multiple muscle groups. In this context, neural adaptations, including increased activation and synchronization of higher-threshold motor units and reduced antagonist co-activation, may play an important role in facilitating more efficient force production (Redondo et al., 2014). Consequently, the medium-to-large effects observed in rear leg kinematics may represent a functional manifestation of these underlying neuromuscular improvements, offering fencers a more explosive and controlled lunge execution.

Several limitations warrant consideration. First, the small sample size ($n = 14$ analyzed) limited statistical power, resulting in wide confidence intervals for many effect size estimates. In addition, unequal dropout between groups, particularly in the GLE group, may have introduced attrition bias and further affected the robustness and precision of the estimated effects. Second, the intervention comprised only leg extension exercises, which may not capture the full range of strength adaptations relevant to fencing performance. Third, the study included only male sabre and épée fencers, limiting generalizability to female athletes and foil fencers. Fourth, the BFR protocol employed a single fixed pressure level (130% of resting systolic blood pressure), and individualized Limb Occlusion Pressure (LOP) was not measured due to equipment constraints. As LOP is considered the gold standard for accounting for inter-individual differences in limb circumference and arterial anatomy (Patterson et al., 2019), its absence may have introduced variability in the degree of vascular occlusion across participants. Future comparative studies examining different BFR pressure settings may help identify optimal protocols for athletic populations. Fifth, although effect sizes were used as the primary outcome measure, it remains unclear whether the observed changes translate into meaningful improvements in real-world fencing performance or functional outcomes. Furthermore, the interpretation of effect sizes depends on underlying assumptions, and the use of a very large expected effect size ($d = 1.47$) in the priori power calculation may have led to an overestimation of the study's sensitivity to detect smaller, yet practically meaningful effects. Sixth, the 1RM was not reassessed during the 6-week intervention; therefore, the relative training intensity may have progressively decreased as participants' absolute strength improved, particularly in the latter weeks of the protocol.

Future research should further investigate the movement-specific nature of the observed adaptations.

Given that the present study identified phase-dependent changes in rear leg kinematics during the fencing lunge, it would be valuable to examine how these adaptations vary under different task conditions, such as changes in lunge distance, speed, or target constraints. In addition, future studies should explore the extent to which these kinematic changes are associated with sport-specific performance outcomes, including lunge velocity and accuracy, to better establish their functional relevance. Furthermore, as the present study employed a single BFR condition, future research should investigate the effects of varying cuff pressure and loading parameters to determine optimal training protocols.

Conclusion

This study compared the effects of low-load BFR training and traditional high-load training on fencing lunge kinematics, quadriceps strength, and balance in collegiate fencers. The results suggested that BFR training produced small-to-large effect sizes ($r = 0.24 - 0.55$) favoring improvements in rear leg hip and knee kinematics across all phases of the fencing lunge, with the largest effect observed in rear leg hip flexion angle during the landing phase ($r = 0.52$, 95% CI: -0.01 to 0.83). Both groups achieved comparable rear leg strength gains, while BFR showed a potential advantage for front leg strength ($r = 0.28$). No meaningful effects were observed for static balance.

These findings suggest that low-load BFR training can effectively enhance lower limb kinematics and strength relevant to fencing performance, offering a practical alternative to high-load training that minimizes mechanical stress. Larger confirmatory trials are warranted to verify the observed effects and establish optimal BFR protocols for sport-specific applications.

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References

- Abe, T., Yasuda, T., Midorikawa, T., Sato, Y., Kearns, C.F., Inoue, K., Koizumi, K. and Ishii, N. (2005) Skeletal muscle size and circulation IGF-1 are increased after two weeks of twice daily "KAATSU" resistance training. *International Journal of KAATSU Training Research* **1**, 6–12. <https://doi.org/10.3806/ijtr.1.6>
- Ahmadi, A., Rowlands, D.D. and James, D.A. (2010) Development of inertial and novel marker-based techniques and analysis for upper arm rotational velocity measurements in tennis. *Sports Engineering* **12**, 179–188. <https://doi.org/10.1007/s12283-010-0044-1>
- American College of Sports Medicine (2009) American College of Sports Medicine Position Stand: Progression models in resistance training for healthy adults. *Medicine & Science in Sports & Exercise* **41**, 687–708. <https://doi.org/10.1249/mss.0b013e3181915670>
- Chida, K., Inami, T., Yamaguchi, M., Yoshida, Y. and Kohtake, N. (2023) Relationship between body center of mass velocity and lower

- limb joint angles during advance lunge in skilled male university fencers. *Biomechanics* **3**, 377–388. <https://doi.org/10.3390/biomechanics3030031>
- Cingoz, Y.E., Asan, S. and Ozdemir, B.K. (2023) The effect of training programs applied to fencing athletes on balance and reaction level. *International Journal of Eurasian Education and Culture* **8**, 1849–1861. <https://doi.org/10.35826/ijoecc.701>
- Citaker, S., Kaya, D., Yuksel, I., Yosmaoglu, B., Nyland, J. and Atay, O.A. et al. (2011) Static balance in patients with patellofemoral pain syndrome. *International Journal of Sports Physical Therapy* **3**, 524–527. <https://doi.org/10.1177/1941738111420803>
- De Queiros, V.S., Rolnick, N., Schoenfeld, B.J., De Franca, I.M., Vieira, J.G., Sardeli, A.V., Kamis, O., Neto, G.R., Tinoco Cabral, B.G.A. and Dantas, P.M.S. (2024) Hypertrophic effects of low-load blood flow restriction training with different repetition schemes: A systematic review and meta-analysis. *PeerJ* **12**, e17195. <https://doi.org/10.7717/peerj.17195>
- DePhillipo, N.N., Kennedy, M.I., Aman, Z.S., Bernhardtson, A.S., O'Brien, L.T. and LaPrade, R.F. (2018) The role of blood flow restriction therapy following knee surgery: Expert opinion. *Arthroscopy: The Journal of Arthroscopic & Related Surgery* **34**, 2506–2510. <https://doi.org/10.1016/j.arthro.2018.05.038>
- Delgado Garcia, G., Vanrenterghem, J., Ruiz Malagon, E.J., Molina Garcia, P., Courel Ibanez, J. and Soto Hermoso, V.M. (2021) IMU gyroscopes are a valid alternative to 3D optical motion capture system for angular kinematics analysis in tennis. *Journal of Sports Engineering and Technology* **235**, 3–12. <https://doi.org/10.1177/1754337120965444>
- Di Martino, G., Giommoni, S., Esposito, F., Alessandro, D., della Valle, C., Iuliano, E., Fiorilli, G., Calcagno, G. and di Cagno, A. (2024) Enhancing focus and short reaction time in épée fencing: The power of the science vision training academy system. *Functional Morphology and Kinesiology* **9**, 213. <https://doi.org/10.3390/fmk9040213>
- Fahs, C.A., Loenneke, J.P., Thiebaud, R.S., Rossow, L.M., Kim, D.Y., Abe, T., Beck, T.W., Feeback, D.L., Bemben, D.A. and Bemben, M.G. (2015) Muscular adaptations to fatiguing exercise with and without blood flow restriction. *Clinical Physiology and Functional Imaging* **35**, 167–176. <https://doi.org/10.1111/cpf.12141>
- Gholipour, M., Tabrizi, A. and Farahmand, F. (2008) Kinematic analysis of lunge fencing using stereophotogrametry. *World Journal of Sport Sciences* **1**, 32–37. <https://doi.org/10.61186/ajsmt.22.27.1>
- Giles, L., Webster, K.E., McClelland, J. and Cook, J.L. (2017) Quadriceps strengthening with and without blood flow restriction in the treatment of patellofemoral pain: A double-blind randomised trial. *British Journal of Sports Medicine* **51**, 1688–1694. <https://doi.org/10.1136/bjsports-2016-096329>
- Guan, Y., Guo, L., Wu, N., Zhang, L. and Warburton, D.E.R. (2018) Biomechanical insight into the determinants of speed in the fencing lunge. *European Journal of Sport Science* **18**, 201–208. <https://doi.org/10.1080/17461391.2017.1414886>
- Guilhem, G., Giroux, C., Couturier, A., Chollet, D. and Rabita, G. (2014) Mechanical and muscular coordination patterns during a high-level fencing assault. *The American Journal of Sports Medicine* **46**, 341–350. <https://doi.org/10.1249/mss.0b013e3182a6401b>
- Karagiannopoulos, C., Griech, S. and Leggin, B. (2022) Reliability and validity of the ActiveForce digital dynamometer in assessing shoulder muscle force across different user experience levels. *Journal of Sports Physical Therapy* **17**, 669–676. <https://doi.org/10.26603/001c.35577>
- Kim, H., Kum, D.M. and Shin, W.S. (2022) Reliability and validity of Balancia 2.5 program using Wii balance board for assessment of static balance ability. *Physical Therapy Rehabilitation Science* **11**, 488–492. <https://doi.org/10.14474/ptrs.2022.11.4.488>
- Kim, K.H. and Kim, T.G. (2014) Correlation of isokinetic strength and angular velocity of knee during fente motion in elite fencer. *Journal of Digital Convergence* **12**, 407–415. <https://doi.org/10.14400/jdc.2014.12.9.407>
- Kim, T.G., Kim, E.K., Park, J.C. and Kang, H. (2011) The effect of mild symptomatic patellar tendinopathy on the quadriceps contractions and the fente motion in elite fencers. *Journal of Sports Science and Medicine* **10**, 700–706. <https://doi.org/10.1111/j.1600-0838.2011.01400.x>
- Korkmaz, E., Gurhan, D., Kubilay, U., Naila, B., Serife Seyma, T. and Levent, O. (2022) Effects of blood flow restriction training on muscle strength and architecture. *Journal of Strength and Conditioning Research* **36**, 1396–1403. <https://doi.org/10.1519/jsc.0000000000003612>
- Kwon, Y.J., Park, S.J. and Jefferson, J. (2013) The effect of open and closed kinetic chain exercises on dynamic balance ability of normal healthy adults. *Journal of Physical Therapy Science* **25**, 671–674. <https://doi.org/10.1589/jpts.25.671>
- Li, X., Li, J., Qing, L., Wang, H., Ma, H. and Huang, P. (2023) Effect of quadriceps training at different levels of blood flow restriction on quadriceps strength and thickness in the mid-term postoperative period after anterior cruciate ligament reconstruction: A randomized controlled external pilot study. *BMC Musculoskeletal Disorders* **24**, 360. <https://doi.org/10.1186/s12891-023-06483-x>
- Li, Y., Fu, S., Zhang, D., Liu, M. and Liu, H. (2025) Effect of low-intensity resistance training at different levels of blood flow restriction on pain, proprioception and muscle strength in patients with knee osteoarthritis: a randomized controlled trial. *BMC Musculoskeletal Disorders* **26**, 769. <https://doi.org/10.1186/s12891-025-09051-7>
- Loenneke, J.P., Wilson, J.M., Marin, P.J., Zourdos, M.C. and Bemben, M.G. (2012) Low intensity blood flow restriction training: A meta-analysis. *European Journal of Applied Physiology* **112**, 1849–1859. <https://doi.org/10.1007/s00421-011-2167-x>
- Ludwig, O., Kelm, J., Hammes, A., Schmitt, E. and Frohlich, M. (2020) Neuromuscular performance of balance and posture control in childhood and adolescence. *Heliyon* **6**, e04541. <https://doi.org/10.1016/j.heliyon.2020.e04541>
- Miller, A.I., Heath, E.M., Dickinson, J.M. and Bressel, E. (2015) Relationship between muscle fiber type and reactive balance: A preliminary study. *Journal of Motor Behavior* **47**, 497–502. <https://doi.org/10.1080/00222895.2015.1015676>
- Paillard, T. (2014) Sport-specific balance develops specific postural skills. *Sports Medicine* **44**, 1019–1020. <https://doi.org/10.1007/s40279-014-0174-x>
- Park, K.J. and Byung, S.B. (2017) Injury in elite Korean fencers: An epidemiological study. *British Journal of Sports Medicine* **51**, 220–225. <https://doi.org/10.1136/bjsports-2016-096754>
- Patterson, S.D., Hughes, L., Warrington, S., Burr, J., Scott, B.R., Owens, J., Abe, T., Nielsen, J.L., Libardi, C.A., Laurentino, G., Neto, G.R., Brandner, C., Martin-Hernandez, J. and Loenneke, J. (2019) Blood flow restriction exercise: Considerations of methodology, application, and safety. *Frontiers in Physiology* **10**, 533. <https://doi.org/10.3389/fphys.2019.00533>
- Piche, E., Guilbot, M., Chorin, F., Guerin, O., Zory, R. and Gerus, P. (2022) Validity and repeatability of a new inertial measurement unit system for gait analysis on kinematic parameters: Comparison with an optoelectronic system. *Measurement* **198**, 111442. <https://doi.org/10.1016/j.measurement.2022.111442>
- Redondo, J.C., Alonso, C.J., Sedano, S. and de Benito, A.M. (2014) Effects of a 12-week strength training program on experimented fencers' movement time. *Journal of Strength and Conditioning Research* **28**, 3375–3384. <https://doi.org/10.1519/jsc.0000000000000581>
- Scott, B.R., Loenneke, J.P., Slatery, K.M. and Dascombe, B.J. (2015) Exercise with blood flow restriction: An updated evidence-based approach for enhanced muscular development. *Sports Medicine* **45**, 313–325. <https://doi.org/10.1007/s40279-014-0288-1>
- Scott, B.R., Loenneke, J.P., Slatery, K.M. and Dascombe, B.J. (2016) Blood flow restricted exercise for athletes: A review of available evidence. *Journal of Science and Medicine in Sport* **19**, 360–367. <https://doi.org/10.1016/j.jsams.2015.04.014>
- Shinohara, M., Kouzaki, M., Yoshihisa, T. and Fukunaga, T. (1998) Efficacy of tourniquet ischemia for strength training with low resistance. *European Journal of Applied Physiology and Occupational Physiology* **77**, 189–191. <https://doi.org/10.1007/s004210050319>
- Suga, T., Okita, K., Morita, N., Yokota, T., Hirabayashi, K., Horiuchi, M., Takada, S., Omokawa, M., Kinugawa, S. and Tsutsui, H. (2010) Dose effect on intramuscular metabolic stress during low-intensity resistance exercise with blood flow restriction. *Journal of Applied Physiology* **108**, 1563–1567. <https://doi.org/10.1152/jappphysiol.00504.2009>
- Takano, H., Morita, T., Iida, H., Asada, K., Kato, M., Uno, K., Hirose, K., Matsumoto, A., Takenaka, K., Hirata, Y., Eto, F., Nagai, R., Sato, Y. and Nakajima, T. (2005) Hemodynamic and hormonal responses to a short-term low-intensity resistance exercise with the reduction of muscle blood flow. *European Journal of Applied Physiology* **95**, 65–73. <https://doi.org/10.1007/s00421-005-1389-1>

- Topley, M. and Richards, J.G. (2020) A comparison of currently available optoelectronic motion capture systems. *Journal of Biomechanics* **106**, 109820. <https://doi.org/10.1016/j.jbiomech.2020.109820>
- Turner, A., Miller, S., Stewart, P., Cree, J., Ingram, R., Dimitriou, L., Moody, J. and Kilduff, L. (2013) Strength and conditioning for fencing. *Strength and Conditioning Journal* **35**, 1–9. <https://doi.org/10.1519/ssc.0b013e31826e7283>
- van der Kruk, E. and Reijne, M.M. (2018) Accuracy of human motion capture systems for sport applications: State of the art review. *European Journal of Sport Science* **18**, 806–819. <https://doi.org/10.1080/17461391.2018.1463397>
- Wang, H., Ji, Z., Jiang, G., Liu, W. and Jiao, X. (2016) Correlation among proprioception, muscle strength, and balance. *Journal of Physical Therapy Science* **28**, 3468–3472. <https://doi.org/10.1589/jpts.28.3468>
- Weygers, I., Kok, M., Konings, M., Hallez, H., De Vroey, H. and Claeys, K. (2020) Inertial sensor-based lower limb joint kinematics: A methodological systematic review. *Sensors* **20**, 673. <https://doi.org/10.3390/s20030673>
- Wortman, R.J., Brown, S.M., Elliot, I.S., Finley, Z.J. and Mulcahey, M.K. (2020) Blood flow restriction training for athletes: A systematic review. *The American Journal of Sports Medicine* **49**, 1–7. <https://doi.org/10.1177/0363546520964454>
- Yamanaka, T., Farley, R.S. and Caputo, J.L. (2012) Occlusion training increases muscular strength in division IA football players. *The Journal of Strength & Conditioning Research* **26**, 2523–2529. <https://doi.org/10.1519/jsc.0b013e31823f2b0e>

Key points

- Little is known about how specific training interventions affect lower limb kinematics during the fencing lunge.
- Six weeks of low-load BFR quadriceps training may have produced small-to-large improvements in rear leg kinematics across all three phases of the fencing lunge in collegiate fencers ($r = 0.24 - 0.52$).
- The strongest evidence of a differential training effect was observed in rear leg hip flexion angle during the final phase ($r = 0.52$; 95% CI = $-0.01 - 0.83$).
- Both BFR and traditional training improved rear leg quadriceps strength; however, BFR training showed a greater increase in front leg strength ($r = 0.28$).
- Low-load BFR training may serve as a joint-friendly alternative to high-load training for enhancing fencing-specific movement kinematics.

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