

Research article

# Effects of Blood Flow Restriction Training at Different Levels of Arterial Occlusion Pressure on Body Composition and Athletic Performance in Youth Soccer Players: A Randomized Controlled Trial

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## Abstract

This study aimed to investigate the effects of low-load blood flow restriction training (BFRT) performed at different levels of arterial occlusion pressure (AOP) on body composition, maximal strength, and athletic performance in youth soccer players. Twenty-four male youth soccer players were randomly assigned to 40% AOP group, 60% AOP group, or control group. Participants in the BFRT groups performed lower-limb resistance training at 30% of one-repetition maximum (1RM) under the corresponding pressure conditions, whereas the control group trained without BFR. Training was conducted three times per week for six weeks. Body composition, back squat 1RM, countermovement jump (CMJ), T-test, and 30-m sprint performance were assessed before and after the intervention. Results showed that lower-limb muscle mass increased significantly in both the 40% AOP group (mean change = 0.55 kg, 95% CI: 0.13 to 0.97 kg,  $P = 0.010$ ) and the 60% AOP group (mean change = 0.83 kg, 95% CI: 0.37 to 1.29 kg,  $P < 0.001$ ), with the 60% AOP group showing significantly greater gains than the control group (between-group difference = 1.48 kg, 95% CI: 0.40 to 2.56 kg,  $P = 0.008$ ). Back squat 1RM improved significantly in both the 40% AOP group (mean change = 6.50 kg, 95% CI: 3.90 to 9.10 kg,  $P < 0.001$ ) and the 60% AOP group (mean change = 9.25 kg, 95% CI: 6.75 to 11.75 kg,  $P < 0.001$ ), with the 60% AOP group demonstrating superior strength gains compared with the 40% AOP group (between-group difference = 2.94 kg, 95% CI: 0.20 to 5.68 kg,  $P = 0.048$ ). CMJ height and T-test performance improved significantly in both the 40% AOP group (CMJ: mean change = 2.07 cm, 95% CI: 0.80 to 3.34 cm,  $P = 0.002$ ; T-test: mean change = -0.23 s, 95% CI: -0.35 to -0.11 s,  $P = 0.001$ ) and the 60% AOP group (CMJ: mean change = 2.65 cm, 95% CI: 1.00 to 4.30 cm,  $P = 0.003$ ; T-test: mean change = -0.26 s, 95% CI: -0.38 to -0.14 s,  $P < 0.001$ ), with no significant differences between the two BFRT groups (all  $P > 0.05$ ). No significant changes were observed in 30-m sprint performance across groups (all  $P > 0.05$ ). This study showed that six weeks of low-load (30% 1RM) blood flow restriction training performed at both 40% and 60% AOP was associated with improvements in lower-limb muscle mass, squat strength, and selected aspects of athletic performance in youth soccer players, compared with low-load training without BFR. While both pressure levels elicited comparable improvements in CMJ and agility performance, training at 60% AOP was associated with greater adaptations in lower-limb muscle mass and squat strength, with no additional benefits observed for 30-m sprint performance.

**Key words:** Blood flow restriction training, adolescent athletes, muscle hypertrophy, squat strength, athletic performance.

## Introduction

Adolescence represents a critical period for the development of physical capacities, during which scientifically designed physical training plays a fundamental role in enhancing long-term athletic performance and reducing injury risk. However, adolescence is characterized by marked variability in biological maturation (e.g., peak height velocity), which can influence strength and hypertrophic responses to resistance training (Retzepis et al., 2025). In competitive sports, soccer is a high-demand, intermittent team sport in which performance is strongly dependent on well-developed lower-limb strength, explosive power, repeated sprint ability, and multidirectional agility (Stølen et al., 2005). Consequently, identifying effective and safe training strategies to optimize physical development in youth soccer players has remained a central focus of sports science research. High-load resistance training ( $\geq 70\%$  1RM) is effective for developing muscular strength and hypertrophy (Kraemer et al., 1990). When properly supervised by qualified professionals, youth resistance training-including at higher intensities-is safe and effective (Faigenbaum and Myer, 2010; Lloyd et al., 2014). However, in settings with suboptimal supervision or inadequate attention to individual readiness and movement quality, concerns regarding cumulative mechanical stress on musculoskeletal structures remain valid (Faigenbaum et al., 2009). International consensus emphasizes prioritizing correct movement patterns and neuromuscular control, with loads increased progressively under qualified supervision (Lloyd et al., 2014). These principles have prompted exploration of alternative modalities-such as BFRT-that may induce neuromuscular adaptations under relatively low mechanical stress, particularly when optimal supervision cannot always be guaranteed.

In recent years, BFRT has gained increasing attention as a novel resistance training method. This approach involves the application of external pressure to the proximal portion of a limb, partially restricting arterial inflow and markedly limiting venous outflow, thereby creating a unique intramuscular environment characterized by localized hypoxia and rapid accumulation of metabolic by-products under low-load conditions (20 - 40% 1RM) (Loenneke et al., 2012). A growing body of evidence indicates that

BFRT, performed under low-load conditions (20 - 40% 1RM), is associated with acute physiological responses such as growth hormone secretion, enhanced muscle protein synthesis, and preferential recruitment of type II muscle fibers. These responses have been linked to muscular hypertrophy and strength gains comparable to those achieved with traditional high-load resistance training (Lixandrão et al., 2018; Scott et al., 2014). Given its “low-load, high metabolic stress” characteristics, BFRT has been proposed as a potentially advantageous training strategy for adolescent athletes, as it may elicit meaningful muscular adaptations while reducing mechanical stress on joints and skeletal structures (Patterson et al., 2019). Importantly, when applied in adolescent populations, appropriate medical screening to identify contraindications, qualified supervision during training, and predefined stopping rules for adverse symptoms are essential to ensure safety (Prue et al., 2022). The effectiveness of BFRT is influenced by multiple variables, among which the magnitude of applied occlusion pressure is considered a key determinant. Previous studies have commonly prescribed relative pressure as a percentage of individually determined AOP to enhance interindividual comparability and safety (Loenneke et al., 2015b). Existing evidence suggests the presence of a potential “pressure-response” window for optimizing BFRT outcomes. For instance, relative pressures of approximately 40 - 50% AOP have been reported to be sufficient to maximize muscle activation during exercise (Loenneke et al., 2015b), whereas excessively high pressures (> 80% AOP) may increase discomfort and overly restrict blood flow, potentially compromising training quality and long-term adherence (Counts et al., 2016). Whether such an optimal pressure range is applicable to adolescent athletes—particularly youth soccer players who require high levels of lower-limb power and multidirectional movement capacity—remains unclear. Although BFRT has demonstrated beneficial effects on muscle function and certain performance outcomes in adult athletic populations, such as handball and rugby players (Yamanaka et al., 2012; Wang et al., 2019), randomized controlled studies systematically comparing the long-term effects of different relative occlusion pressures in youth soccer players are still scarce. Based on the hormesis hypothesis (Loenneke et al., 2014), we selected 40% AOP to represent a moderate pressure within the lower range of the recommended window and 60% AOP to represent a higher pressure approaching the optimal threshold. We hypothesized that 60% AOP would produce greater hypertrophic and strength adaptations compared to 40% AOP, whereas both pressures would yield comparable improvements in power-oriented performance measures (jump and agility) due to potential ceiling effects for these neuromuscular outcomes.

Therefore, the purpose of the present randomized controlled trial was to examine the effects of six weeks of low-load BFRT performed at two different relative pressure levels (40% AOP and 60% AOP) on body composition and key performance indicators, including maximal strength (primary outcome), vertical jump performance, agility, and sprint ability, in youth soccer players. Based on the hormesis hypothesis and existing evidence regarding the pressure-response relationship (Loenneke et al., 2014;

Counts et al., 2016), we hypothesized that both BFRT groups would show improvements in muscle mass, strength, and power-related outcomes compared with the control group, with the possibility that higher occlusion pressure (60% AOP) may confer additional benefits for hypertrophic and strength adaptations. Conversely, we considered that power-oriented outcomes such as vertical jump and agility may be similarly enhanced by both pressure levels, as these adaptations may reach a plateau at moderate pressures. The findings of this study are expected to inform practitioners whether a higher (60% AOP) or moderate (40% AOP) occlusion pressure offers a more favorable efficacy-tolerability trade-off when implementing low-load BFRT in youth soccer players.

## Methods

### Participants

The sample size was calculated using G\*Power software (version 3.1). Based on meta-analyses reporting moderate-to-large effects of BFRT on lower-body strength (Chee et al., 2024) and a minimal clinically important difference of 5 - 7% in back squat 1RM for youth athletes (Luebbers et al., 2019), with an alpha level of 0.05 and statistical power of 0.80, minimum total sample size was 18. Considering potential dropouts, 24 participants were recruited and randomly allocated into three groups. Twenty-four male U16 soccer players were recruited from the China Football School, including four first-class and twenty second-class athletes. All participants and their legal guardians were fully informed of the study procedures and potential risks, and written informed consent was obtained prior to participation. All participants had a training age of  $5.2 \pm 1.8$  years (defined as years of systematic soccer training) and typically engaged in 4 - 5 soccer sessions per week, totaling approximately 8 - 10 hours of weekly soccer activity, consistent with previous reports for elite youth soccer academies (Connolly et al., 2024). Participants were randomly allocated into three groups using a random number table: a 40% AOP group ( $n = 8$ ), a 60% AOP group ( $n = 8$ ), and a control group without BFR ( $n = 8$ ). The distribution of competitive level was balanced across groups (40% AOP: 1 first-class, 7 second-class; 60% AOP: 1 first-class, 7 second-class; Control: 2 first-class, 6 second-class). No significant differences were observed among the three groups in age, height, or body mass at baseline ( $P > 0.05$ ) (Table 1). The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Laboratory of Exercise Science, Beijing Sport University (Approval No. 2022233H). All experimental procedures were conducted at the China Football School under standardized conditions.

**Table 1. Baseline characteristics of participants.**

| Group   | n | Height, cm        | Body mass, kg    | Age, yrs         |
|---------|---|-------------------|------------------|------------------|
| 40% AOP | 8 | $175.28 \pm 7.05$ | $63.09 \pm 5.74$ | $16.49 \pm 0.27$ |
| 60% AOP | 8 | $178.00 \pm 6.46$ | $65.40 \pm 4.36$ | $16.38 \pm 0.24$ |
| Control | 8 | $176.13 \pm 9.16$ | $65.86 \pm 6.89$ | $16.54 \pm 0.21$ |

### Procedures

All participants completed a 6-week lower-limb resistance

training program, three times per week. Each group performed the training with a load of 30% 1RM, under their respective pressure conditions or without blood flow restriction. The training exercises included the back squat, deadlift, and loaded lunge. A wireless blood flow restriction device (Airbands, Australia) was used, with 10-cm-wide cuffs positioned at the proximal third of the thigh in the supine position. Individualized relative pressure levels were determined based on thigh circumference using the arterial occlusion pressure reference chart proposed by Loenneke et al. (2015a) (Table 2), which was derived from prediction equations validated in healthy adults demonstrating that thigh circumference is the strongest independent predictor of lower-limb arterial occlusion pressure. The training protocol consisted of four sets (30, 15, 15, and 15 repetitions), with 60 seconds of rest between sets. This protocol was established in accordance with the optimal loading recommendations for BFRT proposed by Scott et al. (2014). Cuffs were inflated to the target pressure at the beginning of the first set and remained inflated continuously throughout all four sets and the 60-second rest intervals between sets. Total time-under-occlusion per session was approximately 12 - 15 minutes. Tolerability and safety were monitored throughout the intervention (Patterson et al., 2019). At each training session, participants were asked about any discomfort, pain, or adverse sensations (e.g., numbness, excessive soreness, dizziness) related to the BFR procedure. Following each session, participants rated perceived discomfort on Borg CR10 RPE scale, with mean ratings of  $4.2 \pm 1.3$  in the 40% AOP group and  $5.3 \pm 1.6$  in the 60% AOP group. No adverse events were reported in any group during the six-week intervention period. Apart from the experimental intervention, all groups followed identical training schedules, recovery strategies, and dietary regimens. To verify standardization, external training load was monitored using session-RPE recorded 30 minutes post-training, and weekly training logs were maintained to ensure consistency across groups (Anderegg et al., 2025). Dietary standardization was achieved through provision of standardized meals at the China Football School canteen, with compliance verified via weekly food logs completed by participants and reviewed by research staff. Pre- and post-intervention testing procedures, personnel, and equipment were consistent across all measurements.

**Table 2.** Correspondence between thigh circumference and relative arterial occlusion pressure.

| Thigh circumference | Pressure (40% AOP) | Pressure (60% AOP) |
|---------------------|--------------------|--------------------|
| < 51 cm             | 80 mmHg            | 120 mmHg           |
| 51 - 55.9 cm        | 100 mmHg           | 150 mmHg           |
| 56 - 59.9 cm        | 120 mmHg           | 180 mmHg           |
| ≥ 60 cm             | 140 mmHg           | 210 mmHg           |

### Outcome measures

Body composition variables, including body mass, body fat percentage, and lower-limb muscle mass, were assessed using a multi-frequency bioelectrical impedance analyzer (InBody 770, Korea). This device has demonstrated high test-retest reliability in physically active populations, with an intraclass correlation coefficient (ICC)  $\geq 0.999$  for

whole-body mass measurements (Looney et al., 2024). Measurements were conducted in the morning under standardized conditions: participants refrained from strenuous exercise for > 48 h, alcohol consumption for > 24 h, and caffeine, nicotine, and food for > 10 h prior to testing (Looney et al., 2024).

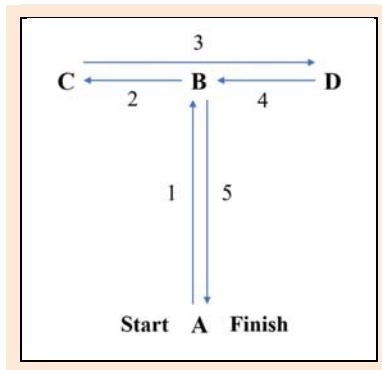
Back squat 1RM was assessed using a linear position transducer (GymAware, Australia) in combination with the load-velocity profiling method. Participants performed incremental loads (starting at approximately 50% of estimated 1RM, with increases of 10 - 20 kg) while mean concentric velocity was recorded for each repetition. Individual load-velocity relationships were established using linear regression ( $\text{velocity} = a + b \times \text{load}$ ), and back squat 1RM was predicted by extrapolating to a velocity threshold of  $0.5 \text{ m} \cdot \text{s}^{-1}$ , consistent with the submaximal velocity method commonly used in 1RM prediction research (Macarilla et al., 2022). The goodness of fit for individual load-velocity profiles ( $R^2$ ) ranged from 0.92 to 0.99 across participants, indicating strong linear relationships. The predictive validity of this method for back squat has been established in resistance-trained individuals, with Thompson et al. (2021) reporting that all predictive models yielded a standard error of the estimate below 5 kg and correlation coefficients exceeding 0.97.

CMJ performance was evaluated using a vertical jump assessment system (Ezejump, Australia). Testing procedures followed the standardized CMJ protocol described by Markovic et al. (2004). Participants stood on the force platform with feet shoulder-width apart, performed a rapid countermovement to approximately parallel thigh position, and then executed a maximal vertical jump with arm swing. Three trials were performed with 60 seconds of rest between attempts, and the highest jump height was recorded for analysis. Using baseline data from all 24 participants, the mean coefficient of variation (CV%) for CMJ height was 2.4% (range: 1.1% - 4.2%).

Sprint performance was assessed on a soccer field using an infrared timing system (Swift Speedlight Timing System, Australia). The testing protocol followed the procedures described by Cronin and Templeton (2008). Infrared sensors were placed at the start and finish lines of the 30-m sprint at hip height. Participants performed a standing start. Three trials were completed with three minutes of rest between sprints, and the fastest time was used for statistical analysis. The mean CV% for 30-m sprint time was 1.1% (range: 0.6% - 1.8%).

Agility performance was evaluated using the T-test, administered with the same infrared timing system (Swift Speedlight Timing System, Australia). The testing layout followed the protocol described by Sporis et al. (2010). The distance between point A and point B was set at 10 m, and the distances between point B and points C and D were each 5 m. Infrared sensors were placed at the start and finish lines, spaced 1 m apart. Participants performed a standing start, sprinted forward to touch the marker at point B, side-shuffled to touch point C, side-shuffled in the opposite direction to touch point D, returned to point B via lateral shuffle, and finally backpedaled to the finish line (Figure 1). Three trials were performed with three minutes of rest between attempts, and the best performance was retained.

The mean CV% for T-test time was 3.5% (range: 2.3% - 4.9%).



**Figure 1.** T-test layout.

### Statistical analysis

Statistical analyses were performed using SPSS (version 26.0). Data are presented as mean  $\pm$  standard deviation. All variables satisfied normality assumptions as assessed by the Shapiro-Wilk test ( $P > 0.05$ ), and no significant baseline differences were observed among groups for any outcome measure ( $P > 0.05$ ). A two-way repeated-measures analysis of variance (ANOVA) (group  $\times$  time) was used to examine the effects of different BFR pressure levels on body composition and athletic performance variables. When significant interaction or main effects were identified, paired-samples t-tests were conducted for within-group pre-post comparisons, and Bonferroni-adjusted post-hoc tests were applied for between-group comparisons to control the family-wise type I error rate. Effect sizes were interpreted according to Cohen (2013): partial eta squared ( $\eta^2$ ) values were classified as small ( $0.01 \leq \eta^2 < 0.06$ ), moderate ( $0.06 \leq \eta^2 < 0.14$ ), or large ( $\eta^2 \geq 0.14$ ); Cohen's  $d$  values were interpreted as trivial ( $d < 0.20$ ), small ( $0.20 \leq d < 0.50$ ), moderate ( $0.50 \leq d < 0.80$ ), or large ( $d \geq 0.80$ ). Statistical significance was set at  $P < 0.05$ , and 95% confidence intervals (CIs) are reported for key between-group contrasts to facilitate interpretation of effect precision.

### Results

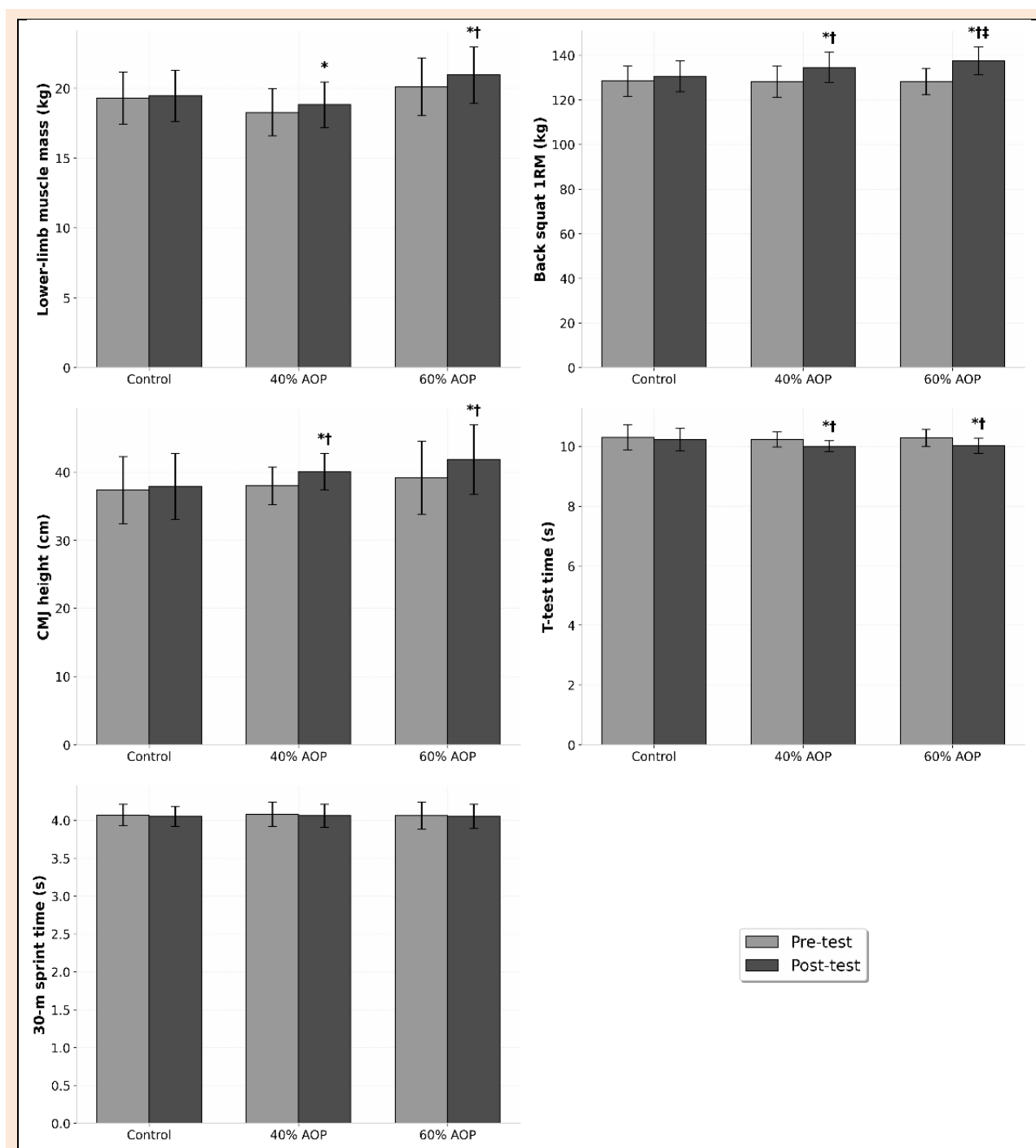
With respect to body composition, the two-way repeated-measures ANOVA revealed a significant group  $\times$  time interaction for lower-limb muscle mass ( $F = 3.98$ ,  $P = 0.035$ , partial  $\eta^2 = 0.28$ ), as well as a significant main effect of time ( $F = 15.23$ ,  $P = 0.002$ , partial  $\eta^2 = 0.37$ ). Within-group comparisons indicated that no significant changes were observed in body mass or body fat percentage in any group (all  $P > 0.05$ ). In contrast, lower-limb muscle mass significantly increased in both the 40% AOP group (mean change = 0.55 kg, 95% CI: 0.13 to 0.97 kg,  $P = 0.010$ ) and the 60% AOP group (mean change = 0.83 kg, 95% CI: 0.37 to 1.29 kg,  $P < 0.001$ ). Post-intervention between-group comparisons demonstrated that lower-limb muscle mass in the 60% AOP group was significantly greater than that in the control group (mean difference = 1.48 kg, 95% CI: 0.40 to 2.56 kg,  $P = 0.008$ , Cohen's  $d = 0.78$ , moderate effect) (Table 3, Figure 2).

In terms of back squat 1RM, a significant group  $\times$  time interaction was observed ( $F = 8.25$ ,  $P = 0.002$ , partial  $\eta^2 = 0.44$ ), along with a significant main effect of time ( $F = 58.91$ ,  $P < 0.001$ , partial  $\eta^2 = 0.74$ ). Within-group analyses revealed significant increases in back squat 1RM in both the 40% AOP group (mean change = 6.50 kg, 95% CI: 3.90 to 9.10 kg,  $P < 0.001$ ) and the 60% AOP group (mean change = 9.25 kg, 95% CI: 6.75 to 11.75 kg,  $P < 0.001$ ), whereas no significant change was detected in the control group (mean change = 2.12 kg, 95% CI: -0.17 to 4.41 kg,  $P = 0.069$ ). Post-intervention comparisons indicated that back squat 1RM was significantly greater in the 60% AOP group than in both the control group (mean difference = 6.86 kg, 95% CI: 3.12 to 10.60 kg,  $P < 0.001$ , Cohen's  $d = 1.07$ , large effect) and the 40% AOP group (mean difference = 2.94 kg, 95% CI: 0.20 to 5.68 kg,  $P = 0.048$ , Cohen's  $d = 0.46$ , small effect). In addition, the 40% AOP group exhibited significantly higher values than the control group (mean difference = 3.92 kg, 95% CI: 0.18 to 7.66 kg,  $P = 0.012$ , Cohen's  $d = 0.59$ , moderate effect) (Table 4, Figure 2).

**Table 3.** Body composition before and after the intervention.

|                             | Group   | Pre-test         | Post-test        | Mean Change (95% CI) | P (within) | Between-group differences at Post-test  | P (between) | Cohen's d |
|-----------------------------|---------|------------------|------------------|----------------------|------------|-----------------------------------------|-------------|-----------|
| Body mass (kg)              | Control | 66.11 $\pm$ 6.67 | 66.37 $\pm$ 6.52 | 0.26 (-0.37, 0.89)   | 0.415      | Control vs 40% AOP: 0.63 (-0.63, 1.89)  | 0.315       | 0.63      |
|                             | 40% AOP | 62.98 $\pm$ 5.32 | 62.68 $\pm$ 5.21 | -0.30 (-0.75, 0.15)  | 0.185      | Control vs 60% AOP: -0.35 (-1.23, 0.53) | 0.452       | 0.24      |
|                             | 60% AOP | 65.39 $\pm$ 4.52 | 65.05 $\pm$ 4.48 | -0.34 (-0.93, 0.25)  | 0.248      | 40% AOP vs 60% AOP: -0.05 (-0.83, 0.73) | 0.918       | 0.48      |
| Body fat (%)                | Control | 11.16 $\pm$ 1.33 | 11.05 $\pm$ 1.30 | -0.11 (-0.28, 0.06)  | 0.124      | Control vs 40% AOP: 0.58 (-0.22, 1.38)  | 0.142       | 0.57      |
|                             | 40% AOP | 10.66 $\pm$ 1.89 | 10.16 $\pm$ 1.82 | -0.50 (-1.16, 0.16)  | 0.158      | Control vs 60% AOP: -0.55 (-1.16, 0.06) | 0.082       | 1.68      |
|                             | 60% AOP | 9.59 $\pm$ 1.33  | 8.91 $\pm$ 1.25  | -0.68 (-1.57, 0.21)  | 0.185      | 40% AOP vs 60% AOP: -0.19 (-1.10, 0.72) | 0.695       | 0.79      |
| Lower-limb muscle mass (kg) | Control | 19.28 $\pm$ 1.87 | 19.44 $\pm$ 1.82 | 0.16 (-0.13, 0.45)   | 0.069      | Control vs 40% AOP: 0.38 (-0.70, 1.46)  | 0.412       | 0.37      |
|                             | 40% AOP | 18.26 $\pm$ 1.68 | 18.81 $\pm$ 1.62 | 0.55 (0.13, 0.97)*   | 0.010      | Control vs 60% AOP: 1.48 (0.40, 2.56)†  | 0.008       | 0.78      |
|                             | 60% AOP | 20.11 $\pm$ 2.05 | 20.94 $\pm$ 2.01 | 0.83 (0.37, 1.29)*   | < 0.001    | 40% AOP vs 60% AOP: 0.98 (-0.06, 2.02)  | 0.062       | 1.17      |

Data are presented as mean  $\pm$  SD. \*Significant difference compared with pre-test ( $P < 0.05$ ). †Significantly greater than the control group at post-test ( $P < 0.05$ ). Mean change = post-test value minus pre-test value. Cohen's  $d$  values are for between-group pairwise comparisons.



**Figure 2.** Changes in primary outcomes before and after the intervention. \*Significant difference compared with pre-test ( $P < 0.05$ ). †Significantly greater than the control group at post-test ( $P < 0.05$ ). ‡Significantly greater than the 40% AOP group at post-test ( $P < 0.05$ ).

Regarding CMJ height, the two-way repeated-measures ANOVA revealed a significant group  $\times$  time interaction ( $F = 4.45$ ,  $P = 0.025$ , partial  $\eta^2 = 0.30$ ) and a significant main effect of time ( $F = 40.15$ ,  $P < 0.001$ , partial  $\eta^2 = 0.66$ ). Significant pre-to-post improvements were observed in both the 40% AOP group (mean change = 2.07 cm, 95% CI: 0.80 to 3.34 cm,  $P = 0.002$ ) and the 60% AOP group (mean change = 2.65 cm, 95% CI: 1.00 to 4.30 cm,  $P = 0.003$ ), whereas no significant change occurred in the control group (mean change = 0.55 cm, 95% CI: -0.23 to 1.33 cm,  $P = 0.158$ ). Post-intervention comparisons showed that CMJ height was significantly greater in both the 60% AOP

group (mean difference = 3.84 cm, 95% CI: 0.77 to 6.91 cm,  $P = 0.015$ , Cohen's  $d = 0.79$ , moderate effect) and the 40% AOP group (mean difference = 2.15 cm, 95% CI: 0.08 to 4.22 cm,  $P = 0.047$ , Cohen's  $d = 0.55$ , moderate effect) compared with the control group, with no significant difference between the two BFRT groups (mean difference = 1.66 cm, 95% CI: -0.42 to 3.74 cm,  $P = 0.210$ , Cohen's  $d = 0.43$ , small effect) (Table 4, Figure 2).

With respect to T-test performance, the analysis revealed a significant group  $\times$  time interaction ( $F = 4.12$ ,  $P = 0.032$ , partial  $\eta^2 = 0.28$ ), as well as a significant main effect of time ( $F = 35.67$ ,  $P < 0.001$ , partial  $\eta^2 = 0.63$ ). Comple-

tion time significantly decreased in both the 40% AOP group (mean change = -0.23 s, 95% CI: -0.35 to -0.11 s,  $P = 0.001$ ) and the 60% AOP group (mean change = -0.26 s, 95% CI: -0.38 to -0.14 s,  $P < 0.001$ ), whereas no significant change was observed in the control group (mean change = -0.08 s, 95% CI: -0.18 to 0.02 s,  $P = 0.124$ ). Post-intervention comparisons indicated that both BFRT groups demonstrated significantly faster T-test times than the control group (40% AOP: mean difference = -0.21 s, 95% CI: -0.39 to -0.03 s,  $P = 0.018$ , Cohen's  $d = 0.74$ , moderate effect; 60% AOP: mean difference = -0.19 s, 95% CI: -0.37 to -0.01 s,  $P = 0.028$ , Cohen's  $d = 0.62$ , moderate effect), with no significant difference between the two BFRT groups (mean difference = 0.03 s, 95% CI: -0.15 to 0.21 s,

$P = 0.851$ , Cohen's  $d = 0.09$ , trivial effect) (Table 4, Figure 2).

In terms of 30-m sprint performance, no significant group  $\times$  time interaction was observed ( $F = 2.01$ ,  $P = 0.160$ , partial  $\eta^2 = 0.16$ ). Within-group comparisons indicated no significant changes in sprint time for the control group (mean change = -0.02 s, 95% CI: -0.06 to 0.02 s,  $P = 0.415$ ), the 40% AOP group (mean change = -0.02 s, 95% CI: -0.08 to 0.04 s,  $P = 0.185$ ), or the 60% AOP group (mean change = -0.01 s, 95% CI: -0.07 to 0.05 s,  $P = 0.248$ ). Post-intervention between-group comparisons also revealed no significant differences among groups (all  $P > 0.05$ , Cohen's  $d$  range: 0.00 - 0.07, trivial effect) (Table 4, Figure 2).

**Table 4. Athletic Performance Before and After the Intervention**

|                             | Group   | Pre-test          | Post-test         | Mean Change (95% CI)  | P (within) | Between-group differences at Post-test                | P (between) | Cohen's d |
|-----------------------------|---------|-------------------|-------------------|-----------------------|------------|-------------------------------------------------------|-------------|-----------|
| <b>Back squat 1RM (kg)</b>  | Control | 128.38 $\pm$ 6.87 | 130.50 $\pm$ 6.82 | 2.12 (-0.17, 4.41)    | 0.069      | Control vs 40% AOP: 3.92 (0.18, 7.66) <sup>†</sup>    | 0.012       | 0.59      |
|                             | 40% AOP | 128.00 $\pm$ 7.07 | 134.50 $\pm$ 6.81 | 6.50 (3.90, 9.10)*    | < 0.001    | Control vs 60% AOP: 6.86 (3.12, 10.60) <sup>†</sup>   | < 0.001     | 1.07      |
|                             | 60% AOP | 128.25 $\pm$ 5.87 | 137.50 $\pm$ 6.21 | 9.25 (6.75, 11.75)*   | < 0.001    | 40% AOP vs 60% AOP: 2.94 (0.20, 5.68) <sup>‡</sup>    | 0.048       | 0.46      |
| <b>CMJ height (cm)</b>      | Control | 37.36 $\pm$ 4.92  | 37.91 $\pm$ 4.81  | 0.55 (-0.23, 1.33)    | 0.158      | Control vs 40% AOP: 2.15 (0.08, 4.22) <sup>†</sup>    | 0.047       | 0.55      |
|                             | 40% AOP | 37.99 $\pm$ 2.75  | 40.06 $\pm$ 2.67  | 2.07 (0.80, 3.34)*    | 0.002      | Control vs 60% AOP: 3.84 (0.77, 6.91) <sup>†</sup>    | 0.015       | 0.79      |
|                             | 60% AOP | 39.16 $\pm$ 5.38  | 41.81 $\pm$ 5.12  | 2.65 (1.00, 4.30)*    | 0.003      | 40% AOP vs 60% AOP: 1.66 (-0.42, 3.74)                | 0.210       | 0.43      |
| <b>T-test time (s)</b>      | Control | 10.30 $\pm$ 0.42  | 10.22 $\pm$ 0.38  | -0.08 (-0.18, 0.02)   | 0.124      | Control vs 40% AOP: -0.21 (-0.39, -0.03) <sup>†</sup> | 0.018       | 0.74      |
|                             | 40% AOP | 10.23 $\pm$ 0.25  | 10.00 $\pm$ 0.18  | -0.23 (-0.35, -0.11)* | 0.001      | Control vs 60% AOP: -0.19 (-0.37, -0.01) <sup>†</sup> | 0.028       | 0.62      |
|                             | 60% AOP | 10.28 $\pm$ 0.28  | 10.02 $\pm$ 0.25  | -0.26 (-0.38, -0.14)* | < 0.001    | 40% AOP vs 60% AOP: 0.03 (-0.15, 0.21)                | 0.851       | 0.09      |
| <b>30-m sprint time (s)</b> | Control | 4.07 $\pm$ 0.14   | 4.05 $\pm$ 0.13   | -0.02 (-0.06, 0.02)   | 0.415      | Control vs 40% AOP: -0.01 (-0.09, 0.07)               | 0.574       | 0.07      |
|                             | 40% AOP | 4.08 $\pm$ 0.16   | 4.06 $\pm$ 0.15   | -0.02 (-0.08, 0.04)   | 0.185      | Control vs 60% AOP: -0.06 (-0.14, 0.02)               | 0.087       | 0.00      |
|                             | 60% AOP | 4.06 $\pm$ 0.18   | 4.05 $\pm$ 0.16   | -0.01 (-0.07, 0.05)   | 0.248      | 40% AOP vs 60% AOP: -0.04 (-0.12, 0.04)               | 0.221       | 0.06      |

Data are presented as mean  $\pm$  SD. \*Significant difference compared with pre-test ( $P < 0.05$ ). <sup>†</sup>Significantly greater than the control group at post-test ( $P < 0.05$ ). <sup>‡</sup>Significantly greater than the 40% AOP group at post-test ( $P < 0.05$ ). Mean change = post-test value minus pre-test value. Cohen's  $d$  values are for between-group pairwise comparisons.

## Discussion

The present study demonstrated that six weeks of low-load BFRT resulted in significant increases in lower-limb muscle mass in both BFRT groups, with the 60% AOP condition eliciting greater hypertrophic adaptations than control group. These findings indicate that, when external load (30% 1RM) and training volume are matched, a higher relative occlusion pressure may provide a stronger hypertrophic stimulus. According to Pearson and Hussain (2014), muscle hypertrophy is primarily mediated by mechanical tension and metabolic stress. Traditional high-load resistance training relies mainly on mechanical tension, whereas low-load BFRT depends on metabolic stress. BFRT creates a localized ischemic and hypoxic environment that promotes metabolite accumulation (e.g., lactate), which may facilitate muscle growth (Takarada et al., 2000). Previous studies have confirmed that low-intensity

resistance exercise ( $< 50\%$  1RM) combined with BFRT can induce marked hypertrophic responses (Sundberg et al., 1993; Takarada et al., 2002). Yu et al., (2020) reported significant increases in lower-limb skeletal muscle mass following two weeks of squat-based BFRT at an absolute pressure of 250 mmHg in adult males. Notably, the present study observed significant hypertrophy even at 40% AOP, although the magnitude of increase was smaller than that observed at 60% AOP. Higher occlusion pressures may result in more complete venous occlusion and a more pronounced ischemic stimulus, which could amplify cell swelling and reactive oxygen species signaling-both of which are hypothesized to contribute to muscle hypertrophy (Loenneke and Pujol, 2009). The present study showed that, although the difference between the 60% AOP and 40% AOP groups did not reach statistical significance, the effect size was large (Cohen's  $d = 1.17$ ). This suggests that the lack of significance is likely due to insufficient statisti-

cal power ( $n = 8$  per group), and the observed difference may be practically meaningful. Future studies with larger sample sizes are warranted to confirm this potential advantage of higher occlusion pressure. Nevertheless, occlusion pressure selection remains subject to individual variability and a potential “ceiling effect”. It has been suggested that pressures exceeding 80% of individual AOP may increase discomfort and alter motor unit recruitment patterns, potentially impairing long-term adherence and training adaptations (Counts et al., 2016). Accordingly, the 60% AOP employed in the present study may approach the upper range of pressures that could be effective for promoting hypertrophic adaptations in this population. These findings are suggestive of a potential dose-response relationship between occlusion pressure and hypertrophic outcomes, consistent with the hormesis framework proposed by Loenneke et al. (2014). However, given that only two pressure levels (40% and 60% AOP) were compared, and direct tolerability or safety outcomes were not assessed, this interpretation remains speculative. Future studies employing multi-level pressure designs are warranted to further characterize the pressure-response relationship in youth athletes. The effects of low-load BFRT on fat loss remain inconclusive. Willis et al. (2012) reported increased muscle mass but unchanged fat mass following eight months of traditional resistance training. Similarly, Sheng et al. (2019) observed significant increases in whole-body and lower-limb muscle mass after two weeks of downhill walking with BFRT, while body fat mass remained unchanged. Previous studies have indicated that adolescent athletes may exhibit elevated anabolic hormone levels (Lloyd et al., 2014). However, the present study did not directly assess hormonal concentrations or maturation status, and individual responsiveness to resistance training is known to vary by maturational stage (Radnor et al., 2017). Future studies should incorporate maturity offset or Tanner staging to better account for individual variability in training adaptations. Consistent with the majority of previous studies, body fat percentage did not change significantly in the present study, reinforcing the notion that BFR training-induced improvements in body composition among adolescents primarily reflect increases in lean mass rather than reductions in fat mass. This adaptation pattern aligns with the predominantly anabolic nature of training responses during adolescence.

Regarding maximal strength, both BFRT groups exhibited significant improvements in back squat 1RM, with the 60% AOP group demonstrating superior gains compared with the 40% AOP and control groups. These results indicate that although both pressure levels are effective for enhancing maximal strength, higher relative occlusion pressure may yield greater adaptive benefits. Back squat 1RM is a widely used indicator of lower-limb maximal strength and has been frequently examined in BFRT research. Godawa et al. (2012) reported significant improvements in squat strength following ten weeks of BFRT in weightlifters. Similarly, Yamanaka et al. (2012) observed increased squat 1RM after four weeks of BFRT in collegiate rugby players, and Che et al. (2022) reported comparable findings in wrestlers following six weeks of

low-load BFRT. The observed strength gains may be attributed to both neural and morphological adaptations. Under blood flow restriction, the ischemic and hypoxic environment combined with elevated metabolic stress may promote earlier recruitment of high-threshold motor units, even at low external loads, thereby enhancing neural drive to type II muscle fibers (Slysz et al., 2016). Additionally, chronic BFRT can induce increases in muscle cross-sectional area, which is considered a key structural determinant of maximal strength development (Lixandrão et al., 2018). Adolescence represents a critical period for the development of neuromuscular coordination. Engaging in resistance training under low mechanical loading—such as BFR training—may facilitate neural adaptations (e.g., enhanced muscle excitation) while minimizing joint stress (Centner and Lauber, 2020). However, these neuromuscular benefits are closely tied to the execution of the exercise itself, including movement technique and coaching quality. This combination is particularly relevant for long-term athletic development and injury prevention (Faigenbaum et al., 2009). Although numerous studies have confirmed the efficacy of lower-limb BFR training in improving squat strength, the influence of different occlusion pressures remains unclear. Fatela et al. (2016) reported that muscle activation during BFRT follows an inverted U-shaped relationship with pressure, suggesting the existence of an optimal pressure window. Li et al. (2021) similarly found that quadriceps muscle activation during squat exercise approached a plateau at approximately 50% AOP. In the present study, the superior strength gains observed in the 60% AOP group may be related to greater increases in lower-limb muscle mass, a higher level of metabolic stress, improved neuromuscular efficiency, or measurement error inherent in the predicted 1RM values. Previous research has indicated that increasing relative occlusion pressure further reduces intramuscular oxygenation and amplifies metabolite accumulation, potentially enhancing neuromuscular adaptation (Yasuda et al., 2008). However, the superior strength gain in the 60% AOP group compared with the 40% AOP group, while statistically significant, was associated with a small effect size (Cohen's  $d = 0.46$ ). This indicates that while higher occlusion pressure produces a measurable increase in maximal strength, the magnitude of this additional benefit is limited.

The athletic performance measures assessed in this study included CMJ height, T-Test, and 30-m sprint performance, which are considered key indicators of lower-limb power output, acceleration capacity, and multidirectional movement efficiency in soccer players (Stølen et al., 2005). The results demonstrated that both BFRT groups achieved significant improvements in CMJ height and T-test performance, with comparable magnitudes of improvement, whereas no significant changes were observed in 30-m sprint performance across groups. Importantly, increasing occlusion pressure from 40% to 60% AOP did not confer additional benefits for CMJ or agility performance, suggesting the presence of a pressure “plateau” effect for these performance outcomes. CMJ height is widely regarded as a gold-standard measure of stretch-shortening cycle efficiency and explosive lower-limb power (Lockie et al.,

2011). Improvements in CMJ performance are closely associated with gains in maximal strength and enhanced recruitment of fast-twitch muscle fibers (Moritani et al., 1992). BFRT has been shown to preferentially recruit type II fibers due to the metabolically demanding environment it creates (Loenneke et al., 2009). Cook et al. (2014) reported that three weeks of resistance training combined with BFRT increased both squat strength and CMJ height in rugby players, attributing these improvements to enhanced neural drive and improved intermuscular coordination. Similar findings were reported by Manimmanakorn et al. (2013), who observed superior gains in muscle strength and vertical jump performance following five weeks of BFRT in basketball players. Consistent with these findings, the present study demonstrated that even at a relatively low load of 30% 1RM, BFRT effectively stimulated neuromuscular adaptations associated with vertical jump performance. However, the absence of additional benefits at 60% AOP suggests that further increases in occlusion pressure may not enhance power-oriented adaptations. Excessive pressure may increase discomfort or induce premature fatigue, potentially impairing movement quality (Loenneke et al., 2014). In the present study, RPE was higher in the 60% AOP group ( $5.3 \pm 1.6$ ) than in the 40% AOP group ( $4.2 \pm 1.3$ ), suggesting greater fatigue with higher pressure (Zhu et al., 2025). However, this interpretation remains inferential as objective indicators (e.g., bar velocity, velocity loss) were not directly monitored. Future studies should incorporate both objective and subjective measures to substantiate this fatigue-mediated pathway. From a practical perspective, 40% AOP may therefore represent a more efficient and tolerable option for improving explosive performance in youth athletes.

Improvements in T-test performance reflect enhanced abilities in rapid deceleration, directional change, and re-acceleration, which are critical components of soccer performance. These capabilities are underpinned by eccentric and concentric strength of the lower-limb musculature, as well as joint stability and neuromuscular control (Sporis et al., 2010). BFRT-induced increases in overall lower-limb strength, including synergistic and stabilizing muscles, may contribute directly to improvements in agility performance. A systematic review by Slys et al. (2016) indicated that BFRT not only enhances prime mover strength but may also improve stabilizer muscle function and dynamic postural control. Additionally, the accumulation of metabolic stress during BFRT has been proposed to enhance muscle spindle sensitivity and proprioceptive feedback, potentially optimizing limb positioning and force application during multidirectional movements (Fujita et al., 2007). Hammami et al. (2017) reported greater improvements in T-test performance following BFRT compared with traditional resistance training under matched loading conditions. A recent systematic review further concluded that BFRT can effectively improve agility-related performance through enhanced neural activation strategies (Patterson et al., 2019). In the present study, the comparable improvements in both BFRT groups suggest that increasing occlusion pressure beyond 40% AOP does not confer additional benefits for agility-related outcomes. This may reflect the specificity of training stimuli,

as agility and explosive performance in youth depend on neuromuscular coordination and movement technique beyond muscle strength alone (Lloyd and Oliver, 2012). Alternative explanations include test familiarization, ceiling effects, or both pressures exceeding the threshold required to maximize performance. The present findings suggest that, for youth soccer players, low-load BFR training at 40% AOP is sufficient to effectively stimulate neuromuscular pathways associated with jump and agility performance, while potentially offering superior comfort and adherence.

In contrast, no significant improvements were observed in 30-m sprint performance in any group. This finding is consistent with existing literature. A recent systematic review and meta-analysis reported that BFRT does not significantly improve short-distance sprint performance compared with traditional resistance training (Deng et al., 2025). Similarly, Zhang et al. (2023) observed no significant changes in 20-m sprint performance following BFRT. Sprint performance is largely determined by technical execution, neuromuscular coordination, and instantaneous high-power output, which may require high-velocity and high-force stimuli rather than localized metabolic stress. Therefore, BFRT may have limited transfer effects to short-distance sprint performance. Zhang et al. (2023) demonstrated that BFRT combined with resisted sprint training can improve early acceleration, which may be because the acceleration phase is more sensitive to BFRT-induced strength gains. Future training interventions in youth soccer players may need to combine BFRT with sprint-specific drills (e.g., resisted sprints, plyometric exercises) to facilitate the transfer of strength gains to linear sprint performance. Additionally, the null sprint finding may also reflect the specificity of the training stimulus, limited statistical power, or insufficient sprint-oriented exposure in the present study.

## Conclusion

Six weeks of low-load (30% 1RM) blood flow restriction training performed at both 40% and 60% arterial occlusion pressure was associated with improvements in lower-limb muscle mass, squat strength, and selected aspects of athletic performance in youth soccer players, compared with low-load training without BFR. While both pressure levels elicited comparable improvements in countermovement jump and agility performance, training at 60% AOP was associated with greater adaptations in lower-limb muscle mass and squat strength, with no additional benefits observed for 30-m sprint performance.

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The authors declare that the experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who was an organizer of the study. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript.

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### Key points

- Six weeks of low-load resistance training combined with blood flow restriction enhanced lower-limb muscle mass and squat strength in youth soccer players.
- Training performed at a higher arterial occlusion pressure (60% AOP) was associated with greater hypertrophic and strength adaptations compared with 40% AOP.
- Both occlusion pressures elicited similar improvements in jump and agility performance, while sprint performance remained unchanged following blood flow restriction training.

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