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Effect of Leg Half-Squat Training With Blood Flow Restriction Under Different External Loads on Strength and Vertical Jumping Performance in Well-Trained Volleyball Players

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Abstract

Purpose: To examine the effect of blood flow restriction resistance training under different external loads on the muscle strength and vertical jumping performance in volleyball players.

Methods: 18 well-trained collegiate male volleyball players were randomly divided into 3 groups: high-load resistance training group (HL-RT, 70% 1RM, n = 6), low-load blood flow restriction resistance training group (LL-BFR-RT, 30% 1RM, 50% arterial occlusion, n = 6), and high-load blood flow restriction resistance training group (HL-BFR-RT, 70% 1RM, 50% arterial occlusion, n = 6). Participants performed leg half-squat exercise 3 times per week for 8 weeks. Measurements of Isokinetic peak torque of knee extension and flexion, 1RM leg half-squat, squat jump, and 3 footed take-off were obtained before and after training. A two-way repeated-measures analysis of variance was used to examine differences among the 3 groups and between the 2 testing time (pre-test vs post-test).

Results: (1) The HL-RT group was significantly greater in muscle strength than that in the LL-BFR-RT group ($P < .05$), but no improvement in vertical jumping performance ($P > .05$). (2) Improvement in muscle strength and vertical jumping performance was significantly greater in the HL-BFR-RT group than that in the LL-BFR-RT group ($P < .05$). (3) The HL-BFR-RT group had greater but not significant improvement in muscle strength and vertical jumping performance than that in the HL-RT group.

Conclusions: Although increases in muscle strength were observed between training groups, HL-BFR-RT increased not only muscle strength but vertical jumping performance to a greater extent compared to LL-BFR-RT and HL-RT.

Keywords
volleyball players, blood flow restriction, KAATSU training, strength, vertical jumping

Introduction

As in all team sports, lower limb strength and jumping performance are important qualities of any player. Especially, when it comes to volleyball, a game that relies on vertical jumping performance on almost every action except reception. Plyometric training is widely used to develop volleyball muscle strength and vertical jumping capacity.[1] However, it might cause musculoskeletal injuries during the landing phase.[2] Blood flow restriction (BFR) training, also known as KAATSU training, is a neuromuscular training method using a

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cuff to bind the proximal end of the limb muscles during physical training.[3] Compression restriction, maintaining arterial blood flow to the muscles while restricting or blocking venous blood return intermittently, promoting muscle protein synthesis, stimulates muscle growth, and improves muscle mass.[4,5] It also reduces pressure on the joints, ligaments, and tendons.[6]

Recently, studies have shown that BFR training can increase muscle size and strength in healthy people,[7] the elderly,[8] and the injured.[9] It is also being widely promoted and applied to athletes. Previous studies have confirmed the positive effect of BFR training on rugby,[10] football,[11] track and field,[12] tennis,[13] and volleyball field.[6] In addition to improving muscle size and increasing strength, studies have demonstrated that this method has a positive influence in improving sports performance such as squat jumps, explosive power,[14] maximum, and repetitive sprinting ability,[14,15] and the ability to change directions quickly.[16] Although numerous studies have confirmed that the use of low-load (20%–30% of 1RM) blood flow restriction training can cause similar effect to traditional high-load resistance training (HL-RT),[8,16-19] some studies have shown that traditional high-load resistance training (70% to 85% of 1RM) has significantly greater improvement in muscle strength than LL-BFR-RT training.[7,20-22] However, the effect of blood flow restriction with high-load training (HL-BFR-RT) in muscle adaptation is also controversial. Cook et al. found that HL-BFR-RT (70% 1RM vs control) had greater improvement in muscle strength and power,[14] while Laurentino et al. did not find that vascular occlusion in combination with HL-RT (60% 1RM or/and 80% 1RM) augmented muscle strength when compared to HL-RT alone.[23] The controversial results between these studies might be caused by the different training experiences of subjects, the way of vascular occlusion, and types of exercise.[14,15,23] Additionally, the effects of different BFR interventions on vertical jumping performance are also different. Abe et al. found that 8 days of LL-BFR-RT improved sprint but not jump performance in collegiate male track and field athletes.[15] Horiuchi et al. also found that BFR training has no effect on jump performance.[24,25] While Cook et al. found that HL-BFR-RT had greater improvement in muscle power and maximum sprint time.[14] It is unclear whether the muscle responses and vertical jumping performance produced by LL-BFR-RT also occur when the loading is high. Heavy training loads are conventionally used and recommended for muscle hypertrophy, strength gains, which are important to improve vertical jumping performance, therefore represent a real world situation.[26] Based on this, further research is needed to test which muscle adaptations and vertical jumping performance would occur under low or high load with vascular occlusion.

Since there are no studies have directly compared the difference between LL-BFR-RT and HL-BFR-RT on muscle adaptation, it is hypothesized that: (1) with or without BFR, the improvement of HL-RT in muscle strength and vertical jumping performance is significantly greater than that in the LL-BFR-RT; (2) under the same degree of BFR (50% AO), the improvement of HL-BFR-RT in muscle strength and vertical jumping performance is significantly greater than that in the LL-BFR-RT; (3) under the same external load (70% 1RM), the improvement of HL-BFR-RT in muscle strength and vertical jumping performance is significantly greater than that in the HL-RT.

Methods

Experimental Approach to the Problem

It was a randomized controlled experiment. Participants were paired according to the baseline of muscle strength value and then randomly assigned to the LL-BFR-RT group that completed training at 30%1RM with BFR; The HL-BFR-RT group that completed training at 70%1RM with BFR; HL-RT (control) that performed training at 70%1RM without BFR. All other training variables (such as rest, movement tempo, training clothes, diet, etc.) were consistent. The training interventions lasted 8 weeks, 3 times per week. Muscle strength and vertical jumping tests were carried out pre-and post-test (Figure 1).

Subjects

The sample size was calculated using G*Power Software,[27] Considering a power of 85%, an effect size of .45, α of .05, eighteen subjects were required. Eighteen young male volleyball players were recruited in this experimental study. The inclusion criteria of participants were: preseason, well-trained collegiate male volleyball players whose sport level are similar to NCAA Division IA, regularly RT trainer (ie, defined as constantly doing RT at least 2–3 times per week for a minimum of 4 year, and regularly performing Push-pull movement of upper and lower limbs, such as bench press, full squat). The exclusion criteria also were: volleyball player with chronic injury, players who were unfamiliar with RT. Subjects of current research were well-trained collegiate male volleyball players without chronic injuries and they were nonsmokers, normotensive (blood pressure <132/80 mmHg), nonobese (body mass index <28 kg/m2), not taking any medication, and free of overt chronic diseases as assessed by medical history.

Design

The athletes were randomly divided into 3 groups (each n = 6) with a similar spread of age, body mass, height, and maximum leg circumference (Table 1). The study was tailored to form an 8-week resistance-training block for the athletes to achieve functional strength and vertical jumping gains that they would normally focus on during preseason resistance training. Each subject was informed of the risks associated with the training and measurements and gave written consent to participate in this study, which was approved by the Ethics Committee of the

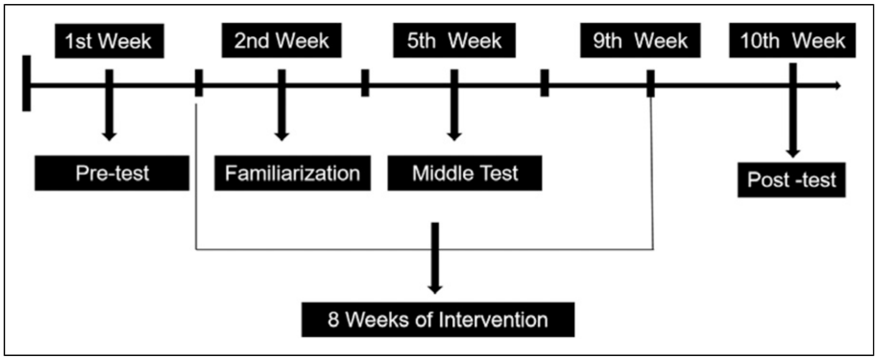

Figure 1. Overall study design, including all measurement points.

Table 1. Anthropometry Information between the Groups.

	HL-RT (n = 6)	LL-BFR-RT (n = 6)	HL-BFR-RT (n = 6)	*P*
Age (years)	20.83 ± 1.47	20.50 ± 1.38	20.17 ± .75	.657
Height (cm)	180.00 ± 6.42	180.50 ± 4.46	184.67 ± 5.43	.300
Weight (kg)	69.83 ± 5.49	74.67 ± 9.29	74.50 ± 9.77	.541
Maximum leg circumference (cm)	58.33 ± 1.63	58.67 ± 1.97	57.33 ± 1.97	.454

Data are mean ± standard deviation.

Beijing Sport University (2021A35). Testing was conducted before the initiation of training (pre) and after 8 weeks of training (post).

During the study, all athletes had set dietary plans that were consistent across the training blocks and were designed to meet their body weight and activity needs. Athletes were encouraged to ensure they got a minimum of 8 hours of sleep, and a self-reported log suggested they achieved this regularly. Alcohol consumption was low or absent.

Methodology

Before beginning training, all athletes attended 3 consecutive days of testing to determine initial strength and vertical jumping performance. All athletes were familiar with the testing protocol from their prior training. They were instructed not to take any anti-inflammatory drugs and to refrain from consuming alcohol the 48 hours before each testing day. Additionally, the players were instructed to consume at least 800 mL of fluid, avoid consumption of caffeinated products, and replicate their dietary consumption on the morning of testing days.

Muscle Strength. On day 1 of testing, athletes assembled at 9:00 AM, having consumed breakfast and a minimum of 750 mL fluid and having been encouraged to have slept at least 8 hours. A standard 15-minutes warm-up comprised 5 minutes of dynamic stretching, 5 min on a cycling ergometer, and 5 minutes on a rowing ergometer. Athletes then performed leg half-squat to just below parallel in a controlled manner under the supervision of a qualified strength-conditioning coach. Using historical records of individual performance, athletes completed the following leg half-squat based on individual percentage of 1RM measured according to Brown et al: 5 × 50%, 3 × 60%, 2 × 80% and then 1 × 90%, 1 × 95%, 1 × 100%. If successful at the 1 × 100% lift, the athlete continued to increase 2.5 kg each attempt until failure.[28] The best lift was recorded as the athlete's 1RM. Athletes were allowed 5 minutes of passive recovery between attempts.

On day 2 of testing, the athletes again assembled at 9:00 AM and performed the same standard warm-up as on day 1. To estimate muscle strength, isokinetic concentric (at an angular velocity of $60°\cdot s^{-1}$ according to Bamman et al.[29]) knee extension and flexion peak torques were measured in both legs using an isokinetic dynamometer (Biodex Medical System 3, Shirley, NY). Before testing, each subject had a familiarization session to orient them to isokinetic testing. In the warm-up activity, subjects performed 3–4 sub-maximal contractions of increasing intensity (from 50 to 90%) for each isokinetic contraction and then rested for 1 minute between the warm-up and the beginning of the test. Each subject was seated upright and stabilized with straps at the shoulders, waist, and thighs, per the manufacturer's guidelines. Each subject's seat position was recorded to be replicated during subsequent testing. Six maximal concentric knee contractions at $60°\cdot s^{-1}$ were performed. Subjects were given verbal encouragement and visual feedback of the torque signal at each repetition. The highest value obtained of all maximum efforts was used as the peak torque value (Nm) for further analysis.

Vertical Jumping. On day 3 of testing, the athletes again assembled at 9:00 AM and performed the same standard warm-up as on day 1. They then performed 3 maximal-effort squat jumps (SJ) and three-footed takeoffs. SJ, in which subjects were jumping from a semi-squatting position without countermovement and with their arms akimbo throughout the movement,[30] and three-footed takeoffs, in which subjects were allowed to perform a 3 steps forward and countermovement with the lower limbs before jumping.[31] In both tests, the subjects were required to land at the same point of takeoff and rebound with straight legs when landing to avoid knee bending and alteration of measurements.[30] Between the testing trials and different tests, each subject paused for 2–3 minutes. Both Jumping test completed on a force plate sampling at 1000 Hz (Kistler Instrument Corp, Amherst, NY, USA), with the best jump being recorded for further analysis.

Training Programs

The 3 groups were randomly assigned to 1 of the 3 training interventions. The training block was 8 weeks long and included 24 experimental resistance-training sessions. All training sessions began at 8:30 AM The resistance training load of each group was adjusted based on the increase degree of subjects' maximum strength after 4 weeks.

High-Load Resistance Training. After completing the standard warm-up described earlier, the athletes performed leg half-squats at 70% of their individually assessed 1RM. Four sets of 8 repetitions were performed with 60 seconds of passive rest between sets.

High-Load Blood Flow Restriction Resistance Training. The BFR training was identical to the standard training just described, except that lower-limb blood flow was restricted with an occlusion cuff (width 7 cm, according to previous studies[32,33] inflated to 50% arterial occlusion). According to Loenneke et al. the influence of the limb circumference and the width of the cuff to describe the method of choosing arterial occlusion (OA),[34] based on this, the following guidelines concerning lower limbs: 45–50 cm = 120 mmHg, 51–55 cm = 150 mmHg, 56–59 cm = 180 mmHg, over 60 cm =210 mmHg.[35] Studies have demonstrated that 50% OA value (45–50 cm = 120 mmHg, 51–55 cm = 150 mmHg, 56–59 cm = 180 mmHg, over 60 cm = 210 mmHg) is likely to be optimal for RT.[36,37] The mean of maximum leg circumference in our study is 58.33 ± 1.63 cm, 58.67 ± 1.97 cm, and 57.33 ± 1.97 cm of the HL-RT, LL-BFR-RT, and HL-BFR-RT groups, respectively. Therefore, the 50% OA value is "56–59 cm=180 mmHg" in our study). A vascular Doppler (DV-600, Brasil) probe was placed over the tibial artery to measure blood pressure (mmHg) of the vascular occlusion. A B-strong cuff inflator (MS, USA) attached to the thigh (inguinal fold region) was inflated up to 180 mmHg. The cuff was inflated during exercise and the interset rest periods (continuous occlusion). Circulatory occlusion was maintained between sets to enhance muscle metabolites and promote greater training effects.[38] Note that the lower-body occlusion cuff was worn bilaterally at the inguinal fold region of the thigh during exercises.

Low-Load Blood Flow Restriction Resistance Training. The BFR training was identical to the standard training described, except that leg half-squats, at 30% of their individually assessed 1RM. Participants performed 4 sets of 75 repetitions (30/15/15/15) with 60 seconds of passive rest between sets.

Statistical Analyses

Statistical analysis was performed using SPSS v.20.0 (SPSS Inc., IBM, China). The data in tables and figures are presented as mean ± standard deviation. The Shapiro–Wilk, Levene, and Mauchly's tests were used to verify the normality, homogeneity, and sphericity of the sample's data variances, respectively. At pre-test, between-group comparisons were analyzed by univariate analysis of variance (ANOVA), and between-group comparisons under the influence of experimental treatment were analyzed by a two-way repeated ANOVA [group (LL-BFR, HL-RT vs HL-BFR-RT) × time (pre-test vs Post-test-8 weeks)] was used. When a significant interaction or main effect was found, post hoc comparisons with Bonferroni adjustment were used to test the discrimination between means. The change (increase or decrease) of all dependent variable values at post-test and pre-test was evaluated by calculating the percentage for each parameter (ie: SJ% = 100*(Post-Test mean − Pre-test mean)/Pre-test mean). Statistical significance was set at $P < .05$.

Results

Before the training period, experimental and control subjects did not differ in terms of any variable measured (Table 2). Based on diary records, every experimental subject except 1 complied completely with the pre-scribed BFR training program. The exception omitted 1 BFR session in 1 week. Also, based on diary records, every subject complied with the instructions to maintain the same program of training that he followed immediately before the study. No harmful effects were noted in the LL-BFR-RT and HL-BFR-RT groups except delayed muscle soreness during the exercise intervention.

Muscle Strength

The 1RM leg half-squat test results are given in Figure 2. They show considerable differences among the groups (group × time interaction was significant: $F(2,10)=15.1$, $P = .001$ and $F(1,5) = 301$, $P = .000$, respectively). Compared to the pre-training, 1RM leg half-squat increased significantly by 9.9% in the LL-BFR-RT group ($P = .001$), 17.3% in the HL-RT group ($P = .003$), and 28.6% in the HL-BFR-RT group ($P = .000$), respectively. Post hoc analysis revealed that 1RM leg

Table 2. Muscle Strength and Vertical Jumping Test before the Training Period.

	LL-BFR-RT	HL-RT	HL-BFR-RT	*P*
Left knee extension PT (Nm)	196.0 ± 19.4	195.7 ± 13.0	198.3 ± 31.2	.780
Left knee flexion PT (Nm)	126.9 ± 11.6	128.2 ± 6.6	126.7 ± 7.6	.938
Right knee extension PT (Nm)	204.6 ± 18.8	208.8 ± 9.6	213.1 ± 11.5	.329
Right knee flexion PT (Nm)	131.0 ± 5.0	131.7 ± 6.1	133.9 ± 6.1	.662
Squat Jump (cm)	41.87 ± 6.50	43.00 ± 3.60	45.45 ± 7.03	.573
Three footed takeoff (cm)	56.85 ± 6.04	59.18 ± 3.72	57.90 ± 8.34	.817
1RM leg half-squat (kg)	180.5 ± 42.84	196.7 ± 52.72	190.2 ± 46.34	.840

Data are mean ± standard deviation. PT: peak torque.

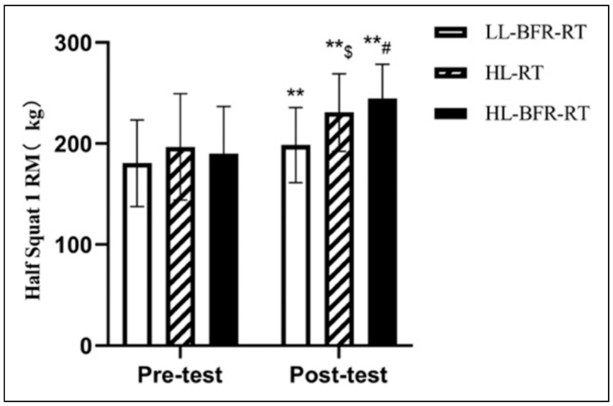

Figure 2. 1RM Leg Half-Squat before (Pre) and after (Post) 8 weeks. *Significantly different from pre-training value, where **P < .01. $Significantly different between the HL-RT and LL-BFR-RT groups value, where $P < .05. #Significantly different between the LL-BFR-RT and HL-BFR-RT group values, where #P < .05.

half-squat gain in the HL-BFR-RT and HL-RT groups were significantly higher than that in the LL-BFR-RT group (P=.019; P = .023, respectively), while there were no significant difference in 1RM leg half-squat between the HL-BFR-RT and HL-RT groups (P = .071).

The isokinetic knee extension and flexion peak torque at $60°\cdot s^{-1}$ test results are given in Figure 3. The left isokinetic knee extension and flexion peak torque at $60°\cdot s^{-1}$ was significant among groups (group × time interaction was significant: the main effect of group on the left extension: F (2,10) = 7.1, P = .012, the left flexion: F (2,10) = 5.1, P = .03; the main effect of time on the left extension: F (1,5) = 43.8, P = .012, the left flexion: F (1,5) = 33.6, P = .002, respectively). While the right isokinetic knee extension and flexion peak torque at $60°s^{-1}$ had no group × time interaction effect.

Compared to pre-training, peak torque of the LL-BFR-RT group increased significantly by 5.1% and 8.6% on the left and right knee extension (P < .05), respectively, and 5.5% and 8.7% on the left (P < .05) and right (P < .01) knee flexion, respectively. The HL-RT group also increased significantly by 11.7% and 12.9% on the left (P < .05) and right (P < .01) knee extension peak torque, respectively, and 10.9% and 13.2% on the left (P < .05) and right (P < .01) knee flexion peak torque, respectively (P < .05). In addition, Peak torque of the HL-BFR-RT group increased significantly by 17.1% and 17.7% on the left and right knee extension (P < .01), and 16.5% and 15.9% on the left and right knee flexion (P < .01), respectively. Post hoc analysis revealed that isokinetic knee extension and flexion peak torque at $60°\cdot s^{-1}$ gain in the HL-BFR-RT and HL-RT groups were significantly higher than that in the LL-BFR-RT group (HL-BFR-RT: left extension: P = .005, left flexion: P = .018; right extension: P = .048, right flexion: P = .007; HL-RT: left extension: P=.037, left flexion: P = .041; right extension: P = .023, right flexion: P = .012, respectively), while there were no significant difference in isokinetic knee extension and flexion peak torque at $60°s^{-1}$ between the HL-BFR-RT and HL-RT groups (P > .05)

Vertical Jumping

The SJ test results are given in Figure 4. The interaction effect between group and time on SJ was not significant (F (2,10) = 1.7, P = .252). The main effect of time on SJ was also not significant (F (1,5) = 5.5, P = .067). There were only significant increase in SJ in HL-BFR-RT group after 8 weeks intervention (P = .020). The main effect of group on SJ was significant (F (2,10) = 11.5, P = .003). Post hoc analysis revealed the HL-BFR-RT group was significantly larger (P = .039) in SJ than that in the LL-BFR-RT group, while there were no significant difference in SJ between the HL-BFR-RT and HL-RT groups (P = .076).

The three-footed takeoff test results are given in Figure 5. The interaction effect between group and time on three-footed takeoff was significant (F (2,10) = 6.0, P = .020; F (1,5) = 17.6, P = .009, respectively). There were only significant increase in three-footed takeoff in the HL-BFR-RT group after 8 weeks intervention (P = .015). Post hoc analysis revealed that the HL-BFR-RT group was significantly larger (P = .002) in three-footed takeoff than that in the LL-BFR-RT group, while there were no significant difference in three-footed takeoff between the HL-BFR-RT and HL-RT groups (P = .080).

Discussion

The findings from this study partly support our hypothesis that improvement in muscle strength and vertical jumping

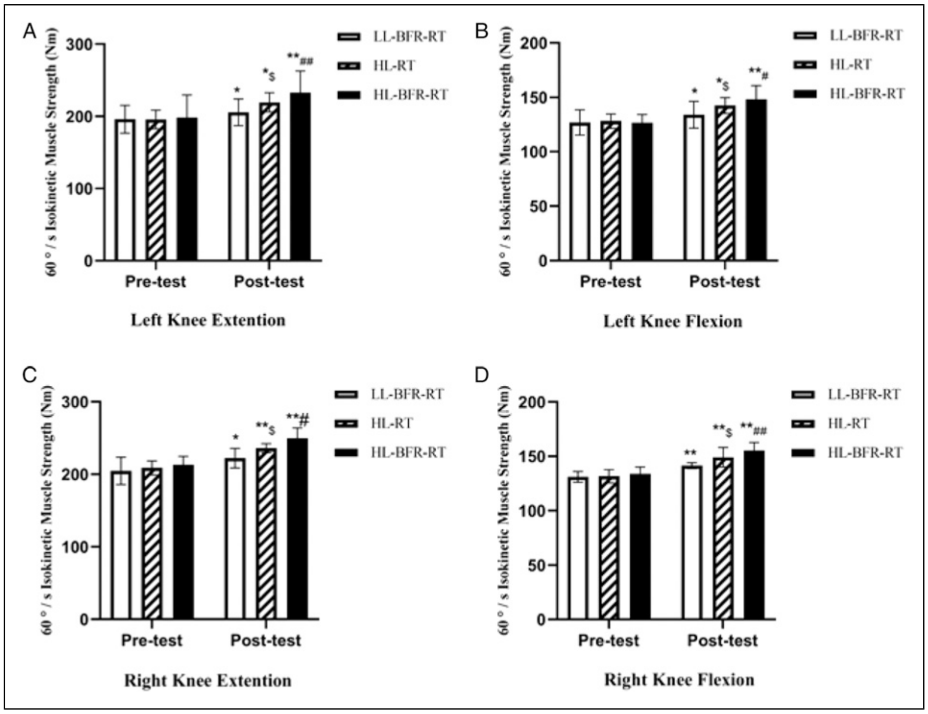

Figure 3. Knee extension and flexion peak torque at $60°s^{-1}$ before (Pre) and after (Post) 8 weeks.
Significantly different from pre-training value, where$P$ <.05, **P<.01. $Significantly different between the HL-RT and LL-BFR-RT groups value, where P < .05. #Significantly different between the LL-BFR-RT and HL-BFR-RT groups value after 8 weeks intervention, where #P < .05, ##P < .01.

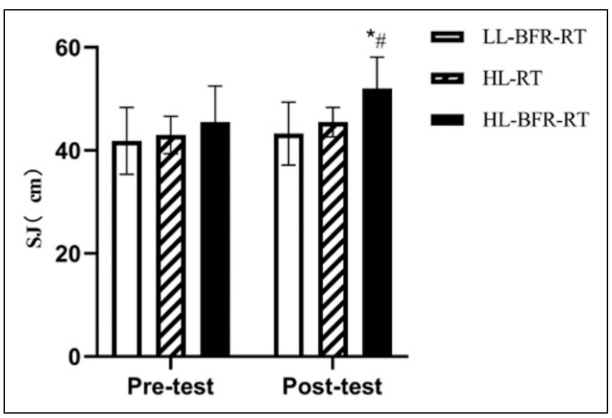

Figure 4. The Height of Squat Jump before (Pre) and after (Post) 8 weeks.
Significantly different from pre-training value, where$P$ <.05. #Significantly different between the LL-BFR-RT and HL-BFR-RT groups value after 8 weeks intervention, where #P < .05.

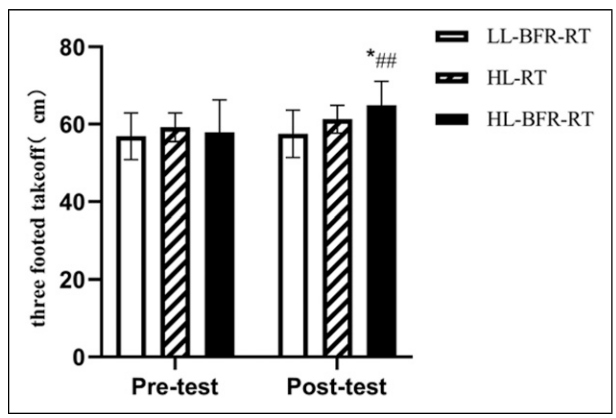

Figure 5. The Height of 3 Footed Takeoff before (Pre) and after (Post) 8 weeks.
Significantly different from pre-training value, where$P$ <.05. #Significantly different between the LL-BFR-RT and HL-BFR-RT groups value after 8 weeks intervention, where ##P < .01.

performance was significantly greater in the HL-BFR-RT group than that in the LL-BFR-RT group. The HL-RT group was also significantly greater in muscle strength than that in the LL-BFR-RT, and greater but not significant improvement in muscle strength and vertical jumping performance in the HL-BFR-RT group after 8 weeks intervention than that in the HL-RT group.

Our results showed that HL-RT induced muscle adaptations are similar to previous studies. A study from Vechin et al. found leg press 1RM following 12 weeks of LL-BFR-RT increased by 17%, while HL-RT increased by 54%, significant differences were revealed between LL-BFR-RT and HL-RT in leg press 1RM.[20] Kubo et al. found that HL-RT was more effective for maximum voluntary contraction (MVC) than LL-BFR-RT.[21] The review of Slysz et al. also showed that HL-RT increased muscle strength better than LL-BFR-RT training, but the HL-RT group and LL-BFR-RT had similar effects on muscle hypertrophy.[39]

LL-BFR-RT was less effective in increasing muscle strength than HL-RT can at least partly be explained by different changes in neural drive (ie, motor unit recruitment, firing frequency, and synchronization) between LL-BFR-RT and HL-RT, which usually estimated by surface electromyography (EMG). Gabriel et al. tested the surface EMG of LL-BFR-RT. They showed that LL-BFR-RT did not show a significant increase in EMG activity.[40] Cook et al. also reported higher EMG amplitudes during an acute HL-RT than LL-BFR-RT sessions.[41] Similar results were observed long-term, with 12 weeks of training significantly increased surface EMG amplitudes in HL-RT (20%), while LL-BFR-RT (3.2%) did not.[21] Moore et al. also demonstrated no change in muscle activation after LL-BFR-RT compared to HL-RT.[42] Therefore, it is possible that the improvement in muscle strength in the HL-RT group might be partly caused by the increase in neural stimulation.

Our results also showed that greater but not significant improvement in muscle strength and vertical jumping performance was observed in HL- BFR-RT, compared with HL-RT after 8 weeks, which was similar to Cook et al.[14] However, this results are contrary to the study of Laurentino et al, which found that vascular occlusion in combination with high-intensity strength training (60% 1RM or/and 80%1RM) did not augment muscle strength when compared to high-intensity strength training alone.[23] This might be caused by the different training experiences, the way of BFR, types of exercise, and the value of occlusion pressures.[14,23] In Laurentino et al., subjects are physically active men, the way of BFR was unilateral and the type of exercise was single-joint movements. According to a meta-analysis, compared to occlusion pressures below 150 mmHg, muscle strength gains were more obvious in the group with occlusion pressures higher than 150 mmHg.[39] While the 60% 1RM and 80%1RM groups had occlusion pressures of 125.6 ± 15.0 mmHg, 131.2 ± 12.8 mmHg, respectively, in this study. In our study and the study of Cook et al., subjects are well-trained athletes, the type of exercise was multi-joint movements and the way of BFR was bilateral BFR, the value of occlusion pressures was about 180 mmHg. Therefore, the training experiences, way of BFR, types of exercise and value of occlusion pressures might cause the different results between this study and previous studies.

A further finding of our study was a significant improvement in muscle strength and vertical jumping performance compared with the HL-BFR-RT group to the LL-BFR-RT group. Compared with the LL-BFR-RT group, the HL-BFR-RT group had a significant increase in muscle strength, possibly because the HL-BFR-RT group caused different hormone responses compared with the LL-BFR-RT group and suffered from severe mechanical stress caused by heavy external load. Previous research has shown that growth hormone secretion is significantly increased after BFR training at low-intensity loads.[5,43,44] Cook et al. presented the novel finding that the HL-BFR-RT was not only associated with differential hormonal profiles but also with large elevations in free testosterone that were maintained across the training block and cortisol responses that were attenuated over the training period.[14] On the other hand, heavy external load causes severe mechanical stress, increases motor unit recruitment, improves the synchronization of muscle firing, and coordination of intermuscular and intramuscular.[40,45] It seems that the HL-BFR-RT makes up for the lack of muscle stimulation of LL-BFR-RT.

Compared with the LL-BFR-RT group, the HL-BFR-RT group had a significant increase in vertical jumping performance, possibly because of the increase in muscle strength and neural adaptations. On the one hand, better jumping performance is associated with greater muscle strength, suggesting lower limb strength is a major factor in vertical jumping performance.[46] A previous study reported 14.6% increase in leg press 1RM and 21.7% increase in leg half-squat 1RM, resulting in 9.3% increase in CMJ height.[47] However, studies using LL-BFR-RT showed 9.6% and 17.4% increases in leg press and extension 1RM, respectively, with no improvement in jumping performance.[15,24] They suggested that a 9.6% or 17.4 increase in muscle strength was insufficient to improve jump performance.[15,46] Additionally, the inability of LL-BFR-RT to improve jump performance is in part attributable to the absence of the increment in motor unit activation.[25] In this study, on the one hand, the degree of strength gain in the HL-BFR-RT group was 28.6% in leg half-squat 1RM, which was significantly larger than that in the LL-BFR-RT group and previous studies,[15,24] resulting in significant improvement in both SJ and three-footed takeoff. Therefore, the degree of strength increase might partly explain the HL-BFR-RT to improve jump performance.

On the other hand, neural adaptations such as increased activation and synchronization of motor units have been regarded as important factors for improving maximal power output.[44,48,49] Studies of conventional heavy resistance training have been shown to increase motor unit activation during maximal voluntary contraction.[50] However, studies on LL-BFR-RT have failed to show changes in motor unit activation.[21,51] In addition, compared with LL-BFR-RT, HL-BFR-RT suffered from severe mechanical stress caused by heavy external load, which could increase motor unit recruitment, improve the synchronization of muscle firing and coordination of intermuscular and intramuscular.[40,45] So it might be the both, increase in muscle strength and neural adaptations contribute to a significant increase in vertical jumping performance in the HL-BFR-RT group. As there are no studies directly investigate the neural adaptation under HL-BFT-RT, further research is needed to explore how neural adapt under HL-BFT-RT.

Several limitations did exist in this study. Firstly, we had a relatively low number of subjects in our study and short duration of the training period. Furthermore, our results may not apply to single-joint movements such as the knee extension and flexion. Additionally, muscle strength testing methods in this study may have an influence on the muscle strength data collected. Our participants did not train specifically for an isokinetic strength measure, and the test time interval between maximal strength and vertical jumping was a little bit short which may also influence the measurement results. Besides, a potential limitation is that the participants in this study were preseason, well-trained, male, collegiate volleyball players. The results might not be generalizable to other or inseason athletic populations, non-athletes, or those who are weight training novices.

Practical Applications

HL-BFR-RT has been demonstrated to enhance muscular development in well-trained volleyball players. However, the current study does not support using LL-BFR exercise as a supplementary stimulus to enhance muscular development or jumping performance during the preseason phase for Chinese volleyball male players. It should be highlighted though that HL-BFR-RT did not have detrimental impacts on muscular development in this study. Strength coaches looking to implement HL-BFR-RT (eg, for athletes who can tolerate training with heavy loads and want to improve muscle strength, especially jumping ability.) can be confident that this training strategy will help.

Declaration of Conflicting Interests

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