

Effect of Supervised Rehabilitation Program Combined with Blood Flow Restriction Training on Muscle Activation and Postural Control in Athletes with Chronic Ankle Instability: A Randomized Controlled Trial

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Abstract:

Blood flow restriction (BFR) training has been advocated as an alternative approach for improving clinical outcomes in patients undergoing musculoskeletal conditions. This study compared effects of a supervised rehabilitation program (R) with and without blood flow restriction training on muscle activation and postural control in athletes with chronic ankle instability (CAI). Twenty-four collegiate athletes with CAI, aged between 18-23 years, participated in this study. They were randomly allocated to the BFR+R (n = 12) and R (n = 12) groups. Both groups underwent similar rehabilitation three days/week for 6 weeks. BFR+R group wore a cuff around the thigh at 80% arterial occlusion pressure, while the R group received no inflation. Pre- and post-intervention electromyography (EMG) activity of the gluteus maximus, gluteus medius, fibularis longus, and tibialis anterior, and reach distances and center of pressure (COP) movement and excursion during the Y-balance test (YBT) were measured at baseline, 4- and 6-week of intervention. The results demonstrated that both groups showed significantly increased normalized EMG amplitudes for all muscles examined during the YBT in all directions compared with baseline, of which the BFR+R group showed greater improvement (all $P < 0.05$). These results were concomitant with the improvement of reach distances, sway velocity, 95% confidence ellipse area, and path length during the YBT, although no statistical differences were detected between the groups. These findings indicated that despite greater activations of hip and ankle muscles over 6-week intervention, including BFR training in traditional rehabilitation has no additional effect on dynamic postural control compared with the traditional one.

Key Words: Ankle sprain, Occlusion, Electromyography, Balance

Introduction

Lateral ankle sprains are the common musculoskeletal injuries in competitive sports (Hootman et al., 2007). Up to 70% of individuals who encounter an initial ankle sprain can develop chronic ankle instability (CAI), which negatively affects daily living and sports activities (Herzog et al., 2019). Patients with CAI typically present a hallmark of residual signs and symptoms, including subjective feeling of ankle instability, pain, muscle weakness, episodes of the ankle giving way that persists for more than 6 months after the initial injury, and recurrent injury (Hertel & Corbett, 2019). CAI is an encompassed term, which can be divided into mechanical instability (MAI), functional ankle instability (FAI), or a combination of the two. MAI is associated with ligament laxity and altered arthrokinematics, whereas FAI is characterized by impaired postural control and decreased strength and neuromuscular control (Hertel, 2002). Despite extensive studies, the underlying mechanism responsible for CAI development is not fully understood (Delahunt, 2007). One of the factors that may contribute to CAI is impairment in neuromuscular control, as evidenced by altered lower extremity muscle activation patterns and decreased postural stability during functional activities (Delahunt et al., 2006). Patients with CAI have less activation of the peroneus longus (PL) and tibialis anterior (TA) during stepping down in gait (Dundas et al., 2014) and jumping (Delahunt et al., 2006).

Moreover, as the ankle per se is not an isolated joint, its movement patterns are influenced by the proximal muscle activity and strength of the lower extremity (DeJong et al, 2020). Patients with CAI have also demonstrated decreased gluteus medius (GD) and gluteus maximus (GM) activity on the affected side compared with the unaffected side and healthy control counterparts (Friel et al., 2006; Webster & Gribble, 2013). In particular, an association between poor postural control and diminished hip and ankle muscle activity is found in individuals with CAI (McCann et al., 2017). To date, many specific exercise programs (e.g., balance training, strength training, proprioceptive training, and neuromuscular training) have been identified to train multiple components of lower extremity function, postural control, and lower extremity neuromuscular control in patients with CAI (Cruz-Diaz et al., 2015; Grueva-Pancheva, 2021). However, most conventional rehabilitation programs have a limitation for which a heavy load or resistance could not be applied, otherwise it can cause pain and recurrent injuries.

Therefore, they may not fully activate muscle contraction and metabolic stress, which provide an important signal for increasing muscle strength and hypertrophy. As a result, this may limit their efficacy and efficiency to improve postural and neuromuscular control. Thus, determining a new rehabilitation strategy, which maximizes lower extremity muscle activation and adaptation and minimizes excessive pain, is important to manage individuals with CAI.

Blood flow restriction (BFR) training has received increasing attention as a new training method in athletes and rehabilitation settings over the past years. This novel training strategy involves the application of an inflatable cuff or tourniquet around the limb, which maintains arterial inflow while occluding venous return during exercise, resulting in local hypoxia (Loenneke et al., 2012). Thus, BFR combined with low load resistance exercise at 20%–30% of one repetition maximum (1 RM) has been reported to be effective in increasing muscle strength and hypertrophy similar to the traditional high load resistance exercise (70%–80% 1 RM) (Scott et al., 2016). Furthermore, BFR training has been used for maintaining and promoting strength in patients with musculoskeletal condition (Killinger et al., 2020; Burkhardt et al., 2021). Although the mechanism underlying the benefits of BFR training remains unclear, BFR training may augment muscle adaptations to low-intensity exercise by inducing muscle hypoxia and metabolic stress, thereby enhancing the recruitment of high-threshold motor units and type 2 muscle fibers (Lauver et al., 2017; Suga et al., 2009; Yanagisawa & Sanomura, 2017; Counts et al., 2016). In one study, BFR training has been reported to elicit greater muscle activation during submaximal isometric resistance exercise in patients with CAI compared with the control (Killinger et al., 2020). Moreover, a recent study has demonstrated that dynamic balance exercise with BFR induces large-to-small increased muscle activation of the vastus lateralis and soleus muscles and increases postural instability and exertion in individuals with CAI (Burkhardt et al., 2021). Collectively, the incorporation of BFR training with conventional rehabilitation session may be used as an alternative strategy to promote muscle activation and postural control in patients with CAI (Faltus et al., 2018). However, to the best of our knowledge, no evidence examining the effectiveness of BFR training combined with rehabilitation program (BFR+R) on lower extremity muscle activity and dynamic postural control in athletes with CAI has been found.

Therefore, the present study aimed to evaluate the effectiveness of the BFR+R versus R program on lower extremity muscle activation and dynamic postural control during a functional task in athletes with CAI. We hypothesized that the BFR+R program would enhance muscle activation of the lower extremities, leading to improved postural control instability incurred by CAI compared with R alone. The results of this study could help physical therapists and practitioners in developing and designing an effective rehabilitation program for managing athletes with CAI.

Material & methods

Participants

Twenty-eight athletes with CAI aged between 18 and 23 years participated in this study. They were rugby, football, volleyball, handball, and basketball players who are members of university team. Then, they were matched by age, sex, and Cumberland Ankle Instability Tool (CAIT) scores and randomly allocated to either the BFR+R group ($n = 14$) or the R group ($n = 14$, Figure 1). The participants were included if they presented a history of unilateral lateral ankle sprain, which occurred at least 12 months prior to study enrolment; a history of self-reported giving way and/or feelings of ankle instability of the involved ankle during activities of daily living and/or sporting activities for at least 6 months; and a score of $\leq 24/30$ on the CAIT. Participants were excluded from the study if they had a history of bilateral ankle instability; pathological joint laxity (a positive result on the talar tilt test or anterior drawer test); ankle fracture; surgery of the hip, knee, and ankle; and musculoskeletal disorders. All participants were informed of the procedures, benefits, and risks of the study, and they provided written informed consent before enrolling in the study. The protocol was approved by The Research Ethics Review Committee for Research Involving Human Research Participants, in accordance with the standards set by the Declaration of Helsinki.

Study design

A single-blinded randomized parallel controlled design was used to compare the effects of conventional rehabilitation with and without BFR training on the activation of lower extremity muscles and dynamic postural control in athletes suffering from CAI. The study involved three testing sessions: at the beginning (pre-training), 4 weeks (post-training 1), and 6 weeks (post-training 2) after intervention. All participants engaged in their assigned treatment protocols 3 days a week for 6 weeks under the supervision of a researcher. Dependent variables included electromyography (EMG) activities from the GM, GD, TA, and PL; reach directions; sway velocity; 95% confidence ellipse area; and path length during the YBT. Before the study, participants were familiar with all the testing apparatus and exercise protocol. All testing and training sessions were performed in a thermoneutral room, which was maintained at 24 °C–25 °C and 40%–45% relative humidity. Before the measurement, all participants were instructed to avoid any strenuous exercise for 24 h and refrain from caffeine intake.

Intervention

Blood flow restriction training

A pneumatic occlusion cuff with 10 cm width and 75 cm length (Large STRAIGHT Cuffs: HS1003, H Plus cuff, Santa Barbara, California, USA) was used for the BFR training. The participants were asked to lie in a supine position and rest for 5 min. Then, an appropriate-size cuff was wrapped around the proximal thigh of participant's involved limb, and a handheld portable doppler probe (SD3 Vascular, Edan Instrument, Inc., Shenzhen, China) was used to measure participant's posterior tibial artery at the affected side by inflating the cuff to 80% of each participant's personalized arterial occlusion pressure (Lixandrao et al., 2015). The BFR cuff of the participants in the BFR+R group remained inflated throughout the duration of the rehabilitation program and deflated during rests between trials. For the sham-operated rehabilitation program, participants wore a BFR cuff similar to that of the experimental group, except for this cuff was not inflated.

Rehabilitation program

The rehabilitation program was designed to challenge the ability of an individual to maintain single-limb stance and double-limb stance on a stable and unstable surface while performing various balance exercises. The program began with a 5 min dynamic stretching for warming up of lower limb muscles, followed by a 30 min supervised rehabilitation program as previously described (Table 1) (Jaber et al., 2018). Training intensity and progression were performed by decreasing the base of support or manipulating sensory information and by adding movement to make the activity more dynamic. These movements included a single-leg heel raised with weight, single-leg squats, single-limb stance on Bosu ball, double-limb stance with throwing, catching on Bosu, single-limb stance with throwing, catching on Bosu, and Y-balance test (YBT) functional reaching (Muehlbauer et al., 2012). Participants completed a supervised rehabilitation program, three times per week for 6 weeks. All training sessions were conducted in a laboratory under a supervision of the same registered physical therapist. Participants did not participate in any other exercise except for the exercise programs provided in this study.

Table 1. Outline of the rehabilitation program

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Program	Dynamic stretching exercise					
	Double-leg heel raises (4 sets × 30/15/15/15: repetitions, rest 30 s)	Single-leg heel raises (4 sets × 30/15/15/15: repetitions, rest 30 s)	Single-leg heel raises with weight (20% one repetition maximum) (4 sets × 30/15/15/15: repetitions, rest 30 s)	Single-leg heel raises with weight (20% one repetition maximum) (4 sets × 30/15/15/15: repetitions, rest 30 s)	Single-leg heel raises with weight (30% one repetition maximum) (4 sets × 30/15/15/15: repetitions, rest 30 s)	Single-leg heel raises with weight (30% one repetition maximum) (4 sets × 30/15/15/15: repetitions, rest 30 s)
	Double-leg squats (3 sets × 10 repetitions, rest 30 s)	Double-leg squats (3 sets × 10 repetitions, rest 30 s)	Single-leg squats (3 sets × 10 repetitions, rest 30 s, each side)	Single-leg squats (3 sets × 10: repetitions, rest 30 s, each side)	Single-leg squats (4 sets × 10: repetitions, rest 30 s, each side)	Single-leg squats (4 sets × 10: repetitions, rest 30 s, each side)
	Double-limb stance on Bosu (10 s, 5 repetitions per set, 5 sets, rest 30 s)	Single-limb stance on Bosu (10 s, 5 repetitions per set, 5 sets, rest 30 s)	Double-limb stance with throwing and catching on Bosu (5 repetitions per set for 5 sets, rest 30 s)	Double-limb stance with throwing and catching on Bosu (5 repetitions per set for 5 sets, rest 30 s)	Y-Balance Test functional reaching (3 sets × 5 repetitions, rest 10 s)	Y-Balance Test functional reaching (3 sets × 5 repetitions, rest 10 s)
	Y-Balance Test functional reaching (1 set × 5 repetitions, rest 10 s)	Y-Balance Test functional reaching (1 set × 5 repetitions, rest 10 s)	Y-Balance Test functional reaching (2 sets × 5 repetitions, rest 10 s)	Y-Balance Test functional reaching (2 sets × 5 repetitions, rest 10 s)	Single-limb stance with throwing and catching on Bosu (5 repetitions per set for 5 sets, rest 30 s)	Single-limb stance with throwing and catching on Bosu (5 repetitions per set for 5 sets, rest 30 s)

Outcome measurements

Electromyography

EMG activity of GM, GD, PL, and TA from the injured side was collected using a surface wireless EMG device (Mini Wave Infinity, Cometa srl, Italy). The EMG signal was recorded at a sampling rate of 1000 Hz using Qualisys track manager 2.13 (Qualisys, Gothenburg, Sweden).

Surface electrodes were placed parallel to the muscle fibers over the midsection of the muscle bellies in accordance with the Surface Electromyography for the Non-Invasive Assessment of Muscles guidelines (Hermens et al., 2000). Prior to electrode placement, the skin over electrode sites was shaved (if necessary), debrided, and cleaned using an alcohol pad. Disposable standard Ag/AgCl electrodes (Blue-Sensor, Ambu A/S, Ballerup, Denmark) were attached over each muscle of the injured side. The GD electrode was placed one-half

of the distance between the iliac crest and greater trochanter, whereas the GM electrode was placed midway between the second sacral vertebrae and greater trochanter. The TA electrode was placed at one-third the distance of a line between the head of the fibula and medial malleolus, whereas the fibularis longus (FL) electrode was placed on the line between the head of the fibula to the lateral malleolus, approximately 4 cm distal to the fibular head. Electrodes and EMG sensors were further secured to the skin with a flora tape to prevent slippage during testing and reduce movement artifact.

Before testing, two 5 s maximum voluntary isometric contraction (MVICs) was assessed for each muscle for normalization. For the GD muscle, the participant was positioned side-lying on the untested leg with fully extended tested leg, whereas the hip and knee of the untested leg was slightly flexed at 30°, and manual resistance was applied to the distal thigh (Boren et al., 2011). For the GM muscle, the participants were positioned prone lying with the tested knee flexed at 90° and the opposite knee positioned in extension, and manual resistance was applied to the distal thigh (Contreras et al., 2015). For the TA muscle, the participants were allowed to sit on the edge of the bed with 90° knee flexion to provide maximum resistance to ankle dorsiflexion and inversion. Manual resistance was applied on the dorsum on the medial border of the foot. For the PL muscle, the participants were allowed to sit on the edge of the bed with 90° knee flexion and ankle in neutral position during dorsiflexion and plantar flexion to provide maximum resistance to ankle plantar flexion and eversion, whereas manual resistance was applied to dorsum on the lateral border of the foot. The participants were instructed to avoid explosive contraction and to increase their effort gradually to their maximum once they hear the signal “Go.” After which, the participants held maximum contraction for 5 s, two repetitions with a rest period of 30 s between set. Standard verbal encouragement was given for each subject during the test.

EMG data were analyzed using MyoResearch-XP 3.8.2. A digital band-pass filter (Lancosh FIR) was set between 20 and 500 Hz. Raw EMG signals were full-wave rectified and smoothed using root-mean-square algorithm with a 50 ms time constant. Muscle activation was defined using the average of 3 s out of the 5 s, which excluded the initial 1 s and final 1 s, and it was normalized by the MVIC signal (%MVIC) for each muscle from toe-off to touch down and returned to the starting position of each YBT trial (Jaber et al., 2018).

Postural control

Postural control was quantified by the reach distance in centimeter (cm) and the magnitude of the center of pressure (COP) movement and excursion during the star excursion balance test (SEBT). In the current study, the YBT was selected because it has been proven to be a valid and reliable measure of dynamic postural control as previously described (Hertel & Corbett, 2019). The three reach directions that we measured included anterior (A), posteromedial (PM), and posterolateral (PL). In brief, the participants stood barefoot with the great toe on the intersection of the three strips of tape during PM and PL directions. The participants were instructed to reach out as far as possible with his or her leg in the target direction without touching the tape or losing balance while standing on the involved limb and hands on hip. The distance was measured from the center of the grid to the farthest reach point. An unsuccessful trial was defined as follows: participants lifted their hands off their hips, moved or lifted the stance foot, lifted the heel, did not return the reach foot to the starting position, lost their balance, or did not maintain a unilateral stance during the trial. Unsuccessful trial was discarded and reattempted. Three trials were completed for the three directions, and the maximum distance for each reach direction was recorded. A 30 s rest period was allowed between trials. The participants completed at least three practice trials for each exercise before testing, and the starting position was random to avoid a learning effect. Reach distances were normalized to a lower limb length (LL), which was measured from the anterior superior iliac spine to the distal end of the medial malleolus with the subject lying supine. The YBT composite score was calculated by dividing the sum of the three reach distances in A, PM, and PL by three times the LL of the individual and then multiplied by 100, $[(A + PM + PL) / (LL \times 3)] \times 100$ (Plisky et al., 2009).

The COP measures, including the COP sway area (95% ellipse area; mm²), mean sway velocity (mm/sec), and path length (mm), were simultaneously recorded during the performance of YBT using a force plate (Bertec force plates, MIE Medical Research Ltd., United Kingdom). A Qualisys track manager 2.13 (Qualisys, Gothenburg, Sweden) was used to acquire COP data during the YBT. In addition, the sway area was defined as the magnitude of distribution of COP trajectories, and the average speed of COP movement was calculated by dividing the total COP excursion with the sampling period. Moreover, the COP path length was the traveling distance of COP excursion from the starting position to the maximal position of the COP during each test. COP data were acquired at a sampling rate of 100 Hz (Jaber et al., 2018).

Statistical analysis

All results were analyzed using SPSS v. 26 (SPSS Inc., Chicago, IL, USA). Data were expressed as mean and standard deviation. The Shapiro–Wilk test was used to check whether the data were normally distributed. A 2 (group) $\times$ 3 (time) repeated measure ANOVA was used to determine the main interaction of dependent variables within the group (pre-training vs. post-training) and between the groups (BFR+R vs. R). When a significant interaction was indicated, the Bonferroni correction and independent t test were applied for post hoc analysis where appropriate. Effect sizes were calculated with regard to η^2 , with values of 0.25, 0.09, and 0.01 corresponding to large, medium, and small effect, respectively (Jung, 2020). A *P*-value <0.05 was considered statistically significant.

Results

In total, 37 athletes with CAI were screened for eligibility to participate in this study. Nine athletes were excluded (six had a history of bilateral ankle instability; two had a knee surgery, and one refused to participate in the study). Therefore, a total of 28 athletes with CAI were included in the study (Figure 1). After enrolment, four participants (two from the BFR+R group and two from the R group) were dropped out and excluded from the analysis. No adverse events were reported during training. Furthermore, no significant differences in baseline characteristics were found between the groups ($P > 0.05$, Table 2).

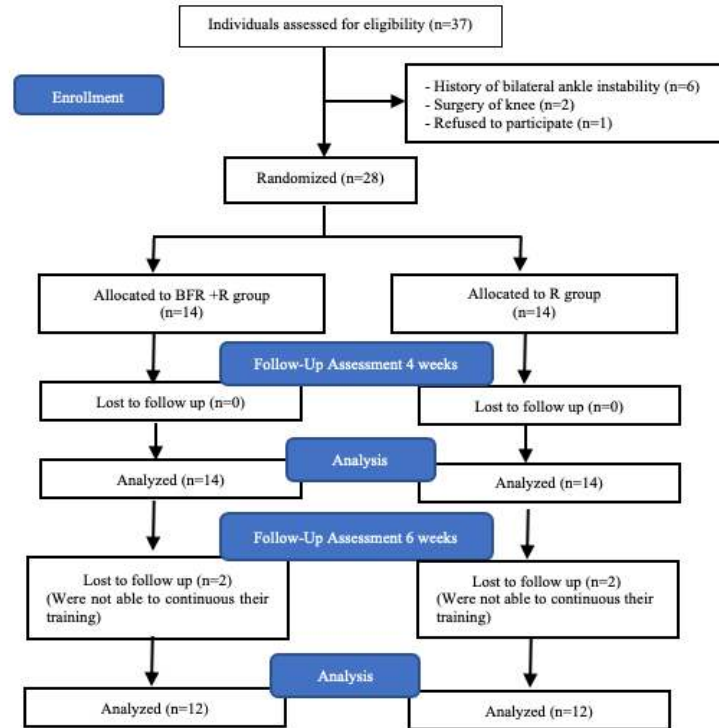


Figure 1. Flow chart of the participants

Table 2. Descriptive data of the subjects

	BFR+R program (n = 14)	R program (n = 14)
Sex, men:women	9:5	9:5
Age (years)	20.50 ± 1.02	20.36 ± 1.08
Weight (kg)	64.64 ± 7.56	61.29 ± 7.58
Height (cm)	171.93 ± 7.13	170.14 ± 7.14
Body mass index (kg/m ²)	21.80 ± 1.05	21.08 ± 1.10
CAIT scores	17.79 ± 3.56	17.86 ± 3.01
Leg length (cm)	81.30 ± 4.89	80.15 ± 3.78

Values were presented as mean ± standard deviation

Abbreviations: BFR, blood flow restriction; R, rehabilitation; kg, kilograms; cm, centimeters; m, meter; LL, leg length

EMG activation

As shown in Figs. 2 A–C, time for normalized EMG activity of GM ($P < 0.001$, $\eta^2 = 0.49$), GD ($P < 0.001$, $\eta^2 = 0.18$), FL ($P < 0.001$, $\eta^2 = 0.43$), and TA ($P < 0.001$, $\eta^2 = 0.41$) in the anterior (A) direction showed significant effects. A post hoc test revealed that the BFR+R and R groups exhibited significant improvements in the EMG activation of GM, GD, FL, and TA following the 4- and 6-week intervention compared with baseline (all, $P < 0.05$). A significant time × group interaction, but not of group, for EMG activity of GM ($P < 0.001$, $\eta^2 = 0.15$), FL ($P < 0.01$, $\eta^2 = 0.27$), and TA ($P = 0.02$, $\eta^2 = 0.18$) was observed in the A direction. Compared with the R group, the BFR+R group showed a significantly greater FL activation at 4-week intervention and significantly higher GM, GD, FL, and TA activation at 6-week intervention.

For PM direction, time for normalized EMG activity of GM ($P < 0.001$, $\eta^2 = 0.52$), GD ($P < 0.001$, $\eta^2 = 0.71$), FL ($P < 0.001$, $\eta^2 = 0.61$), and TA ($P < 0.001$, $\eta^2 = 0.54$) showed significant main effects. A post hoc test revealed that the BFR+R and R groups exhibited significant improvements in EMG activation of GM, GD, FL,

and TA following 4 and 6-week intervention compared with baseline (all, $P < 0.05$). A significant time $\times$ group interaction for EMG activity of GD ($P = 0.04$, $\eta^2 = 0.16$), FL ($P < 0.01$, $\eta^2 = 0.35$), and TA ($P < 0.001$, $\eta^2 = 0.31$) and a significant group interaction for EMG activity of TA ($P < 0.001$, $\eta^2 = 0.45$) were observed in the PM direction. Compared with the R group, the BFR+R group showed significantly greater GM and TA activities at 4-week intervention and significantly higher GD, FL, and TA activation at 6-week intervention (all, $P < 0.05$).

For PL direction, time for normalized EMG activity of GM ($P < 0.001$, $\eta^2 = 0.66$), GD ($P < 0.001$, $\eta^2 = 0.72$), FL ($P < 0.001$, $\eta^2 = 0.46$), and TA ($P < 0.01$, $\eta^2 = 0.42$) showed significant effects. A post hoc test revealed that the BFR+R and R groups exhibited significant improvements in EMG activation of GM, GD, FL, and TA in the PL direction over 6-week intervention (all $P < 0.05$). In addition, a significant time $\times$ group interaction for EMG activity of GM ($P < 0.01$, $\eta^2 = 0.23$), GD ($P = 0.03$, $\eta^2 = 0.15$), FL ($P < 0.01$, $\eta^2 = 0.35$), and TA ($P < 0.01$, $\eta^2 = 0.33$) and a significant group interaction for EMG activity of GM ($P = 0.02$, $\eta^2 = 0.21$) and TA ($P < 0.01$, $\eta^2 = 0.40$) were found. Compared with the R group, the BFR+R group showed significantly greater GM and TA activities at 4-week intervention and significantly higher GM, GD, FL, and TA activation at 6-week intervention (all $P < 0.05$).

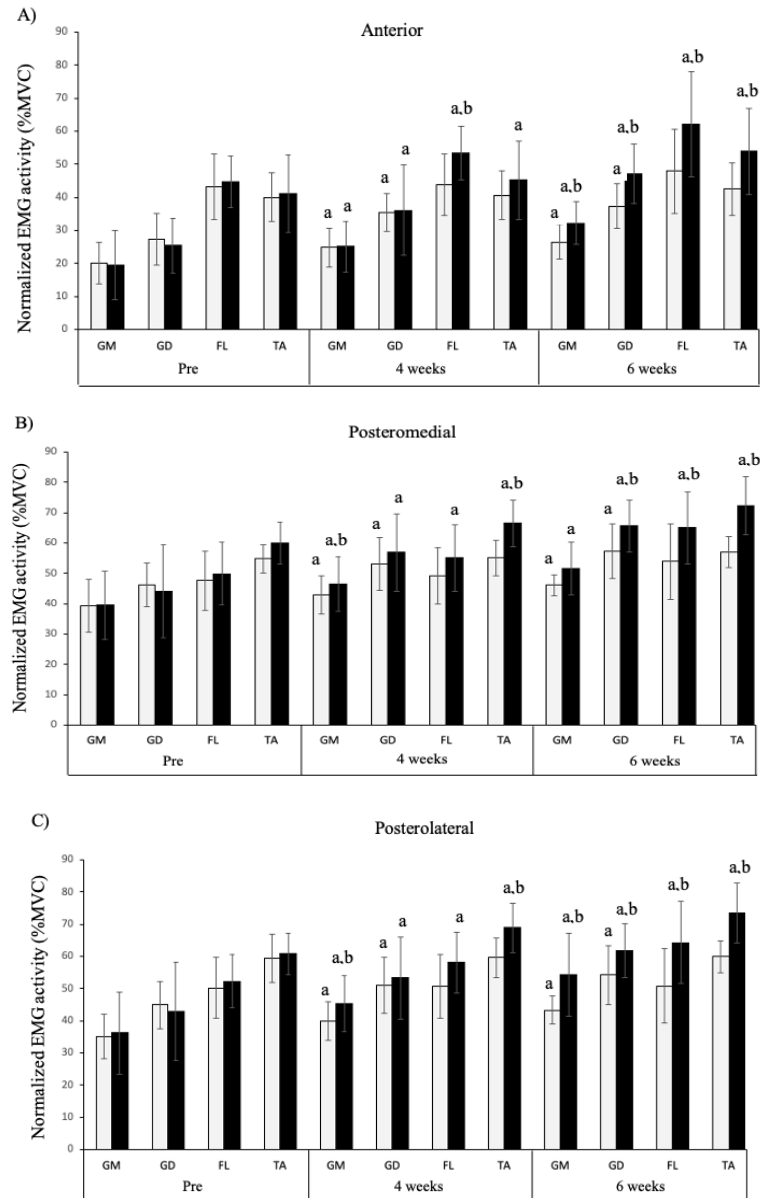


Figure 2 A–C. Mean and standard deviation of the EMG activity of the gluteus maximus (GM), gluteus medius (GD), fibularis longus (FL), and tibialis anterior (TA) during the YBT in anterior (A), posteromedial (B), and posterolateral (C) reach directions between the BFR+R (black bar) and R (open bar) groups.

^a Significantly different between pre- and post-intervention, $P < 0.05$

^b Significantly different from the R group, $P < 0.05$

Postural control**Composite scores and YBT reach distance**

As shown in Table 3, a significant main effect of time for composite scores and reaching distance in all directions (C; $P < 0.001$, $\eta^2 = 0.96$, A; $P < 0.001$, $\eta^2 = 0.95$, PM; $P < 0.001$, $\eta^2 = 0.88$, and PL; $P < 0.001$, $\eta^2 = 0.89$) and a significant time $\times$ group interaction for reaching distance in all directions during the performance of YBT (C; $P < 0.001$, $\eta^2 = 0.52$, A; $P < 0.001$, $\eta^2 = 0.54$, PM; $P < 0.01$, $\eta^2 = 0.30$, and PL; $P < 0.01$, $\eta^2 = 0.25$) were found. Both groups exhibited significant improvements in YBT composite scores and reaching distances in all directions over a 6-week intervention (all $P < 0.05$).

COP sway measures and path length

A significant time $\times$ group interaction for mean sway velocity was observed across directions (A; $P < 0.01$, $\eta^2 = 0.24$, PM; $P = 0.01$, $\eta^2 = 0.21$, and PL; $P < 0.001$, $\eta^2 = 0.61$, respectively). In addition, a significant main effect of time but not of group for mean sway velocity was observed in all directions (A; $P < 0.001$, $\eta^2 = 0.79$, PM; $P < 0.001$, $\eta^2 = 0.92$, and PL; $P < 0.001$, $\eta^2 = 0.93$, respectively). Similarly, a significant main effect of time for the mean 95% confidence ellipse area was observed across directions (A; $P < 0.001$, $\eta^2 = 0.88$, PM; $P < 0.001$, $\eta^2 = 0.89$, and PL; $P < 0.001$, $\eta^2 = 0.79$, respectively), and a significant time $\times$ group interaction of the mean 95% confidence ellipse area was found in the anterior ($P = 0.01$, $\eta^2 = 0.21$) and PM ($P = 0.02$, $\eta^2 = 0.19$) directions. Moreover, a significant main effect of time but not of group and a time $\times$ group interaction for path length were found in all directions (A; $P < 0.001$, $\eta^2 = 0.83$, PM; $P < 0.001$, $\eta^2 = 0.83$, and PL; $P < 0.001$, $\eta^2 = 0.81$, respectively). No significant differences between groups in all COP were observed, regardless of time (Table 3).

Table 3. Postural control during the YBT at baseline, following 4 and 6-week intervention in the BFR+R and R groups

Direction		BFR+R program			R Program		
		Pre	4 weeks	6 weeks	Pre	4 weeks	6 weeks
Composite scores		96.48 ± 8.46	100.17 ± 8.37 ^a	103.41 ± 8.96 ^a	96.26 ± 6.35	98.38 ± 6.06 ^a	100.35 ± 5.49 ^a
Reach Distance (%LL)	A	92.76 ± 9.99	97.06 ± 9.78 ^a	100.49 ± 10.35 ^a	92.21 ± 6.14	94.04 ± 6.00 ^a	95.62 ± 5.29 ^a
	PM	99.24 ± 10.35	103.24 ± 10.18 ^a	106.76 ± 10.61 ^a	99.50 ± 7.58	101.97 ± 7.42 ^a	104.04 ± 6.89 ^a
	PL	97.45 ± 7.94	100.20 ± 7.98 ^a	102.97 ± 8.23 ^a	97.07 ± 7.03	99.13 ± 6.87 ^a	101.40 ± 6.40 ^a
Sway velocity (mm/s)	A	64.61 ± 7.48	60.74 ± 6.24 ^a	56.68 ± 6.18 ^a	64.44 ± 7.52	62.55 ± 7.44 ^a	61.82 ± 6.92 ^a
	PM	70.61 ± 3.67	67.86 ± 3.59 ^a	64.91 ± 3.96 ^a	70.80 ± 4.05	68.45 ± 3.98 ^a	67.40 ± 3.54 ^a
	PL	70.79 ± 2.58	67.81 ± 2.99 ^a	65.58 ± 2.92 ^a	70.74 ± 4.03	69.27 ± 4.21 ^a	67.61 ± 4.23 ^a
95% Confidence Ellipse Area (mm ²)	A	3100.18 ± 296.19	2861.90 ± 229.74 ^a	2738.80 ± 224.34 ^a	3130.29 ± 239.92	3024.36 ± 277.11 ^a	2871.26 ± 263.41 ^a
	PM	3106.95 ± 209.50	2910.71 ± 162.43 ^a	2747.99 ± 160.06 ^a	3128.80 ± 234.96	2970.41 ± 174.14 ^a	2857.51 ± 179.61 ^a
	PL	2767.12 ± 181.98	2607.22 ± 225.21 ^a	2445.52 ± 199.50 ^a	2793.85 ± 165.86	2685.39 ± 179.35 ^a	2599.63 ± 183.42 ^a
Path Length (mm)	A	875.66 ± 101.46	750.66 ± 84.10 ^a	714.54 ± 89.19 ^a	892.92 ± 110.03	797.89 ± 88.82 ^a	772.78 ± 99.23 ^a
	PM	971.41 ± 105.57	826.14 ± 72.97 ^a	776.67 ± 60.50 ^a	970.75 ± 92.83	880.37 ± 66.50 ^a	812.24 ± 75.08 ^a
	PL	958.47 ± 75.41	850.39 ± 65.52 ^a	811.74 ± 61.46 ^a	951.94 ± 105.90	881.23 ± 59.84 ^a	863.23 ± 56.80 ^a

Values were expressed as mean and standard deviation

Abbreviations: BFR, blood flow restriction; R, rehabilitation; LL, leg length; sec, second; mm, millimeters; A, anterior; PM, posteromedial; PL, posterolateral

^a Significantly different from pre-intervention, $P < 0.05$

Discussion

This study aimed to determine whether the BFR training combined with traditional rehabilitation program would result in greater lower extremity muscle activation, thus leading to improved postural control in athletes with CAI compared with traditional rehabilitation alone. We found that although the BFR+R program produced significantly greater EMG activation in hip and ankle muscle compared with traditional rehabilitation alone, they failed to show any additional benefits on dynamic postural control during the YBT in athletes with CAI.

In the present study, a supervised rehabilitation exercise (including balance exercise, strengthening, and proprioceptive training) was selected because of its effectiveness in improving postural control and preventing recurrent injury compared with a single specific exercise (Hale et al. 2007; Jaber et al., 2018; Werasirirat and Yimlamai, 2022). Our finding that the EMG amplitude of FL and TA muscles were considerably increased during the YBT in the BFR+R group than in the R group supported our hypothesis, which was consistent with the findings of previous reports. For example, Killinger et al. (2020) examined the acute effect of BFR on muscle activation in patients with CAI and demonstrated greater TA and FL activation during BFR with isometric dorsiflexion and eversion exercises, respectively, compared with controls. By contrast, Burkhardt et al. (2021) found no beneficial

effects of BFR training on FL and TA muscle activation during acute resistance exercise or dynamic balance exercise with BFR in individuals with CAI compared with balance exercise alone. These different results may be due to the differences in exercise protocol (isometric vs. dynamic exercise) and duration (acute vs. chronic effect) employed among studies. Although the mechanism underpinning this adaptive response is unclear, an increased recruitment of higher threshold motor units (primarily composed of fast twitch fibers) after BFR+R training has been suggested. In particular, previous studies have demonstrated that a reduction in oxygen availability and metabolic accumulation induced by BFR training and exercise can augment recruitment of fast twitch motor units possibly through the stimulation of group III and IV afferent to maintain force production, thereby increasing EMG activity (Scott et al., 2016).

In addition, we found that the BFR+R group elicited greater activation of GM and GD in all directions than the R group. This finding is in line with the report of other studies. Recent studies have shown that BFR training not only results in greater activation of distal muscles but also proximal muscles to the occlusion area (Bowman et al., 2019; Dankel et al., 2016). The precise mechanism underlying this occurrence is unknown. Theoretically, it is possible that distal occlusion (proximal thigh) may result in muscle fatigue below the cuff and recruitment of synergistic proximal muscles above the occlusion area (gluteal muscles), which helps maintain pelvic stability and dynamic posture control (Madarama et al., 2008).

Dynamic postural control performance is a widely reported activity limitation related to CAI (Gribble et al., 2012). Traditionally, the SEBT has been used as a functional test of dynamic postural control. Shorter reach distances are identified as indicative of dynamic postural control deficits. However, in the present study, the performance of YBT was selected to evaluate the changes in three unique aspects (i.e., anterior and PL directions) of dynamic postural control. Compared with baseline, the BFR+R and R groups showed significant improvements in YBT performance (composite score and reach distances) for 6 weeks, with minimal improvement detected after 4-week intervention. This result indicates the efficacy of the combined rehabilitation program used in the present study in improving dynamic postural control in athletes with CAI.

This finding was consistent with the findings of previous reports (Cruz-Diaz et al., 2015; Huang et al., 2014). For example, Cruz-Diaz et al. (2015) showed that a 6-week balance training resulted in significant improvements in SEBT performance in athletes with CAI. Moreover, proprioceptive training for 8-week resulted in improvements in both static and dynamic balance in patients with unilateral CAI (Grueva-Pancheva, 2021). In the current study, dynamic postural control was also quantified by assessing COP movement and excursion. Similarly, we found that neither the reach distances nor COP measures (sway velocity, 95% confidence ellipse area, and path length) in all directions were statistically different between the groups.

This finding was unexpected because the activation of hip and ankle muscles was significantly higher after the BFR+R versus the R program. In addition, the reason for the lack of additive effect is currently unknown, but it may imply that the great muscle activation of lower extremity muscles induced by the BFR+R training may be insufficient to promote postural stability during the YBT in athletes with CAI. On the contrary, the measurement of YBT might not discriminate a subtle improvement in dynamic postural control in athletes with CAI. Additional research with a specific or more challenging functional task is required to answer this question. Nevertheless, this information can help physical therapists and practitioners in selecting an appropriate therapeutic strategy for improving dynamic postural control in athletes with CAI.

Limitations

This study has several limitations. First, the present study did not include a BFR and a control group; thus, their synergistic effects were not investigated. Second, considering the relatively small number of participants and their varying sport disciplines used in this study, the result should be interpreted with caution and not be extrapolated to other athletic populations.

Third, in the current study, only EMG was measured to determine the extent of motor unit recruitment, although athletes with CAI presented neuromuscular deficits in a wide range of outcomes (e.g., decreased neural excitability and strength deficits). Further studies are required to address this issue and to support the abovementioned hypothesis. Fourth, in this study, we did not include a follow up design; therefore, the long-term benefits of the BFR+R program in athletes with CAI are unknown.

Conclusions

Considering patients with CAI typically demonstrated decreased lower extremity muscle activity and altered postural control. The present finding revealed that the addition of BFR training to traditional rehabilitation program over a 6-week period elicits greater activations of both hip and ankle muscles in athletes with CAI. However, it does not further promote postural stability during the YBT compared with the traditional one. Therefore, physical therapists and practitioners should use this adjunctive therapy with caution for improving postural instability in athletes with CAI.

Conflicts of interest

The authors declare no conflict of interest.

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