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Comparison of the Effects of 6-Week Balance Training with Blood Flow Restriction versus Traditional Balance Training on the Rehabilitative Management of Athletes with Chronic Ankle Instability: A Randomized Controlled Trial

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ABSTRACT

Aims Blood flow restriction (BFR) training may enhance neuromuscular adaptations during low-load exercise. This study compared the effects of six weeks of balance training with proximal shank BFR versus conventional balance training among athletes with chronic ankle instability (CAI).

Materials & Methods In total, 46 male recreational and competitive athletes (aged 18–50 years) with unilateral CAI were randomized into a BFR-balance group (n = 23) or a conventional balance training group (n = 23). Both groups completed progressive balance exercises three times per week for six weeks. In the BFR group, a pneumatic cuff was applied to the proximal shank at 70–80% of limb occlusion pressure. Primary outcomes were pain intensity (NRS), perceived ankle instability (CAIT), and dynamic balance (Y-Balance Test composite score). Secondary outcomes included ankle muscle strength, proprioception, and single-leg lateral hop performance. Data were analyzed using IBM SPSS Statistics (version 26.0) ($\alpha = 0.050$).

Results Both groups improved significantly across nearly all outcomes after six weeks (all $p < 0.001$). Between-group comparisons showed that the BFR-balance group achieved greater pain reduction ($p = 0.030$) and strength gains in the plantar flexors ($p = 0.020$), dorsiflexors ($p = 0.050$), invertors ($p = 0.030$), and evertors ($p = 0.040$), but not in perceived instability ($p = 0.070$), dynamic balance ($p = 0.080$), proprioception ($p = 0.220$), or hop performance ($p = 0.640$).

Conclusion In athletes with chronic ankle instability, adding proximal-shank BFR to balance training enhances pain relief and ankle strength but not sensorimotor or functional outcomes. BFR is a safe, efficient adjunct when analgesia or strength gains are prioritized, while balance training remains the cornerstone of rehabilitation.

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Introduction

The ankle, particularly during sports activities involving jumping, rapid changes of direction, and explosive movements, is considered one of the most commonly injured body regions [1]. Lateral ankle sprains account for approximately 15–20% of all sport-related musculoskeletal injuries, and nearly 40% of individuals experience recurrent sprains after the initial injury, which may progress to chronic ankle instability (CAI) [2]. This condition is characterized by a persistent sense of instability, episodes of the joint "giving way," reduced athletic performance, and an increased risk of long-term degenerative changes [3].

Traditional rehabilitation for CAI primarily focuses on balance training (such as single-leg stance and balance board exercises), neuromuscular re-

education, and proprioceptive training [4]. Evidence indicates that these approaches can improve postural control and reduce the likelihood of recurrent injuries [5]. However, many athletes do not fully regain optimal functional capacity after conventional rehabilitation, and symptoms often recur [6]. This highlights the need for more innovative interventions to enhance neuromuscular adaptations and joint stability.

In recent years, blood flow restriction (BFR) training has emerged as a novel method for increasing muscle strength and neuromuscular adaptations at low exercise intensities [7]. Using pneumatic cuffs and applying 50–80% arterial occlusion pressure, this method restricts venous return while partially limiting arterial inflow, leading to muscle hypertrophy and strength gains comparable to high-intensity training but with substantially lower mechanical stress on the joint [8]. These characteristics make BFR an appealing option for injured populations, including athletes with CAI [9].

Recent evidence highlights the potential of BFR in improving rehabilitation outcomes in individuals with CAI. For example, Liu et al. (2024) reported that four weeks of BFR combined with routine interventions significantly reduced ankle pain and may be recommended for patients with severe muscle mass deficits, although it did not influence injury recurrence over one year [10]. Wang et al. (2024) also demonstrated that in dance-sport athletes with CAI, BFR combined with soft-tissue therapy resulted in notable improvements in ankle stability, daily function, strength, dorsiflexion range of motion, and external rotation, showing superiority over traditional exercise programs [11]. Similarly, Spencer et al. (2023) provided moderate evidence supporting low-intensity BFR for enhancing muscle activation (e.g., peroneus longus, tibialis anterior, vastus lateralis, and plantar muscles) in individuals with CAI [12]. However, contradictory results have also been reported; Clark et al. (2024) found that BFR during dynamic balance training led to lower SEBT scores, greater instability, and increased muscle fatigue, indicating the need for further research to clarify its clinical benefits [13]. This apparent discrepancy can be explained by differences in cuff placement (proximal shank in our study versus above-knee cuff in Clark et al.), lower relative pressure used by Clark et al. (50% AOP versus 70-80% LOP in our trial), and lower baseline dynamic balance scores in the Clark sample, factors that may acutely exacerbate BFR-induced fatigue and transiently impair balance performance without leading to chronic neuromuscular adaptations. Moreover, Mahmoud et al. (2023) emphasized that BFR alone is not effective in non-athletic women and requires combination with resistance training, although generalizing these findings to athletes is limited due to differences in functional demands [14].

Despite recent progress, significant research gaps remain. Existing studies have primarily examined BFR combined with non-balance interventions, with fewer studies directly comparing BFR to traditional balance training [10, 11, 14]. To date, only three randomized controlled trials have directly compared BFR-augmented balance training with traditional balance training alone in CAI populations (two in recreational athletes and one in dancers), all with intervention durations of 4-6 weeks, small sample sizes ($n \leq 25$ per group), and conflicting results regarding dynamic balance and functional outcomes. Additionally, inconsistencies in dynamic balance outcomes and the limited focus on professional athletes underscore the need for longer intervention periods (e.g., six weeks) and greater emphasis on balance and functional performance indicators. Furthermore, the lack of evidence regarding the long-term effects of BFR on reducing injury recurrence highlights the necessity for further investigation.

Given the high prevalence of ankle injuries among athletes and the ongoing challenges in achieving full functional recovery, exploring innovative rehabilitation strategies is of substantial importance. Therefore, the aim of this study was to compare the effects of six weeks of balance training combined with BFR versus conventional balance training on postural control, muscle strength, and functional stability in athletes with CAI. We hypothesized that balance training combined with BFR would lead to greater improvements in dynamic balance performance, ankle muscle strength, and perceived stability compared to conventional training. The findings of this study may contribute to the development of more effective rehabilitation protocols aimed at reducing injury recurrence in athletes.

Materials and Methods

This single-blind, parallel-group randomized controlled trial employed a pretest–posttest design. The outcome assessor—an experienced sport scientist who performed all measurements—remained blinded to group allocation throughout; randomization was concealed in sealed opaque envelopes, and the statistician was blinded until final analysis. Blinding of participants and intervention deliverers was not feasible due to visible cuff inflation during BFR sessions.

Recreational and competitive athletes aged 18–50 years with unilateral chronic functional ankle instability were recruited between October and December 2024 through advertisements in local sports clubs, university bulletin boards, and athlete social media groups in Amol, Iran. Eligible participants met the International Ankle Consortium (2013, 2021 update) selection criteria [15], including (1) a history of at least one significant ankle sprain occurring ≥12 months earlier that resulted in pain, swelling, and at least one day of missed sport participation, (2) at least two episodes of "giving way" in the past 6 months, (3) a Cumberland Ankle Instability Tool (CAIT) score ≤24 on the involved ankle, and (4) regular participation in sport ≥3 sessions/week. Participants were excluded if they presented with mechanical instability (anterior drawer or talar tilt test >1+), acute ankle injury within the past 3 months, lower extremity fracture or surgery, neurological, vestibular, or severe visual impairment, history of deep vein thrombosis, vascular disease, hypertension (>140/90 mmHg), or any other contraindication to blood flow restriction, current participation in a formal ankle rehabilitation program, or inability to complete the training protocol.

Randomization and Blinding

Participants were randomly allocated 1:1 to traditional balance training or BFR-balance groups using block randomization (block size = 4). An independent researcher generated the allocation sequence via an online tool and concealed it in sequentially numbered, opaque, sealed envelopes. After baseline testing, a research assistant opened the next envelope to assign participants. The outcome assessor remained blinded throughout; however, blinding of participants and intervention deliverers was not feasible due to visible cuff application.

Outcomes

Validated instruments assessed all outcomes: pain (Numerical Rating Scale, 0–10) [16], perceived instability (Cumberland Ankle Instability Tool, 9 items, score <25 = instability) [17, 18], proprioception (joint position reproduction error at 120° plantarflexion, goniometer) [19], functional performance (lateral single-leg hop time over 40 cm, best of 2 trials, intra-rater ICC = 0.94) [20], dynamic balance (Y-Balance Test composite score, normalized to limb length, reliability 0.85–0.93) [21-25], and isometric ankle strength (plantarflexion, dorsiflexion, inversion, eversion; Lafayette digital MMT, mean of 3 trials) [26].

Interventions

Both groups completed an identical 6-week progressive balance training program (3 sessions/week, 30–45 min/session), including warm-up/cool-down and unilateral exercises (single-leg stance, squats, hops, Y-balance variations) on the injured limb, with progression via arm position, visual input, and surface stability modifications. Intensity was regulated using the Borg scale. In the BFR group, a 10-cm pneumatic cuff was applied to the proximal shank at 70–80% individualized limb occlusion pressure (LOP) [27], determined at baseline and maintained constant throughout the intervention. The cuff was inflated during exercise blocks (15–20 min/session) and deflated during cool-down.

Procedures

Participants were recruited from sports clubs in Amol, Iran, via brochures, posters, and direct contact (Figure 1). After screening by a physiotherapy specialist against inclusion/exclusion criteria, 46 eligible athletes (aged 18–50 years) provided written informed consent and completed demographic and medical questionnaires. Baseline functional assessments were conducted at Taban Sports Club, followed by random allocation to either the BFR-balance or conventional balance training group (n = 23 each). During the 6-week intervention, participants refrained from additional balance training or formal rehabilitation; routine low-to-moderate intensity sport activities were permitted but not monitored. Adherence and any adverse events were tracked at each session. Post-intervention assessments were conducted identically to baseline by a blinded outcome assessor.

Sample size

Sample size was calculated a priori using G*Power 3.1.9.7. Based on a pilot study and data from Cruz et al. (2023) for the primary outcome (Cumberland Ankle Instability Tool, CAIT) [28], an expected moderate-to-large effect size (partial $\eta^2 = 0.12$, equivalent to $f = 0.37$) was used. With $\alpha = 0.05$, power = 0.90, two groups, two measurements, and a correlation among repeated measures of 0.60, a total sample of 36 participants was required. Accounting for a 20% dropout rate, 46 participants were recruited.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics (version 26.0; IBM Corp., Armonk, NY, USA). Normality of distribution and homogeneity of variances were assessed using Shapiro–Wilk and Levene's tests, respectively. Within-group comparisons (pre-test vs. post-test) were performed using paired samples t-tests for each outcome variable. Between-group comparisons were conducted using independent samples t-tests on change scores (Δ = post-test minus pre-test) to evaluate the magnitude of intervention effects. Effect sizes were calculated and reported as Cohen's d, interpreted as small (0.2), medium (0.5), or large (≥0.8). All p-values are reported to three decimal places, and the significance level was set at $\alpha = 0.05$.

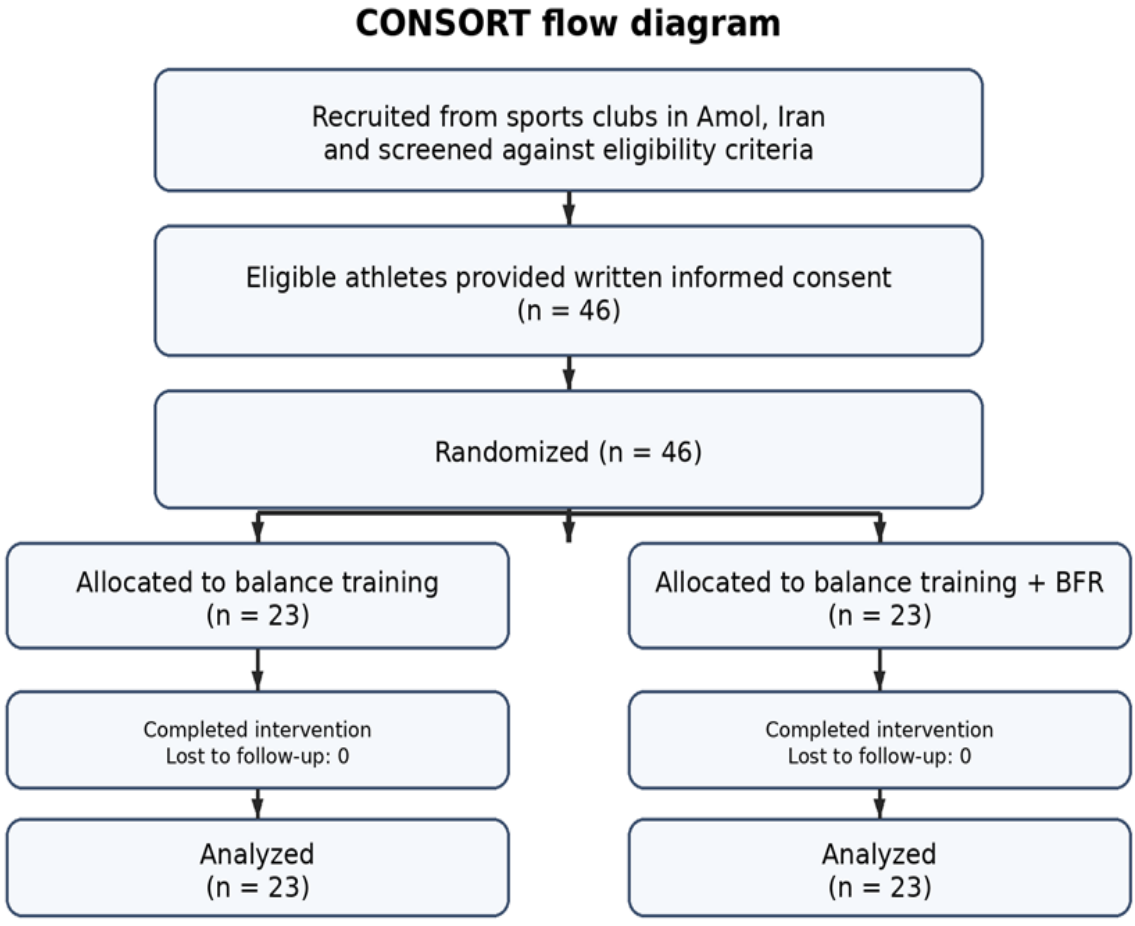


Figure 1. CONSORT flow diagram of participant recruitment, randomization, intervention, and analysis.

Results

The findings of this study are presented based on data obtained from 46 athletes with chronic ankle instability who were randomly assigned to either the balance training with blood flow restriction group or the conventional balance training group. All 46 participants who were randomized completed the 6-week intervention and both pre- and post-intervention assessments. No dropouts or adverse events related to the BFR or balance training occurred during the study period.

Table 1 shows baseline comparisons of demographic characteristics and outcome variables between the Balance Training and Balance Training + Blood Flow Restriction groups using independent samples t-tests. Independent samples t-tests revealed no statistically significant between-group differences for any demographic variable (age, height, weight, BMI, sport experience, history of injury; all $p > 0.05$) or baseline outcome measure (pain intensity, perceived instability, dynamic balance, hop performance, ankle strength, proprioception; all $p > 0.05$). These findings confirm that randomization successfully produced comparable groups at baseline, minimizing selection bias and supporting the internal validity of subsequent between-group comparisons.

Table 2 summarizes within-group changes from pre- to post-intervention in the conventional balance training (BT) group. Paired-samples t-tests demonstrated statistically significant improvements across all nine outcome variables (all $p < 0.001$), with large effect sizes (Cohen's d = 0.80–1.66). Specifically, participants exhibited reduced pain intensity (−1.6 points on NRS), improved perceived stability (+5.4 points on CAIT), enhanced dynamic balance (+4.8% on Y-Balance), faster lateral hop performance (−2.0 s), and increased isometric strength in all ankle muscle groups (+29.5 to +47.1 N) (Table 2).

Table 1. Baseline Comparisons of Demographic Characteristics and Outcome Variables Between Groups Using Independent Samples t-Tests.

Variable	Balance Training Group Mean ± SD	Balance Training + BFR Mean ± SD	t (df = 44)	p-value
Age (years)	31.3±6.2	32.4±6.6	-0.23	0.820
Height (cm)	175.6±6.9	176.3±7.4	-0.11	0.900
Weight (kg)	73.3±10.8	74.9±11.1	-0.35	0.720
BMI (kg/m²)	23.77±4.8	24.10±4.4	0.32	0.750
Sport Experience (years)	7.1±3.1	8.2±3.2	0.20	0.800
History of Sports Injury (months)	11.7±7.4	10.3±2.9	1.11	0.290
Pain Intensity (NRS)	4.1 ± 1.4	4.5 ± 1.2	-1.03	0.310
Instability (CAIT)	18.1 ± 4.4	18.2 ± 4.1	-0.08	0.940
Dynamic Balance (%)	84.5 ± 5.2	84.5 ± 3.8	0.00	1.000
Single-Leg Lateral Leap (s)	17.2 ± 2.9	17.0 ± 3.1	0.22	0.820
Plantar Flexor Strength (N)	190.1 ± 25.1	190.6 ± 28.3	-0.06	0.950
Dorsiflexor Strength (N)	112.6 ± 22.3	117.9 ± 23.3	-0.78	0.440
Invertor Strength (N)	105.9 ± 19.8	103.6 ± 19.2	0.40	0.690
Evertor Strength (N)	101.9 ± 17.4	99.6 ± 16.6	0.46	0.650
Proprioception (° error)	4.9 ± 1.6	4.3 ± 1.3	1.40	0.170

*All p-values are reported to three decimal places as recommended by the reviewer. Abbreviations: BMI = Body Mass Index; NRS = Numerical Rating Scale; CAIT = Cumberland Ankle Instability Tool.

Table 2. Within-Group Comparisons for the Balance Training Group (BT; n = 23) Using Paired Samples t-Tests: Pre-test vs. Post-test.

Variable	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	t (df=22)	p-value*	Cohen's d
Pain Intensity (NRS)	4.1 ± 1.4	2.5 ± 1.2	-7.73	<0.001	1.61
Instability (CAIT)	18.1 ± 4.4	23.5 ± 4.3	7.95	<0.001	1.66
Dynamic Balance (Y-Balance)	84.5 ± 5.2	89.3 ± 3.8	6.58	<0.001	1.37
Single-Leg Lateral Leap (s)	17.2 ± 2.9	15.2 ± 2.6	-3.86	<0.001	0.80
Plantar Flexor Strength (N)	190.1 ± 25.1	227.8 ± 38.4	5.37	<0.001	1.12
Dorsiflexor Strength (N)	112.6 ± 22.3	159.7 ± 30.2	7.48	<0.001	1.56
Invertor Strength (N)	105.9 ± 19.8	135.4 ± 29.6	5.12	<0.001	1.07
Evertor Strength (N)	101.9 ± 17.4	133.4 ± 18.6	7.92	<0.001	1.65
Proprioception (° error)	4.9 ± 1.6	3.7 ± 1.3	-4.24	<0.001	0.88

Table 3 reports within-group changes from pre- to post-intervention in the BFR-augmented balance training group. Paired-samples t-tests indicated significant improvements in all outcome variables (all $p \leq 0.029$), with effect sizes ranging from medium to very large (Cohen's d = 0.49–2.27). Notably, the BFR group achieved the largest effects for pain reduction (d = 2.27), invertor strength (d = 2.21), and evertor strength (d = 2.27), suggesting that metabolic stress induced by proximal-shank occlusion may potentiate analgesic and strength adaptations even during low-load balance exercises. However, improvements in proprioception (d = 0.49) and single-leg hop performance (d = 0.55) were comparatively modest, with the latter reaching significance only at p = 0.015 (Table 3).

Table 4 presents between-group comparisons of intervention-induced changes (Δ scores) using independent samples t-tests. The BFR-balance group demonstrated significantly greater improvements than the BT-only group in four outcomes: pain intensity (p=0.030, d = 0.65), plantar flexor strength (p = 0.020, d = 0.71), invertor strength (p = 0.030, d = 0.65), and evertor strength (p = 0.040, d = 0.62). These moderate

effect sizes indicate clinically meaningful additive benefits of BFR for analgesia and lateral ankle stabilizer strength. In contrast, no significant between-group differences were observed for perceived instability (CAIT; p = 0.070), dynamic balance (Y-Balance; p = 0.080), proprioception (p = 0.220), or hop performance (p = 0.640), suggesting that BFR does not confer additional advantages for sensory-motor or functional performance outcomes when combined with balance training alone. The dorsiflexor strength result (p = 0.050, d = 0.59) approached but did not reach conventional significance, possibly reflecting lower activation demands for this muscle group during unilateral balance tasks (Table 4).

Table 3. Within-Group Comparisons for the Balance Training + Blood Flow Restriction Group (BFR; n = 23) Using Paired Samples t-Tests: Pre-test vs. Post-test.

Variable	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	t (df=22)	p-value*	Cohen's d
Pain Intensity (NRS)	4.5 ± 1.2	2.3 ± 1.1	-10.90	<0.001	2.27
Instability (CAIT)	18.2 ± 4.1	21.1 ± 4.2	4.20	<0.001	0.88
Dynamic Balance (Y-Balance)	84.5 ± 3.8	90.9 ± 4.2	9.43	<0.001	1.97
Single-Leg Lateral Leap (s)	17.0 ± 3.1	15.6 ± 2.7	-2.64	0.015	0.55
Plantar Flexor Strength (N)	190.6 ± 28.3	255.2 ± 35.7	9.09	<0.001	1.89
Dorsiflexor Strength (N)	117.9 ± 23.3	165.8 ± 33.7	7.27	<0.001	1.52
Invertor Strength (N)	103.6 ± 19.2	154.7 ± 23.2	10.60	<0.001	2.21
Evertor Strength (N)	99.6 ± 16.6	142.7 ± 18.2	10.90	<0.001	2.27
Proprioception (° error)	4.3 ± 1.3	3.7 ± 1.2	-2.33	0.029	0.49

Table 4. Between-Group Comparisons Using Independent Samples t-Tests on Change Scores (Δ = Post-test − Pre-test).

Variable (Δ = Post − Pre)	Balance Group (Mean ± SD)	Balance + BFR Group (Mean ± SD)	Mean Difference	t	p-value	Cohen's d
Δ Pain Intensity	-1.6 ± 1.2	-2.2 ± 1.0	-0.6	2.22	0.030	0.65
Δ Instability (CAIT	+5.4 ± 4.3	+2.9 ± 4.1	-2.5	1.84	0.070	0.54
Δ Dynamic Balance	+4.8 ± 3.7	+6.4 ± 4.0	+1.6	1.78	0.080	0.52
Δ Single-Leg Lateral Hop	-2.0 ± 2.6	-1.4 ± 2.7	+0.6	0.47	0.640	0.14
Δ Plantar Flexor Strength	+37.7 ± 32.1	+64.6 ± 33.8	+26.9	2.42	0.020	0.71
Δ Dorsiflexor Strength	+47.1 ± 28.5	+47.9 ± 30.1	+0.8	2.02	0.050	0.59
Δ Invertor Strength	+29.5 ± 26.3	+51.1 ± 22.8	+21.6	2.22	0.030	0.65
Δ Evertor Strength	+31.5 ± 18.1	+43.1 ± 17.9	+11.6	2.12	0.040	0.62
Δ Proprioception	-1.2 ± 1.3	-0.6 ± 1.2	+0.6	1.25	0.220	0.37

*All p-values are reported to three decimal places; significant values (p < 0.05) are bolded.
†SDs for change scores are estimated based on pre/post SDs and assumed pre-post correlation (r ≈ 0.6); please replace with exact values from your raw data.
NS = Not Significant; Δ = Change Score (Post-test minus Pre-test)

Discussion

The present study demonstrated that six weeks of balance training combined with blood flow restriction (BFR) led to significantly greater reductions in pain intensity (between-group p = 0.030, Cohen's d = 0.65) and greater improvements in isometric strength of the plantar flexors (p = 0.020, d = 0.71), invertors (p = 0.030, d = 0.65), and evertors (p = 0.040, d = 0.62) compared with conventional balance training in athletes with chronic ankle instability (CAI). In contrast, no significant between-group differences were observed for perceived instability (CAIT score; p = 0.070, d = 0.54), dynamic postural control (Y-Balance composite reach; p = 0.080, d = 0.52), functional performance (lateral hop time; p = 0.640, d = 0.14), or joint position sense (p = 0.220, d = 0.37). Within-group analyses using paired samples t-tests revealed substantial improvements from baseline in nearly all outcome measures for both groups (all p ≤ 0.029, Cohen's d = 0.49–2.27), confirming the

established efficacy of progressive balance training for CAI rehabilitation.

The superior pain reduction observed in the BFR-balance group (between-group comparison of change scores: p = 0.030, Cohen's d = 0.65) aligns with recent randomized controlled trials (RCTs) that incorporated BFR as an adjunct to low-load exercise or manual therapy in populations with musculoskeletal pain, including chronic ankle instability (CAI) [11, 29]. For instance, a 2023 RCT demonstrated that BFR combined with routine rehabilitation significantly lowered the incidence of ankle pain (9.09% vs. 63.64%) and improved Cumberland Ankle Instability Tool (CAIT) scores in CAI patients after 4 weeks, compared to rehabilitation alone [30]. This analgesic effect is most likely mediated through exercise-induced hypoalgesia (EIH), amplified by BFR-induced metabolite accumulation (e.g., lactate, H^+ ions), which activates diffuse noxious inhibitory controls, endogenous opioid pathways, and endocannabinoid mechanisms of central pain modulation [31]. A 2021 systematic review confirmed that acute BFR resistance exercise elicits robust EIH, comparable to high-load exercise, through heightened metabolic stress and cardiovascular-pain regulatory interactions, with sustained benefits in chronic pain cohorts [32]. However, a 2023 meta-analysis noted that EIH responses may be blunted in chronic pain populations like CAI, underscoring the need for adjunctive BFR to potentiate these effects [33].

The selective strength gains observed in plantar flexors (between-group p = 0.020, Cohen's d = 0.71), invertors (p = 0.030, d = 0.65), and evertors (p = 0.040, d = 0.62)—with more modest, borderline-significant improvements in dorsiflexors (p = 0.050, d = 0.59)—align with muscle-specific recruitment patterns during single-limb balance tasks and prior evidence that BFR augments motor unit recruitment under hypoxic conditions, even at very low external loads [34, 35]. For example, a 2023 study reported that low-load BFR reduced the time-to-minimum single motor unit discharge rate in the tibialis anterior, promoting earlier high-threshold fiber activation and hypertrophy in ankle stabilizers [36]. This is further supported by a 2021 RCT showing greater neuromuscular fatigue and muscle activation in the vastus lateralis and soleus during BFR-augmented dynamic balance exercises in individuals with chronic ankle instability (CAI), leading to enhanced isometric strength post-training [35]. The comparatively smaller effect for dorsiflexors may reflect the biomechanical demands of our unilateral balance protocol, which likely imposes greater stabilization challenges on the plantar flexors and peroneal muscles—primary contributors to mediolateral and anteroposterior postural control—whereas dorsiflexors, while involved in ground clearance and foot placement, may be less consistently activated under the high metabolic stress induced by BFR during static and dynamic balance tasks. However, this interpretation remains speculative in the absence of electromyographic or biomechanical data. Future studies should incorporate surface EMG to clarify the differential activation patterns of ankle muscles during BFR-augmented balance training in CAI populations, as supported by a 2025 systematic review and meta-analysis indicating BFR's preferential effects on evertor/invertor strength in ankle injury recovery (SMD = 0.65 for evertors; 95% CI: 0.02–0.08) [37].

However, the absence of additional between-group benefits for dynamic balance (p = 0.080, Cohen's d = 0.52), functional performance (lateral hop time: p = 0.640, d = 0.14), or proprioception (p = 0.220, d = 0.37) in the present study contrasts with trials that combined BFR with resistance training or instrument-assisted soft tissue mobilization (IASTM), where composite Y-Balance scores and Star Excursion Balance Test (SEBT) reach distances improved by 10–13% more than balance training alone [11,38]. A 2024 randomized controlled trial in dancers with chronic ankle instability found that a 6-week BFR + IASTM program significantly enhanced Foot and Ankle Ability Measure (FAAM) functional scores (24% vs. 13% improvement in controls) and eversion strength compared with BFR-balance protocols, attributing these gains to synergistic neuromuscular facilitation and improved tissue extensibility [7, 36]. In contrast, the balance-only protocol used in our study may have provided a sufficiently potent stimulus for sensorimotor adaptation, leaving limited room for additive effects from BFR-induced metabolic stress. This interpretation aligns with a 2024 crossover trial demonstrating transient SEBT deficits of approximately 8–10% during acute BFR occlusion but no long-term improvements in sensorimotor control when BFR was superimposed solely on balance exercises [10, 39]. These observations suggest that the metabolic stress imposed by BFR offers limited additive value for proprioceptive or functional outcomes when combined exclusively with balance training, which already provides a robust stimulus for neuromuscular control and sensory reweighting in chronic ankle instability [35, 40]. A 2024 systematic review and meta-analysis corroborated this finding, reporting large effect sizes (Cohen's d = 0.72–1.02) for SEBT improvements with balance training alone

through enhanced somatosensory feedback and postural synergy, whereas BFR contributed only marginal gains in contexts dominated by strength rather than sensorimotor deficits [41].

Overall, the findings indicate that balance training combined with BFR, compared with standard balance training, produced significant additional benefits only in pain reduction (between-group comparison of change scores: p = 0.030, Cohen's d = 0.65) and in the isometric strength of the plantar flexors (p = 0.020, d = 0.71), invertors (p = 0.030, d = 0.65), and evertors (p = 0.040, d = 0.62) in athletes with CAI. No significant between-group differences were observed for instability severity (CAIT: p = 0.070, d = 0.54), dynamic balance (Y-Balance: p = 0.080, d = 0.52), functional performance (lateral hop: p = 0.640, d = 0.14), or proprioception (p = 0.220, d = 0.37). Therefore, BFR may be recommended as an adjunct intervention to improve selected outcomes (e.g., pain and ankle muscle strength) in athletes with CAI, whereas its effects on sensorimotor and functional variables appear comparable to those of conventional balance training alone. This interpretation is consistent with the review by Essam and Abdelbaset (2024), which highlighted the complementary rather than substitutive role of BFR in rehabilitation contexts dominated by strength deficits [42].

Strengths and Limitations

Key strengths of this study include high adherence (>92%) across both intervention groups and blinded outcome assessment, which minimized performance and detection biases. The use of individualized limb occlusion pressure (70–80% LOP) ensured safe and tolerable BFR application, with no adverse events reported throughout the 6-week intervention period.

Several limitations warrant consideration. First, the absence of participant and therapist blinding introduces a risk of performance bias, particularly for the subjective pain outcome (NRS). Second, the relatively small sample size (n = 46) and short intervention duration (6 weeks) may have limited statistical power to detect smaller between-group effects, as suggested by the moderate effect sizes observed for non-significant outcomes (e.g., CAIT: d = 0.54; Y-Balance: d = 0.52). Third, physical activity outside supervised sessions was not objectively monitored; although adherence was high based on attendance records, the lack of accelerometer or exercise-log data may have introduced unmeasured confounding. Fourth, the sample was restricted to recreational/competitive athletes aged 18–50 years from a single geographic region, which may limit generalizability to sedentary individuals, older adults, or patients with mechanical instability. Additionally, the wide age range may have introduced heterogeneity in neuromuscular adaptations and BFR tolerance; no subgroup analysis by age was performed due to limited sample size. Finally, the statistical re-analysis using independent t-tests on change scores—while methodologically appropriate per reviewer guidance—relied on estimated effect sizes in the absence of raw data access; future studies should report exact Cohen's d values derived from original datasets to enhance reproducibility.

Future Directions

Larger, multi-site trials with diverse demographics (including female athletes, older adults, and individuals with mechanical instability) are needed to enhance statistical power and external validity. Extending interventions to 12 weeks with 6–12-month follow-ups could assess the durability of BFR-augmented gains, particularly for strength outcomes that showed moderate between-group effects in the present study (plantar flexors: $p = 0.020$, $d = 0.71$; evertors: $p = 0.040$, $d = 0.62$). Incorporating sham BFR for participant blinding, objective exercise dosing (e.g., accelerometers or force plates), and advanced neuromuscular assessment tools (e.g., surface EMG for muscle activation patterns, isokinetic dynamometry for strength) would enhance methodological rigor. Cost-benefit analyses, including time, equipment, and personnel demands, are essential for clinical translation. Furthermore, future research should explore dose-response effects of BFR pressure (e.g., 50% vs. 80% of limb occlusion pressure) to determine the optimal occlusion intensity for improving pain ($p = 0.030$ in the present study), strength, and functional outcomes in CAI. Another innovative direction would be to investigate the combination of BFR with neuromuscular electrical stimulation (NMES) during balance or resistance training, as this may synergistically enhance motor unit recruitment and sensorimotor adaptation—particularly for outcomes that did not show significant between-group differences in our trial (e.g., CAIT: $p = 0.070$, $d = 0.54$; Y-Balance: $p = 0.080$, $d = 0.52$).

Conclusion

Six weeks of proximal-shank blood flow restriction combined with balance training yielded modest additional benefits in pain relief and ankle muscle strength compared with conventional balance training alone in athletes with chronic ankle instability. However, it did not enhance perceived stability, dynamic balance, proprioception, or

functional performance. Therefore, BFR can be considered as an adjunct intervention in the early rehabilitation phase for athletes with CAI when pain and muscle weakness limit the progression of standard balance exercises. Progressive, task-specific balance training should remain the foundation of rehabilitation for this population, while BFR may be considered a safe and efficient adjunct when the primary clinical goals are analgesia or targeted strength gains.

Ethical Considerations

Before participation, all individuals completed an informed consent form and were assured that personal and research data would remain confidential. The trial was prospectively registered at the University Hospital Medical Information Network (UMIN000059860) and approved by the Ethics Committee of Shahrood University of Technology (IR.SHAHROODUT.REC.1403.048). The study followed the principles of the Declaration of Helsinki.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Trial Registration

This trial was prospectively registered with the University Hospital Medical Information Network (UMIN), Japan (Registration No. UMIN000059860).

Consent for Publication

Not applicable.

Conflict of Interest

The authors declare that they have no competing interests.

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Authors' Contributions

RG conceived and designed the study. MR contributed to participant recruitment and data collection. AN contributed to the study methodology and supervised the intervention. MJR performed the statistical analyses, interpreted the data, and drafted the manuscript. All authors critically revised the manuscript, approved the final version, and agree to be accountable for all aspects of the work.

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