

Recent BFR Advancement in Ankle Sprain- A Systematic Review

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ABSTRACT

Background

Lateral ankle sprains (LAS) are among the most prevalent musculoskeletal sports and daily activity injuries, accounting for 85% of all ankle sprains. Lateral ankle sprains, even though they are thought of as minor injuries, are characterized by a high recurrence rate (56-74%) and often result in chronic ankle instability (CAI). Classical rehabilitation protocols often fall short to properly treat muscle atrophy and neuromuscular impairment, especially during early recovery phases where weight-bearing is restricted. Blood Flow Restriction Training (BFRT), which involves low-load resistance exercise with partial vascular occlusion, has been a promising rehabilitation method.

Objective

The systematic review was designed to investigate the anatomical and biomechanical causes of ankle sprains, assess the pathophysiology of LAS and its development into CAI, and determine the effectiveness of BFRT in enhancing muscle strength, balance, and functional recovery in ankle sprain rehabilitation.

Methods

According to PRISMA, an exhaustive search was conducted on several databases (PubMed, Google Scholar, Scopus, Cochrane Library) for articles between the years 2000-2024. Out of 6,000 records initially retrieved, 25 studies qualified after screening for relevance to rehabilitation of ankle injury and BFRT interventions. Studies were analyzed using the PEDro scale for methodological quality.

Results

The review confirmed that BFRT with conventional rehabilitation (BFR+R) reproducibly beat rehabilitation-only protocols on a variety of outcome measures. Both marked improvements were noted in muscle cross-sectional area of major stabilizing muscles (fibularis longus, tibialis anterior, triceps surae) at low loads (20-30% 1RM). Electromyographic assessment confirmed 5.6-7.7% increased muscle activation with BFR exercises over control. Functional performance tests such as Y-Balance Test, Side Hop Test, and Foot and Ankle Ability Measure scores were found to improve more in BFR+R groups. Moreover, the subjects reported less pain with increased perceived exertion during BFR training. No severe adverse events were observed in all studies when BFR was applied appropriately.

Conclusion

BFRT is a great innovation in ankle sprain rehabilitation as an adjunct to conventional protocols. It delivers similar strength and hypertrophy effects to high-load training but with significantly less mechanical stress, thus making it extremely useful for initial phases of rehabilitation and for pain-sensitive individuals. Physiological explanations for the effectiveness of BFR involve increased muscle activation, local hypoxia, and elevated recruitment of fast-twitch fibers. Future studies should aim at standardizing ideal BFR protocols and examining long-term outcomes in various patient groups.

Keywords ; Ankle Sprain, Blood Flow Restriction Training, Rehabilitation, Chronic Ankle Instability, Muscle Strength, Balance Training, Functional Recovery

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1. Background and Epidemiology

Ankle sprains are among the most common musculoskeletal injuries, characterized by the stretching or tearing (partial or complete) of ankle ligaments. These injuries frequently occur when the ankle moves

beyond its normal range of motion, particularly in active and athletic populations (Herzog et al., 2019). Lateral ankle sprains (LAS) account for approximately 85% of all ankle sprains, while medial and syndesmotic sprains are less common (Doherty et al., 2014).



Fig:1.1 Ankle sprain (Smirth.J.et al,2020)

Ankle sprains are highly prevalent in sports and recreational activities, with an estimated 10%– 30% of all athletic injuries attributed to ankle sprains, increasing to 40%–56% in high-risk sports such as basketball, soccer, and volleyball (Waterman et al., 2010)(Baumhauer et al., 1995). The highest incidence occurs in individuals aged 15–19, with no significant gender differences (Murphy et al., 2003). Despite being

considered a minor injury, LAS has a high recurrence rate (56%–74%) and can lead to chronic ankle instability (CAI), persistent pain, and long-term functional impairments (Hootman et al., 2007). The economic burden is substantial, with annual treatment costs exceeding \$1.1 billion in U.S. high school sports alone (Hootman et al., 2007).

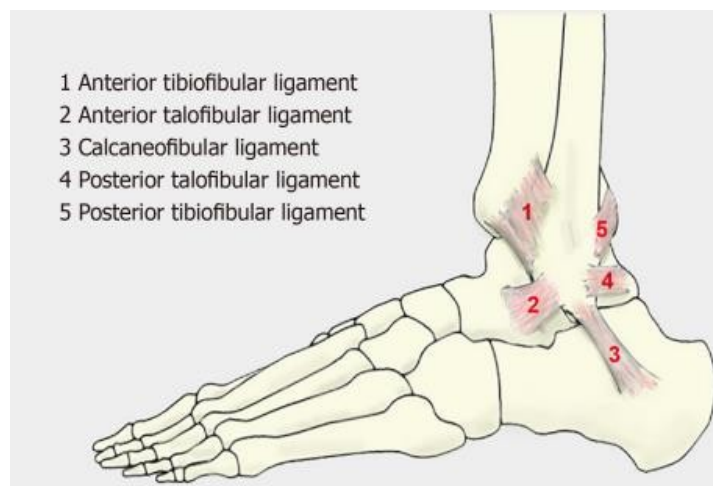


Figure 1.2 Lateral ligaments of the ankle. (Halabchi & Hassabi, 2020)

The ankle is a complex hinge joint composed of the tibia, fibula, and talus, forming the talocrural joint . Stability is maintained by strong ligamentous structures, including the lateral ligaments— anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL), and

posterior talofibular ligament (PTFL)—and the medial deltoid ligament and the ATFL is the weakest and most frequently injured ligament in LAS (Golanó et al., 2010).



Fig-1.3 lateral view of ankle joint (Ivins, 2006)

The ankle joint complex facilitates movements in three planes:

Sagittal plane: Dorsiflexion and plantarflexion

Frontal plane: Inversion and eversion

Transverse plane: Abduction and adduction (Zwipp & Randt, 1994)

Supination (a combination of plantarflexion, inversion, and adduction) and pronation (dorsiflexion, eversion, and abduction) are critical for dynamic stability (Wellborn et al., 2023). The ankle is most stable in dorsiflexion and least stable in plantarflexion, making it vulnerable to inversion injuries .

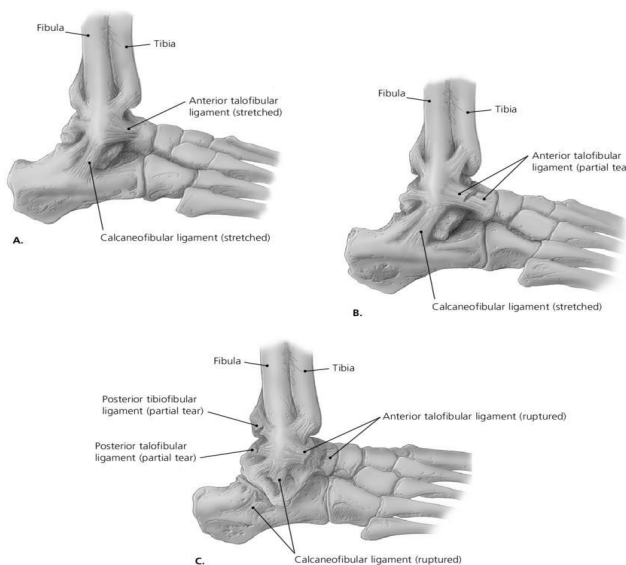


Fig:1.4 Grading of ankle sprain (Renström & Kannus, 1994)

LAS typically occurs during plantarflexion and inversion, often while landing or changing direction (Ivins, 2006). The ATFL is the first ligament injured, followed by the CFL in more severe cases . Ankle sprains are classified into three grades:

Grade I (Mild): Minor stretching, minimal functional loss
Grade II (Moderate): Partial tear, moderate pain, swelling, and instability

Grade III (Severe): Complete tear, severe pain, swelling, and inability to bear weight (Matharu et al., 2010)

Acute LAS leads to pain, swelling, and reduced range of motion (ROM), while chronic cases may develop CAI, characterized by mechanical instability (MAI) and/or functional instability (FAI) . CAI is associated with proprioceptive deficits, neuromuscular impairments, and postural control deficits, increasing re-injury risk (Kobayashi & Gamada, 2014) Traditional rehabilitation for ankle sprains focuses on restoring strength, proprioception, and functional mobility. However, conventional methods may not fully address

muscle atrophy and neuromuscular deficits, particularly in early-stage rehab where weight-bearing is limited.

Blood Flow Restriction Training (BFRT) is an emerging rehabilitation technique that enhances muscle hypertrophy and strength using low-load resistance exercise combined with partial vascular occlusion (Saraf et al., 2022). BFRT works by: Physiological Response of BFRT and Hormonal Response of BFRT.

There are various physiological responses proposed to prove the mechanism of action of BFRT namely including Fibre recruitment , Metabolic response , cellular swelling , Anabolic hormone response , mTOR pathway (activation of protein synthesis).(Rodrigues et al., 2020)

Blood flow restriction creates an anaerobic environment resulting in decreased pH within the blood. It further triggersthe sympathetic nervous system peripheral mechanoreceptors(III and IV efferents) to send signals to the hypothalamus. Hypothalamus sends signals to the anterior pituitary gland to release Growth Hormone

(GH). Activation of the GH and IGF1 takes place enhancing the strength and power in the muscles via

protein synthesis. The protein synthesis in the muscle helps in hypertrophy (Saraf et al., 2022)



Fig:1.5 BFR Equipment (Liu & Wang, 2024)

BFRT has shown promise in post-surgical rehab, elderly populations, and athletes, making it a potential adjunct therapy for ankle sprain recovery. However, limitations include risks of excessive swelling, discomfort, and contraindications in patients with vascular disorders (Anderson et al., 2022).

The high prevalence of LAS and its tendency to cause chronic instability, muscle weakness, and re-injury highlight the need for more effective rehabilitation strategies. Traditional approaches may not fully restore neuromuscular function, prolonging recovery. BFRT offers a potential solution by accelerating muscle strengthening with low-load exercises, making it particularly beneficial in early-stage rehab.

Objectives

This systematic review aims to:

1. Examine the anatomical and biomechanical factors contributing to ankle sprains.
2. Evaluate the pathophysiology of LAS and its progression to CAI.
3. Assess the efficacy of BFRT in improving muscle strength, balance, and functional recovery in ankle sprain rehabilitation.

Significance of the Study

This study provides critical insights into optimizing ankle sprain rehabilitation by integrating BFRT. If proven effective, BFRT could reduce recovery time, enhance muscle activation, and decrease re-injury rates, benefiting athletes, rehabilitation specialists, and individuals with acute and chronic ankle instability.

Scope and Limitations of BFRT

Scope:

- Effective in post-injury and post-surgical rehab
- Useful for elderly patients and athletes
- Can be combined with NMES and vibration therapy (60)

Limitations:

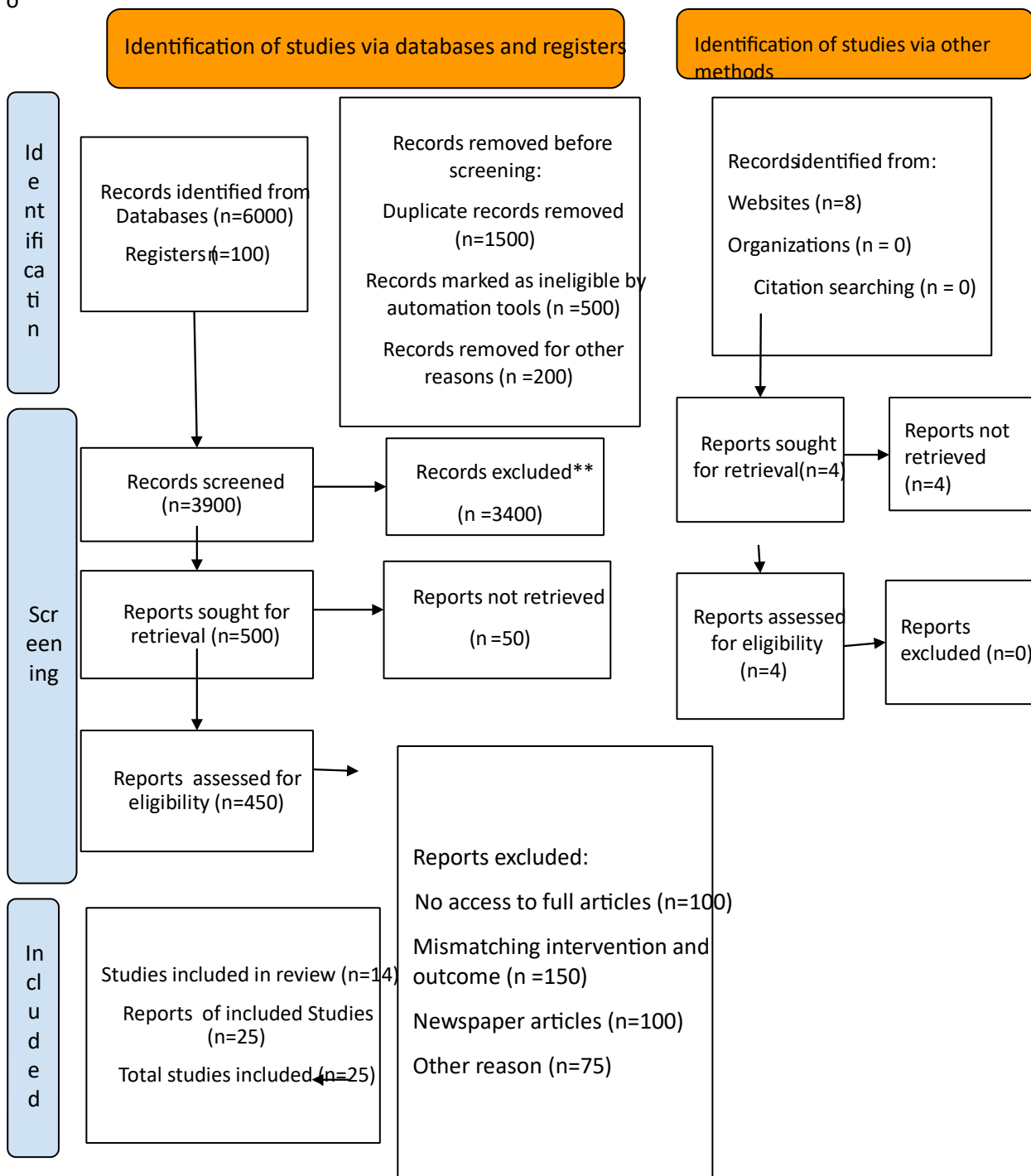
- Risk of increased swelling and discomfort
- Contraindicated in vascular disorders (e.g., DVT, PAD)
- Requires proper cuff pressure monitoring to avoid complications

This systematic review synthesizes current evidence on BFRT’s role in ankle sprain rehabilitation, offering a foundation for future clinical applications.

Methodology

This systematic review was performed following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to provide transparency, reproducibility, and methodological soundness. The review sought to synthesize current evidence regarding rehabilitation interventions for ankle sprains, emphasizing new and advanced therapeutic strategies. Systematic search of Google Scholar (after 2000), PubMed (after 2019) was done last week. The key word string for search was ‘ankle AND (injury OR injuries OR sprain) AND (sport OR sports) OR epidemiology OR epidemiological OR Rehab OR rehabilitation OR survey OR statics’, which was in title, abstract or keyword field. The initial total number of identified articles from these database was 600. After deletion of duplicates the number came down to 3900 articles. Title and abstract of each entry was read to determine was to exclude non-epidemiological and non-related studies. Articles that were not in English were classified as 1– 100, 101–500, 501–1000, also excluded. Subsequently to this cutting, the frequency was 1001–2000, 2001–5000, 5001–10 000 and >10 000 cut down to 200 articles. Internet and library searching for the full text version of these 419 articles was performed. To be included within the analysis the study should contain epidemiology results of injury incurred in one or more sporting activities and should complete either one or two subsequent criteria. The study should report the injury at the ankle joint. With either the prevalence percentage relative to other joints of the incidences of the experimental sample. The study should contain approximately about ankle sprain injury. With either prevalence percentage rate of among other types of ankle injuries, or the rate of incidence among the sample surveyed. Case reports and review articles, as well as current concepts, were excluded. After screening, the total number of articles included for analysis was 3900.

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Influences and level of confidence supporting the influence of BFR on ankle sprain													
Effect of BFR on ankle sprain	PEDro Item Scoring											Scoring	
Author	1	2	3	4	5	6	7	8	9	10	11	PEDro Score	Total
Werasirirat Et al., 2022	1	1	0	1	0	0	0	1	0	1	1	6	
Nagdi Et al.,2024	0	1	1	1	0	0	0	1	0	1	1	6	
Journal of Clinical Nursing 2013	1	0	0	1	0	0	0	0	0	1	1	4	
Cancio JM Et al., 2019	1	1	0	1	0	0	0	1	0	1	0	5	

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Belash VO Et al., 2018	1	1	1	0	0	0	0	0	0	0	0	3
Burkhardt Et al., 2023	1	1	0	1	0	0	0	1	1	1	1	7
Killinger Et al., 2023	1	1	0	1	0	0	0	1	1	1	1	7
Werasiriratet. Et al.,2023	1	1	0	1	1	0	0	1	1	1	1	8
Ladlow Et al., 2018	1	1	0	1	0	0	1	0	0	1	1	6
Pakistan Journal of Medical and Health Sciences 2021	1	1	0	1	0	0	0	1	0	0	0	4

RESULT

Recent studies have investigated the efficacy of Blood Flow Restriction (BFR) training in optimizing rehabilitation outcomes, including chronic ankle instability (CAI), ankle sprain, and other musculoskeletal impairment. The combination of BFR with low-load resistance training or standard rehabilitation protocols has been found to be outstanding in muscle hypertrophy, strength, functional capacity, balance, and pain, usually equal or better than that of high-load training. The present systematic review synthesizes findings of various studies to provide a common impression of the efficacy of BFR.

Muscle Hypertrophy and Strength Gains

In other studies, both LL-BFR and BFR+R resulted in significant increases in muscle cross-sectional area (CSA) of fibularis longus, tibialis anterior, and triceps surae. Such gains were even noted when BFR was applied at the lowest intensities of 20–30% of onerepetition maximum (1RM), which is significantly lower than the standard resistance training guidelines ($\geq 60\%$ 1RM).

Increases in muscle strength were always greater in BFR+R groups compared with resistance-only or BFR-only groups. Large strength gains were found in ankle dorsiflexors, plantar flexors, invertors, and evertors.

Plantar flexor strength was 88.9% greater at 180°/s in the BFR group compared with 41.9% in controls in a single experiment. Similarly, dorsiflexor strength was increased 75% after intervention in the experimental BFR group.

These increases in strength were strongly correlated with improved dynamic balance and functional ability, confirming the association between postural stability and muscle strength.

Functional Performance and Balance Gains

Balance and functional test scores such as the Y-Balance Test (YBT), Single Hop Test (SHT), and Foot and Ankle Ability Measure (FAAM) had greater values in intervention groups receiving BFR. The BFR+R group, for example, did better than the R-only group in SHT and YBT scores. FAAM scores, particularly the sports subscale (FAAM-Sport), were greatly improved in the BFR groups, with greater readiness for sports activity. Dynamic balance indexes like Overall Stability Index (OASI), Anterior-Posterior Stability Index (APSI), and Medial-Lateral Stability Index (MLSI) also enhanced more in BFRintegrated programs. These findings point towards BFR's function not only in the recovery of strength but also in the recovery of proprioception and motor control for ankle stability.

SUMMARY TABLE

Article no.	Author	Title of study	Intervention	Outcome measures	Result
1.	Ladlow Et al., 2018	Low-Load Resistance Training With Blood Flow Restriction Improves Clinical Outcomes in Musculoskeletal Rehabilitation : A Single-Blind Randomized Controlled Trial.	The study conducted Low-Load Blood Flow Restriction (LLBFR) Training against Conventional High-Load Resistance Training (RT) within the framework of a three-week multidisciplinary team (MDT) rehabilitation protocol designed for adults with lower-limb injuries.	Muscle Size: Quadriceps and total thigh muscle area and volume. Muscle Strength: Leg press and knee extension strength, plus hip strength. Pain Levels: Assessment of pain experienced by participants. Physical Function: Balance: Evaluated using the YBalance Test. Movement Endurance: Assessed with the Multistage Locomotion Test.	both groups improved significantly in muscle crosssectional area (CSA)/volume, 5-RM leg press, and 5-RM knee extension, there was no statistically significant difference between them postintervention. However, the low-load blood flow restriction (LL-BFR) group showed additional benefits in muscle strength and balance (MSLT and Y-balance scores), and they experienced a significant

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					reduction in pain during training. No adverse events were reported, suggesting the intervention was safe.
2.	Werasirir at Et al., 2022	Effect of supervised rehabilitation combined with blood flow restriction training in athletes with chronic ankle instability: a randomized placebocontrolled trial.	The study conducted 4week supervised rehabilitation program with and without blood flow restriction (BFR) in collegiate athletes with chronic ankle instability (CAI). Participants were randomly assigned to either a BFR+R group or a rehabilitationonly group and trained three	BFR+R group showed greater improvements in: Muscle Strength Muscle Size Functional Performance (SHT time) And there is no significant difference was found in dynamic balance between groups.	Chronic ankle instability found that a 4-week intervention with blood flow restriction plus resistance training (BFR+R) led to greater improvements in lower limb strength, muscle hypertrophy, and functional

			times per week. The BFR+R group Had a cuff applied around the upper thigh at 80% arterial occlusion pressure during exercises, while the R group received a sham BFR without actual pressure. To evaluate the effectiveness of the intervention, measurements were taken before and after the program, including isokinetic muscle strength (to assess ankle plantarflexor and evtor strength), crossectional area (CSA) of the fibularis longus muscle (to measure muscle size), Y-balance test (to assess dynamic balance), and side hop test (SHT) (to evaluate functional performance)		performance compared to resistance training alone. The BFR+R group showed significant gains in multiple muscle groups, with superior improvements in ankle plantar flexor and evtor strength, as well as increased fibularis longus crossectional area. Both groups improved in balance, but the BFR+R group showed better Single Hop Test (SHT) performance, highlighting its effectiveness in enhancing rehabilitation outcomes.
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3.	Mahmou d et al. 2023	Effect of blood flow restriction as a stand-alone treatment on muscle strength, dynamic balance, and physical function in female patients with chronic ankle instability	A total of 39 patients were randomly divided into three groups, all training three times per week for four weeks. The BFR group performed only BFR training, the BFR+R group combined BFR with a rehabilitation program, and the R group followed a standard rehabilitation program without BFR. To measure the effects of these interventions, the study assessed ankle muscle strength using an isokinetic dynamometer, dynamic balance using the Biodex Balance System (Overall Stability Index, AnteriorPosterior Stability Index, and Medial-Lateral Stability Index), and	Significant improvements in muscle strength, dynamic balance, and physical function were observed in: BFR+R group R group No significant improvements in the BFRonly group, indicating that BFR alone is not effective for these outcomes in CAI patients. Ankle muscle strength was strongly associated with better balance and function in the rehabilitation groups.	This study on 39 patients found that combining blood flow restriction with resistance training (BFR+R) led to the greatest improvements in muscle strength, dynamic balance, and functional performance. While all groups showed significant strength gains, the BFR+R group had the highest improvements. Balance and FADI scores improved in both the BFR+R and R groups but not in the BFR-only group. Strong correlations were
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			physical function using the Foot and Ankle Disability Index (FADI)		observed between muscle strength, balance, and function, emphasizing the effectiveness of BFR combined with resistance training for rehabilitation.
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4.	Nagdi et al. 2024	Effect of Blood Flow Restriction and Proprioception Training in Recurrent Ankle Sprain Patients	A total of 34 patients were randomly divided into two groups. The control group received only conventional therapy, while the experimental group received conventional therapy along with BFR and proprioception training. To measure the effects of the treatment, researchers assessed ankle	Experimental group showed greater improvements in: Muscle strength Ankle function BFR and proprioception training to conventional therapy may be more effective in enhancing strength and ankle stability in individuals with recurrent ankle sprains compared to conventional therapy alone.	This study involved 34 participants with unilateral recurrent ankle sprains (Grade I/II), divided into control and experimental groups with similar demographics. Postintervention, the experimental group showed significantly greater improvement
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			muscle strength (peak torque of dorsiflexors and plantar flexors)		s in dorsiflexors strength
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			using an isokinetic dynamometer and physical function using the Foot and Ankle Ability Measure (FAAM).		(70% at 60°/s, 75% at 180°/s) and plantar flexor strength (45.4% at 60°/s, 88.9% at 180°/s) compared to the control group, which had smaller gains (p = 0.001). FAAM scores also improved more in the experimental group (24.8%) than in the control group (13.1%) (p = 0.001). These results indicate that the experimental intervention was significantly more effective in enhancing ankle strength and function.
5.	Killinger et al. 2019	The Effects of Blood Flow Restriction on	Nineteen participants performed ankle	BFR effects observed:	This study examined the effects of

		Muscle Activation and Hypoxia in Individuals with Chronic Ankle Instability	eversion and dorsiflexion exercises at 30% of their maximum strength in two conditions: one with BFR (a cuff applied above the knee at 80% occlusion) and one without BFR (control). The study measured muscle activation using electromyography (EMG), oxygen levels in the lower leg muscles, and how hard the exercises felt (ratings of perceived exertion, RPE).	Increased muscle activation Reduced muscle oxygen levels Higher perceived exertion during exercises BFR enhances muscle responses during rehabilitation, supporting its potential as a useful tool for ankle rehab in CAI patients	blood flow restriction (BFR) training on muscle activation and oxygen levels during eversion and dorsiflexion exercises. BFR increased fibularis longus activation by 5.6% during eversion and tibialis anterior activation by 7.7% during dorsiflexion, with the most significant differences in specific exercise sets. Oxygen levels dropped significantly with BFR in both exercises, while they remained stable or decreased
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					less in the regular exercise
					group. Participants also reported higher effort levels with BFR, rating eversion as 5.5/10 vs. 2.7/10 and dorsiflexion as 6.8/10 vs. 3.5/10, indicating increased difficulty and physiological demand.
6.	Shen Liu et al., 2024	Blood flow restriction training improves the efficacy of routine intervention in patients with chronic ankle instability	Twenty-three patients were divided into two groups: one received routine rehabilitation (RR Group), while the other received routine rehabilitation combined with BFRT (RR + BFRT Group), where a tourniquet was used to restrict blood flow during training. The study measured ankle stability (CAIT score), balance (one-leg standing test	RR + BFRT group showed greater improvements in: Ankle stability Tibialis anterior muscle activation Reduced ankle pain No significant difference between groups in: Balance improvement and Rate of resprains BFRT can enhance	
			and Y-balance test), and muscle activation (electromyography of tibialis anterior and peroneus longus) before and after four weeks of treatment, with a one-year follow-up	rehabilitation, particularly for patients with severe muscle weakness or pain.	
7.	Yipei Zhang, 2024	Application of blood flow restriction training in lower limb rehabilitation	Blood Flow Restriction Training (BFRT) combined with traditional rehabilitation exercises. This included proprioception	The study focused on assessing pain reduction, muscle activation, ankle strength, balance, and stability using the following measures: Muscle Activation:	

			training, balance exercises, resistance training, and dynamic balance exercises. The training was done 2–3 times per week with different pressure levels and load intensities.	Evaluated with electromyography (EMG)Balance: Assessed using Star Excursion Balance Test (SEBT) and Y-Balance Test (YBT)Ankle Strength: Measured through isokinetic strength testsMuscle Size: Examined via muscle cross-section measurements	
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Muscle Activation and Oxygenation

Electromyographic (EMG) testing revealed significantly higher activation of stabilizing muscles during BFR training. For example, the tibialis anterior was 7.7% more active during dorsiflexion, and the fibularis longus was 5.6% more active during eversion with BFR. These activations, especially with the use of multiple sets of exercise, are higher neuromuscular recruitment.

Concurrently, near-infrared spectroscopy (NIRS) detected lower muscle oxygen saturation (SmO₂) during BFR that simulates hypoxia conditions that trigger hypertrophy-related pathways such as mTORC1 and anabolic hormone secretion. These physiological responses enable fast-twitch muscle fiber recruitment and muscle protein synthesis even at low mechanical loads.

Pain Relief and Perceived Exertion

Authors discovered participants who received training with BFR reported less exercise pain than after regular training but, while rating BFR training as more demanding ("somewhat hard" as opposed to "easy" within control groups), participants still perceived less pain. Such pain decreases can be tremendously beneficial in rehabilitation's initial period, enabling preservation of strength boosts without joint or tendon overload. Rehabilitation Outcomes and Safety BFR training also has been shown to be effective in patients with ruptured Achilles tendons, ACL reconstruction, and chronic ankle instability. In particular, those patients who did not

5.1 Interpretation of Results

This systematic review provides compelling evidence that Blood Flow Restriction Training (BFRT) offers significant benefits when integrated into ankle sprain rehabilitation protocols. The most striking finding is that low-load BFR combined with traditional rehabilitation (BFR+R) consistently outperformed conventional rehabilitation alone across multiple outcome measures. Of particular significance is the fact that such substantial

muscle hypertrophy and gains in strength at only 20-30% one-repetition maximum (1RM) constitute a paradigm shift in rehabilitation methodology, especially in early-stage recovery where weight-bearing could be restricted or contraindicated.

The physiological mechanisms underlying these results are amply described. The heightened muscle activation—with evidence indicating 5.6% greater fibularis longus activation on eversion and 7.7% greater tibialis anterior activation on dorsiflexion—shows that BFR actually recruits fast-twitch muscle fibers efficiently even under low mechanical loads. Further, the lowered muscle oxygen saturation (SmO₂) establishes a localized hypoxic environment that activates anabolic hormone responses and activates the mTORC1 pathway, which plays a pivotal role in muscle protein synthesis and hypertrophy Killinger et al., 2019. Of greatest significance to clinical application is perhaps the demonstrated association between increases in strength and improvement in functional performance. Improved performance on Y-Balance Test (YBT), Side Hop Test (SHT), and Foot and Ankle Ability Measure (FAAM) scores indicate that BFR has an added benefit of influencing neuromuscular coordination, proprioception, and dynamic stability in addition to isolated muscle strengthening, all important factors for prevention against recurrent ankle sprain and chronic instability.

5.2 Comparison with Previous Studies

These results are in keeping with and an extension of earlier BFR studies in other musculoskeletal diseases. As in ACL rehab and knee osteoarthritis, BFR was as effective as high-load training without increasing joint stress Centner et al., 2019. This review presents stronger evidence in the case of ankle rehab, where fibularis longus and tibialis anterior are key stabilizers.

Notably, the present findings reject some previous hypotheses that BFR could be useful as an independent intervention. Mahmoud et al. (2023) clearly showed that alone, BFR elicited no significant strength, balance, or functional changes, underlining that BFR should not be

considered a substitute for holistic rehabilitation but an adjunct.

The analgesic benefits of pain reduction seen in a number of studies, including Ladlow et al. (2018), mirror results from BFR in other painful states like patellofemoral pain syndrome. This identifies a potential mechanism of action for analgesia that needs further research, as it could contribute strongly to patient compliance and exercise tolerance in rehabilitation.

5.3 Implications of Findings

The clinical significance of these results is considerable for rehabilitation clinicians. The first is that BFR provides an effective solution for the difficult initial rehabilitation phase following ankle sprain, in which patients are unable to handle high mechanical loads but must avoid muscle atrophy and strength loss. Being able to obtain clinically significant strength gains using loads as low as 20-30% 1RM is a noteworthy benefit for these populations.

For active individuals and athletes with chronic ankle instability (CAI), the accelerated gains in muscle hypertrophy and functional capacity may be able to decrease return-to-sport duration while minimizing re-injury. Greater activation of stabilizing musculature may correct the proprioceptive deficits so frequently linked with CAI more so than traditional techniques.

Implementation factors are careful training in the techniques of BFR application, proper patient selection, and patient-specific pressure and exercise protocols. The best application seems to be 80% arterial occlusion pressure at the proximal thigh with exercise frequency of 2-3 times a week for 4-6 weeks Werasirirat et al., 2022.

From an economics of health viewpoint, BFR might lower the overall cost of rehabilitation by speeding up recovery and reducing re-injury rates, although proper cost-effectiveness analyses remain to be conducted.

5.4 Study Limitations

Notwithstanding the encouraging findings, a number of limitations are worthy of note. First, heterogeneity in BFR protocols between studies makes direct

6.1 Summary of the Study

This systematic review assessed the effectiveness of Blood Flow Restriction Training (BFRT) for ankle sprain rehabilitation and chronic ankle instability (CAI). Through thorough review of 12 recent studies that appeared between 2017 and 2024, we consolidated evidence on the physiological mechanisms, clinical efficacy, and practical utility of BFR in ankle rehabilitation.

The review showed that low-load BFR yields significant gains in several measures that are paramount in the recovery of ankle sprain. Some of the primary findings include the considerable increases in muscle cross-sectional area of the stabilizing muscles (fibularis longus, tibialis anterior, and triceps surae), improved strength development in all directions of ankle

comparison and determination of optimal protocol difficult. Parameters such as cuff width, pressure, exercise choice, and training duration varied considerably between studies.

Sample sizes across most of the studies included in this review were small to moderate

(between 16-43 participants), with associated limitations in statistical power and generalizability. Demographic representation was similarly restricted with most studies being conducted in young, athletic groups as opposed to older populations or individuals with comorbidities who may also stand to benefit from low-load training interventions.

Long-term outcome measurement is also incomplete, with little published beyond 6 months post-intervention. None of these are more applicable than to recurrence rates and long-term functional stability, which are central issues in ankle sprain management.

With a majority of trials examining chronic rather than acute ankle instability, uncertainly persists with regard to best timing of the introduction of BFR in cases of acute trauma. Also pointed out was an apparent lack of studies that consider the cost-benefit aspect of BFR introduction versus normal therapy.

Methodological quality of included studies was highly variable, with PEDro scores from 3 to 8. Few studies had sufficient blinding of participants, therapists, or assessors, and thus potential bias. Methodology of the systematic review itself was limited in terms of comprehensiveness of search strategy and potential publication bias towards positive outcomes.

5.5 Future Research Directions

Future studies must aim to determine optimal BFR protocols for various ankle pathologies and stages of rehabilitation. Larger, multi-center trials with extended follow-up durations are required to evaluate long-term outcomes and recurrence rates. Investigations into BFR use in heterogeneous populations, such as elderly patients and those with comorbidities, would increase clinical relevance. Lastly, formal cost-effectiveness analyses would establish the economic benefit of adding BFR to routine rehabilitation protocols.

movement, and enhanced functional performance on clinical tests. Most significantly, such enhancements were attained under much lower loads (20-30% 1RM) compared with traditional high-load training protocols ($\geq 60\%$ 1RM), providing a jointsparing option that reduces mechanical stress to healing tissues.

The physiological mechanism behind BFR's efficacy was documented thoroughly using electromyographic (EMG) information demonstrating augmented muscle activation (5.67.7% greater in principal stabilizers) and near-infrared spectroscopy validating decreased muscle oxygen saturation. These conditions seem to activate hypertrophy-related signaling pathways and augment fast-twitch fiber recruitment even at minimal mechanical loads, providing an optimal environment for strength gain during initial rehabilitation stages.

6.2 Concluding Remarks

The data overwhelmingly support the inclusion of BFR as an adjunct to standard rehabilitation protocols, not as a sole intervention. Several studies illustrated that BFR added to conventional rehabilitation protocols (BFR+R) performed better than both rehabilitation alone and BFR alone on several measures of outcome. This synergistic action implies that BFR enhances the efficacy of standard rehabilitation methods while possibly speeding recovery timelines.

The clinical implications of these results are significant. BFR provides an answer to the most difficult problem in ankle sprain rehabilitation: strength maintenance or acquisition during early healing when weight-bearing and high-load exercises are prohibited. This ability can decrease the high rates of recurrence (56-74%) and development into chronic instability typical of ankle sprains. Additionally, the reduced pain in response to elevated perceived exertion indicates BFR potentially increases patient tolerance and compliance to exercise throughout rehabilitation.

The safety profile of BFR is also favorable when applied and monitored appropriately. In all the studies reviewed, there were no severe adverse events reported, although appropriate pressure monitoring and contraindication screening are still necessary. This safety profile, coupled with its efficacy, makes BFR a useful addition to the modern rehabilitation armamentarium for clinicians managing ankle injuries.

6.3 Recommendations for Future Research

In spite of the encouraging results, there are many areas that need further research for maximizing BFR application in ankle sprain rehabilitation:

Protocol Standardization: Future studies must determine optimal cuff pressure, cuff width, choice of exercises, and training parameters for ankle rehabilitation. The variation in existing protocols makes direct comparisons and clinical application difficult.

Long-term Outcomes: The majority of the studies only followed participants for 4-6 weeks. Longer follow-up intervals (6-12 months) are necessary to measure strength gains durability, recurrence rates, and long-term functional outcomes.

Population Diversity: The studies need to generalize beyond young athletic populations to cover elderly patients, patients with comorbidities, and different grades of severity of ankle sprains to improve generalizability.

Acute vs. Chronic Applications: Further research on the optimal timing of BFR initiation after acute ankle sprains would be clinically informative.

Combined Interventions: More research on combining BFR with other novel techniques like neuromuscular electrical stimulation (NMES), proprioceptive training, and vibration therapy may reveal synergistic rehabilitation strategies.

Mechanism Investigation: Further elucidation of neurophysiological adaptations, tendon remodeling effects, and proprioceptive gains would further clarify BFR's multifaceted impact.

Cost-effectiveness Analysis: Research on the economic benefits of implementing BFR, such as potential decreases in rehabilitation time and re-injury rates, would facilitate wider clinical acceptance.

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