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Blood Flow Restriction Training for Prevention and Treatment of Foot and Ankle Injuries

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Abstract. Foot and ankle injuries are extremely common in sports and daily activities. They not only cause pain and dysfunction but may also develop into chronic instability or osteoarthritis. Traditional rehabilitation relies on high-load resistance training, which is difficult to implement safely in the early stage of injury and may lead to muscle atrophy and functional decline. As an emerging rehabilitation method, blood flow restriction training applies controllable pressure to the proximal end of the limb combined with low-intensity exercise. This creates a local metabolic stress and hypoxic environment, which simulates some physiological effects of high-intensity training. Thus, it promotes muscle adaptation, enhances muscle strength, and regulates pain under low mechanical stress, which provides a new approach for the prevention and treatment of foot and ankle injuries. Studies have shown that this training exhibits positive potential in preventing Achilles tendon and periankle muscle injuries in healthy populations, promoting muscle strength recovery after Achilles tendon rupture, and improving muscle function and sports performance in patients with chronic ankle instability. However, the field still faces issues such as high research heterogeneity, inconsistent intervention parameters, insufficient evidence on long-term effects and safety. This article reviews the mechanism of blood flow restriction training, its application in preventing foot and ankle injuries in healthy populations, and its rehabilitation effects on Achilles tendon rupture and chronic ankle instability. The aim is to systematically elaborate on its theoretical basis and practical value, which provides references for future research and application.

Keywords: Blood Flow Restriction Training, Foot and Ankle Injuries, rehabilitation, prevention

1. Introduction

As a key structure for human weight-bearing and movement, the foot and ankle have a high risk of injury in sports and daily activities. Epidemiological data show that ankle sprains account for approximately 15-20% of all sports injuries, which make them one of the most common musculoskeletal injuries clinically [1]. Such injuries not only cause severe pain, swelling, and limited mobility but may also progress to chronic ankle instability or post-traumatic osteoarthritis, which seriously affect patients' quality of life and sports ability [1]. Currently, conventional rehabilitation strategies for foot and ankle injuries, especially post-surgical or post-acute phase

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management, often follow a progressive model of "protection - moderate loading - functional enhancement". However, traditional progressive resistance training usually requires high loads to effectively stimulate muscle hypertrophy and strength gain, which is difficult to implement in the early stage of injury or when patients experience significant pain and functional limitations. Prolonged immobilization or insufficient loading easily leads to muscle atrophy, decreased strength, and proprioceptive dysfunction, which form a vicious cycle of "immobilization - atrophy - re-injury". Therefore, exploring a training method that can effectively induce muscle adaptive responses, promote structural repair, and prevent secondary dysfunction under low mechanical stress has become an urgent need in rehabilitation medicine. Blood flow restriction training, as an innovative rehabilitation method, provides a new idea for solving the above dilemmas.

Blood flow restriction training applies controllable external pressure to the proximal end of the limb, which partially restrict arterial blood flow and significantly blocking venous return. This creates a unique metabolic stress environment in muscle tissue during very low-intensity (usually 20-30% 1RM) resistance exercise or passive states. This environment has been proven to simulate some physiological effects of high-intensity training, such as effective recruitment of fast-twitch muscle fibers, promotion of anabolic hormone secretion, and stimulation of muscle protein synthesis. At the same time, it avoids direct mechanical stress of high loads on damaged or fragile tissues. For the prevention and treatment of foot and ankle injuries, BFR training shows unique potential advantages. In terms of prevention, its low-load nature allows strengthening of the Achilles tendon and periankle muscles during injury-prone periods or seasons without excessively increasing local burden. In terms of rehabilitation, it enables patients to start safe and effective muscle strength and functional training in the early stage of injury or post-surgery when conventional loads cannot be tolerated, which may significantly shorten the time window for returning to sports and reduce the re-injury rate. This article aims to outline the epidemiology and hazards of foot and ankle injuries, analyze the limitations of conventional rehabilitation methods, and introduce the theoretical and application advantages of blood flow restriction training as a promising supplementary or alternative strategy. It lays a foundation for subsequent in-depth discussion of its specific mechanisms and empirical research in the prevention and treatment of foot and ankle injuries.

2. Mechanism of blood flow restriction training

As an innovative exercise intervention method, the physiological effects of blood flow restriction training stem from complex mechanisms rather than a single pathway. Studies have shown that this training mode applies external pressure to the limb during exercise, restricts local blood flow, which thereby simulate the physiological stress of high-intensity training under low-intensity exercise load, and producing unique muscle adaptation and pain regulation effects [1]. Its mechanism mainly involves multiple physiological stimuli to muscle tissue and activation of central and peripheral pain regulation systems.

In promoting muscle adaptation, the core mechanism of blood flow restriction training is closely related to creating a specific metabolic environment within the muscle. Local ischemia and hypoxia caused by training can lead to a decrease in pH value and accumulation of metabolites (such as lactic acid) in exercising muscles, which form significant metabolic stress [2]. This metabolic stress is believed to stimulate the pituitary gland to secrete growth hormone and activate the mammalian target of rapamycin signaling pathway, which thereby promotes muscle protein synthesis and providing a molecular basis for muscle hypertrophy and strength gain. At the same time, the ischemic environment may change the recruitment pattern of motor units, prompting high-threshold (type II) muscle fibers, which are usually mobilized only at higher intensities, to participate in work

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preferentially under low loads. This helps effectively stimulate fast-twitch muscle fibers while avoiding high mechanical stress, which thereby increases muscle cross-sectional area and strength.

In terms of pain regulation, blood flow restriction training shows potential in inducing exercise-induced hypoalgesia. Its mechanism may be similar to that of high-intensity exercise-induced hypoalgesia. Firstly, exercise combined with ischemic stimulation can act as a strong conditioned nociceptive stimulus, activating the diffuse noxious inhibitory control mechanism, that is, inhibiting pain perception in one part through pain in another part. Secondly, the accumulation of metabolites during training and the resulting muscle discomfort may stimulate type III and IV nociceptive afferent nerve fibers, which thereby activate descending pain inhibition pathways including opioids and endocannabinoids. In addition, blood flow restriction training is usually accompanied by a significant increase in heart rate and blood pressure. There are overlapping neural circuits between cardiovascular activation and pain regulation systems in the central nervous system. Increased blood pressure may indirectly enhance central descending inhibitory function and reduce pain sensitivity through stimulation of baroreceptors [3].

The mechanism of blood flow restriction training is a complex process of multi-system interaction. By inducing local muscle ischemia, metabolic stress, and early fatigue, it promotes anabolism at the molecular level and optimizes fiber recruitment at the neuromuscular level. At the same time, its unique internal environment (ischemia, metabolite accumulation, pain) and physiological responses (cardiovascular activation) jointly act on peripheral and central pain processing systems, which possibly produce immediate analgesic effects. This provides a theoretical basis for its application in injury prevention, treatment, and rehabilitation [2,3].

3. Blood flow restriction training for prevention of foot and ankle injuries

3.1. Blood flow restriction training for prevention of Achilles tendon injuries in healthy populations

As one of the strongest and thickest tendons in the human body, the Achilles tendon plays a crucial role in basic functional activities such as walking, running, and jumping, and its structure and function are easily affected by mechanical loads [4]. In recent years, low-intensity blood flow restriction training has attracted attention as a new training strategy because it can induce significant physiological adaptations under low loads, which especially shows unique acute effects on Achilles tendon morphology and temperature response.

A study on healthy populations explored the immediate effect of a single session of low-intensity blood flow restriction training on Achilles tendon thickness [4]. The study randomly divided subjects into a low-intensity training group, a low-intensity plus blood flow restriction group, and a high-intensity training group, each performing plantar flexion exercises. Ultrasound measurement results showed that only in the low-intensity plus blood flow restriction group, the Achilles tendon thickness significantly decreased immediately after exercise, 60 minutes, and 24 hours later, while no significant changes were observed in the other two groups. This decrease in thickness is believed to be related to changes in collagen fiber arrangement and intra-tissue fluid migration during exercise, which suggested that blood flow restriction intervention may induce positive short-term morphological adaptations by promoting the redistribution of water in the Achilles tendon [4].

Another study used infrared thermography to evaluate the short-term effects of blood flow restriction training on skin temperature in different regions of the Achilles tendon [5]. The study compared the temperature changes of the bilateral lower limbs of the same subject during bodyweight plantar flexion exercises with and without blood flow restriction. The results showed

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that under blood flow restriction conditions, the skin temperature at the calcaneal insertion site of the Achilles tendon significantly decreased, while no significant differences were found in the free segment of the tendon and the muscle-tendon junction. In addition, regardless of whether blood flow restriction was applied, the skin temperature showed a linear recovery trend over time. This result indicates that blood flow restriction may specifically affect the local thermal metabolism of the Achilles tendon insertion site, which may be related to its regulation of vascular responses and mechanical load distribution in this region [5].

In summary, the above studies show that low-intensity blood flow restriction training can cause acute reduction in Achilles tendon thickness and decrease in skin temperature at the insertion site in healthy populations. These changes in morphology and temperature may reflect early adaptations of the tendon under low load combined with blood flow restriction, including water migration, collagen remodeling, and local blood flow regulation. Although its long-term effects and specific mechanism in injury prevention need further exploration, existing evidence suggests that blood flow restriction training may serve as a potential auxiliary method for Achilles tendon health care in healthy populations, especially for those who cannot tolerate high-load training [4,5]. Future studies need to extend the observation time, include symptomatic individuals, and further explore changes in relevant molecular markers such as collagen metabolism to more comprehensively evaluate its role in maintaining Achilles tendon health.

3.2. Blood flow restriction training for prevention of periankle muscle injuries in healthy populations

In the field of sports medicine and rehabilitation, effectively preventing muscle atrophy and strength decline caused by immobilization or chronic unloading is a core issue. As an emerging intervention method, blood flow restriction (BFR) training has gradually attracted attention for its potential in muscle protection.

For healthy populations, limb immobilization due to injury or other reasons is a common cause of rapid decline in muscle function under non-weight-bearing conditions. An early study provided preliminary evidence [6]. In this study, the left ankle joints of healthy male subjects were immobilized with plaster for two weeks without weight-bearing, and they were randomly divided into a low-pressure (50 mmHg) BFR intervention group and a non-intervention control group. The results showed that after two weeks of immobilization, the torque of knee extensors and flexors of subjects in the control group significantly decreased under different contraction modes (concentric, eccentric, isometric) and angular velocities. In contrast, although the circumference measurements of the lower limbs (thighs and calves) of subjects in the BFR intervention group also significantly decreased, which indicated that muscle atrophy was not completely prevented, the degree of muscle strength decline was significantly mitigated. The percentage decrease in eccentric contraction torque of knee extensors at an angular velocity of 60°/s in the intervention group (-12.5% ± 10.7%) was significantly lower than that in the control group (-30.1% ± 10.9%). More notably, the strength decline of knee flexors under various test conditions was significantly alleviated. This indicates that even simple blood flow restriction with low pressure (50 mmHg) without accompanying exercise can to a certain extent resist muscle strength loss caused by immobilization and non-weight-bearing. However, the study also suggests that the effect of this low-pressure scheme in preventing the reduction of muscle cross-sectional area may be limited, and its anti-atrophy effect is weaker than that of higher pressure (such as 200 mmHg) schemes [6].

Although the above study shows positive effects of BFR in specific experimental models, the certainty and consistency of evidence need to be cautiously evaluated when extending the effects of its preventive application to a wider range of healthy populations or different contexts. A systematic review on the recovery of knee muscle morphology and strength in patients after anterior cruciate ligament (ACL) reconstruction, although the research subjects are patient populations, its conclusions have important reference value for understanding the overall evidence quality of BFR training in preventing muscle dysfunction [7]. The review included multiple studies to evaluate the effects of combining BFR training with open-chain, closed-chain, or passive exercises on thigh muscle morphology and knee extensor/flexor strength. The analysis found that although some studies reported positive trends of BFR training in maintaining early post-surgical muscle mass, improving muscle thickness symmetry, or maintaining isokinetic muscle strength, there was significant heterogeneity in the results of various studies. Effect size (ES) analysis showed that for both muscle morphological indicators (such as cross-sectional area, volume) and strength indicators, the effect sizes of comparisons between the BFR training group and the conventional treatment group ranged from negligible to large, with wide confidence intervals. This means that there is currently no consistent and clinically significant evidence that BFR training is significantly superior to traditional methods in maintaining or increasing muscle volume and improving muscle strength. The review pointed out that differences in study methodology quality, confounding factors such as post-surgical pain, joint effusion, and neuromuscular inhibition, as well as significant differences in BFR intervention schemes themselves in pressure setting, application mode, training type, and intensity, may all lead to inconsistent study results [7].

In conclusion, low-pressure BFR-based interventions have shown potential in alleviating muscle strength decline caused by immobilization in healthy individuals under experimental conditions, especially having a protective effect on specific muscle groups. However, the effect of low-pressure BFR in preventing muscle atrophy may be inferior to that of high-pressure schemes. Future studies with rigorous design and standardized schemes are needed to further explore the optimal scheme, long-term effects, and clear mechanisms of BFR training in preventing periankle muscle injuries or functional disorders in healthy populations under various potential risk scenarios (such as anticipated immobilization, weight-loss activities).

4. Blood flow restriction training for rehabilitation of foot and ankle injuries

4.1. Blood flow restriction training for rehabilitation of Achilles tendon rupture

Rehabilitation after Achilles tendon rupture often faces challenges such as muscle atrophy, persistent strength deficits, and incomplete functional recovery. Traditional rehabilitation methods may still leave obvious functional defects even after surgical or non-surgical treatment [8]. Therefore, exploring a rehabilitation strategy that can be intervened early, effectively stimulate muscles under low load, and avoid excessive tissue stress is crucial. As an emerging auxiliary method, blood flow restriction training provides a new approach for functional reconstruction after Achilles tendon rupture by combining local blood flow restriction with low-intensity exercise. This section will discuss the application value, feasibility, and safety of BFR in the rehabilitation of Achilles tendon rupture based on two clinical studies.

Yow et al. reported two cases of military personnel with severe strength and functional deficits after Achilles tendon rupture [8]. On the basis of poor results from traditional rehabilitation, the patients received BFR-assisted training for 5 to 6 weeks. The training used thigh proximal compression cuffs with pressure set at 80% of the limb's complete occlusion pressure, combined with leg and calf push exercises at 30% 1RM load. The results showed that both patients achieved significant improvements in ankle plantar flexion peak torque and power, with one patient showing a

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522% increase in torque and 4475% increase in power at an angular velocity of 60 degrees/second. Although there was still a certain gap compared with the healthy side, both patients ultimately successfully achieved unassisted walking and returned to running and sports [8].

A case series study by Bentzen et al. evaluated the feasibility and safety of BFR training in the early rehabilitation stage of patients with Achilles tendon rupture treated non-surgically [9]. Eighteen patients received a 12-week BFR intervention three times a week, which included seated knee extension under 40% to 80% limb occlusion pressure and later blood flow-restricted walking. The results showed that 16 patients who completed the intervention had a training compliance rate of 88% and good acceptance of the intervention. Although 2 cases of Achilles tendon re-rupture and 1 case of deep vein thrombosis were reported during the study, the incidence rate was consistent with the range reported in previous literature on conservative treatment of Achilles tendon rupture. During the study, most of the patients' post-exercise ankle pain scores were in the mild acceptable range, and no thigh circumference atrophy was observed after the intervention, which suggested that BFR may help slow down muscle loss during the immobilization period [9]. However, only a few patients could complete single-leg heel raises at 12 weeks, and the calf circumference showed a slight decrease, reflecting the impact of early weight-bearing restrictions on functional recovery. This study indicates that BFR training is highly feasible and acceptable in this patient population, but its effectiveness and safety compared with conventional care need further verification.

In summary, existing evidence suggests that integrating blood flow restriction training into the rehabilitation plan after Achilles tendon rupture is a promising strategy. BFR allows patients to perform effective training with lower mechanical loads in the early stage of tissue healing, thereby potentially alleviating muscle atrophy, enhancing strength, and promoting functional recovery [8, 9]. However, its clinical application still requires caution, attention to potential risks such as re-rupture and thrombosis, and full consideration of patients' specific weight-bearing restriction stages and individual differences. Future studies need more well-designed randomized controlled trials to clarify the optimal scheme, long-term benefits, and risk management of BFR in the rehabilitation of this specific injury.

4.2. Blood flow restriction training for rehabilitation of ankle instability

Chronic ankle instability (CAI), as a common sequela of sports injuries, faces the challenge in rehabilitation treatment that traditional strength training is difficult to fully activate muscles due to pain or load restrictions. As an emerging rehabilitation auxiliary method, blood flow restriction (BFR) training provides a new idea for improving muscle function, strength, and sports performance of CAI patients by combining low-load exercise with local blood flow restriction (See table 1).

Zhou Jiaqi et al. explored the effects of BFR training with different pressure levels on lower limb function of football players with CAI [10]. The study randomly divided 35 subjects into a control group, a high-load BFR group, and a low-load BFR group. All groups received a 6-week strength training program combined with balance training. The results showed that all groups had significant improvements in subjective ankle stability scores, Y-balance test performance, and some sports function test results on the affected side after the intervention. Notably, the high-load BFR group showed significantly greater increases in peak torque of plantar flexion and eversion of the affected ankle compared with the low-load BFR group. Meanwhile, the high-load BFR group also showed improvements in dorsiflexion and plantar flexion strength of the unaffected ankle, which suggested a possible cross-training effect. In addition, only the high-load BFR group showed a significant increase in vertical jump height. This study indicates that BFR training can effectively improve balance, strength, and proprioception in CAI athletes. Especially, BFR training with higher pressure

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shows additional advantages in enhancing muscle strength in specific directions, explosive power, and adaptation of the contralateral limb [10].

Another randomized placebo-controlled trial by Werasirirat and Yimlamai evaluated the efficacy of adding BFR training to a supervised rehabilitation program for CAI athletes [11]. The study randomly divided 16 college student athletes into a BFR combined with rehabilitation training group and a rehabilitation training alone group, with an intervention of three times a week for 4 weeks. Compared with the rehabilitation alone group, the BFR combined with rehabilitation group showed significant enhancement in isokinetic muscle strength of ankle plantar flexors and extensors, significant increase in cross-sectional area of the peroneus longus muscle, and significant reduction in lateral jump test time after the intervention. However, there was no significant difference in the improvement of dynamic balance ability (Y-balance test) between the two groups. The study concluded that BFR is superior to traditional rehabilitation programs alone in improving muscle strength, inducing muscle hypertrophy, and enhancing some functional performances of CAI athletes [11].

Table 1. Application of blood flow restriction training in the rehabilitation of ankle and foot injuries

Authors and Year	Research Subjects	Intervention Protocol	Key Results
Yow et al. (2017) [8]	2 military personnel with severe strength and functional deficits after Achilles tendon rupture	Used proximal thigh compression cuffs combined with leg and calf push exercises at 30% 1RM load for 5-6 weeks	The patients' ankle plantarflexion peak torque and power were significantly improved; both patients ultimately achieved independent walking and returned to running and sports
Bentzen et al. (2024) [9]	18 patients with Achilles tendon rupture treated non-operatively	Blood flow restriction training 3 times a week for 12 weeks, with blood flow restriction walking added in the later stage	Most patients reported mild and acceptable ankle pain after exercise, and no thigh circumference atrophy occurred
Zhou Jiaqi et al. (2022) [10]	35 football players with chronic ankle instability	Received 6 weeks of strength training combined with balance training	The high-load blood flow restriction group showed more significant improvements in plantarflexion and eversion peak torque of the affected ankle, as well as a significant increase in vertical jump height
Werasirirat et al. (2022) [11]	16 college athletes with chronic ankle instability	Randomly divided into blood flow restriction + rehabilitation training group and rehabilitation training alone group	The blood flow restriction + rehabilitation training group had significantly enhanced isokinetic muscle strength of ankle plantarflexors and extensors, significantly increased cross-sectional area of the peroneus longus muscle, and significantly shortened lateral jump test time

In conclusion, integrating BFR training into the rehabilitation program for CAI can effectively make up for the deficiency of insufficient muscle stimulation by traditional low-load training. Through low load combined with local occlusion, BFR training may promote metabolic stress and muscle activation, which thereby achieves muscle strength gain, muscle hypertrophy, and improvement of functional performance under relatively safe loads. Although the two studies have inconsistent conclusions on the improvement of balance function, which may be related to differences in intervention duration, specific training content, and evaluation tools, both support the potential of BFR as an effective auxiliary method for CAI rehabilitation. Future studies can further refine BFR application parameters, such as setting pressure values based on individual arterial occlusion pressure, and explore its long-term effects and specific mechanisms in reducing the risk of re-injury.

5. Conclusion

Blood flow restriction training provides a practical new path for addressing the core pain point of "early safe load stimulation" in the prevention and treatment of foot and ankle injuries. In terms of

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mechanism, this technology effectively promotes muscle anabolism and centrally regulates pain perception under low load by creating a unique local metabolic and ischemic environment. In terms of prevention, studies have shown that it can induce positive morphological changes in the Achilles tendon of healthy populations and exhibit certain potential in protecting periankle muscle strength from loss caused by immobilization, especially with significant effects on specific muscle groups. In rehabilitation application, as an auxiliary method, it can effectively promote the recovery of muscle strength and function in patients after Achilles tendon rupture, and make up for the deficiency of insufficient load in traditional training in the rehabilitation of chronic ankle instability. BFR can also improve muscle strength, muscle circumference, and some sports performances, verifying its safety, feasibility, and unique value in early intervention of injuries. Looking forward to the future, the development of blood flow restriction training technology will become increasingly refined and personalized. Its evolution direction will focus on the accurate quantification and dynamic regulation of key parameters (such as real-time pressure optimization based on individual physiological signals), and the intelligent integration with traditional and emerging rehabilitation methods (such as neuromuscular electrical stimulation, vibration training, biofeedback). The application scenarios will further expand from existing musculoskeletal rehabilitation to broader fields such as neurological rehabilitation, prevention of sarcopenia in the elderly, and scientific fitness for the general public. Relying on the continuous accumulation of evidence-based medicine and the empowerment of digital technology, this technology is expected to develop into a standardized, individualized, and integrated active health intervention system.

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