
# Effects of Blood Flow Restriction Training in Rehabilitation of Athletes with Musculoskeletal Injuries

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## Article Info

**ISSN (online):** 2582-7138
**Volume:** 06
**Issue:** 04
**July - August 2025**
**Received:** 10-05-2025
**Accepted:** 06-06-2025
**Published:** 03-07-2025
**Page No:** 823-828

**Abstract**

Musculoskeletal injuries are prevalent among athletes and often lead to prolonged rehabilitation due to muscle atrophy, strength deficits, and joint dysfunction. Traditional high-load resistance training, while effective for muscle hypertrophy and strength recovery, may be contraindicated during early phases of rehabilitation or in individuals experiencing pain or surgical restrictions. Blood flow restriction (BFR) training has emerged as a novel strategy that enables low-load exercise to elicit similar adaptations to high-load training, making it a valuable adjunct in sports rehabilitation. This narrative review explores current evidence on the effects of BFR training in the rehabilitation of athletes with musculoskeletal injuries, with a focus on its physiological mechanisms, clinical applications, pain modulation effects, safety considerations, and limitations. Relevant peer-reviewed articles from 2018 to 2025 were reviewed based on thematic relevance. Studies involving ACL reconstruction, tendon injuries, patellofemoral pain, upper and lower extremity rehabilitation, and pain-related outcomes were considered. BFR training demonstrates significant benefits in preserving muscle mass and strength, accelerating return to sport after ACL reconstruction, and improving functional outcomes in load-compromised rehabilitation scenarios. It also shows promise in reducing pain through mechanisms such as exercise-induced hypoalgesia. Despite its advantages, clinical protocols vary widely, and safety monitoring remains essential. BFR training is a promising rehabilitation modality that bridges the gap between early and late-stage recovery in athletic populations. While current evidence supports its efficacy, further standardized trials are needed to refine protocols and enhance its safe integration into routine sports rehabilitation.

**DOI:** https://doi.org/10.54660/.IJMRGE.2025.6.4.823-828

**Keywords:** Blood Flow Restriction Training, Musculoskeletal Injuries, Rehabilitation, Athletes, ACL Reconstruction, Tendon Injuries, Hypoalgesia, Low-Load Exercise, Return To Sport, Sports Physiotherapy

## 1. Introduction

Musculoskeletal injuries such as ligament sprains, muscle tears, tendinopathies, and postoperative complications are common in athletic populations and often necessitate structured rehabilitation to restore functional performance and reduce reinjury risk. One of the central goals of musculoskeletal rehabilitation is the restoration of muscle strength and mass.

However, conventional high-load resistance training, although effective for inducing hypertrophy, may be impractical or unsafe during early phases of rehabilitation when tissues are healing or when patients experience pain, swelling, or surgical precautions (Lorenz et al., 2021) [5]. In this context, blood flow restriction (BFR) training has gained increasing attention in sports medicine. BFR involves the application of controlled occlusion, typically via pneumatic cuffs or bands, to partially restrict arterial inflow and fully restrict venous outflow during low-load resistance exercises. This technique enables physiological adaptations similar to those achieved with high-intensity training, even when using significantly reduced loads (Jack *et al*., 2023; Hedt *et al*., 2022) [4, 3].

The physiological rationale for BFR includes increased metabolic stress, cellular swelling, muscle fiber recruitment, and upregulation of anabolic hormones such as growth hormone and IGF-1 (Centner *et al*., 2019) [1]. These mechanisms collectively promote muscle hypertrophy and strength without the mechanical stress typically associated with traditional resistance training. Furthermore, BFR training has been shown to elicit systemic and localized analgesic effects, potentially enhancing exercise tolerance and recovery through the mechanisms of exercise-induced hypoalgesia (Cervini *et al*., 2023) [2].

Given the increasing evidence base, this narrative review aims to synthesize current findings related to BFR training in the rehabilitation of athletes with musculoskeletal injuries. Specifically, we discuss its physiological foundations, evidence-based applications in clinical practice (e.g., ACL reconstruction, tendon repair, patellofemoral pain), safety considerations, and the limitations of existing research.

## 2. Physiological Basis of Blood Flow Restriction Training

Blood flow restriction (BFR) training functions through a combination of mechanical and metabolic stimuli that enhance muscle hypertrophy and strength, even when low-load exercises are employed. The central mechanism involves the application of external pressure to the proximal portion of the limb using pneumatic cuffs or elastic bands, which partially restricts arterial inflow and substantially limits venous outflow during exercise (Lorenz *et al*., 2021) [5]. This hemodynamic environment promotes metabolic stress and hypoxia in the working musculature, both of which are key drivers of muscle adaptation.

One of the most significant physiological responses to BFR training is the increase in type II muscle fiber recruitment. Under normal low-load conditions, type I fibers are predominantly activated; however, the oxygen-deprived environment created by BFR leads to early fatigue of type I fibers and forces the recruitment of high-threshold type II fibers, which are essential for strength and hypertrophy development (Centner *et al*., 2019) [1]. This adaptation closely mirrors the neuromuscular demands of high-intensity resistance training, making BFR an effective surrogate when high loads are contraindicated.

Additionally, BFR training elicits a potent anabolic hormonal response. Acute BFR sessions have been shown to significantly elevate levels of growth hormone (GH), insulin-like growth factor 1 (IGF-1), and vascular endothelial growth factor (VEGF), all of which contribute to muscle protein synthesis and vascular remodeling (Krzysztofik *et al*., 2019) [7]. These responses facilitate both muscular and tendon regeneration in the injured or post-surgical limb.

Another noteworthy physiological effect is cellular swelling, which occurs due to the pooling of blood in the occluded limb. This increased intracellular pressure acts as a signal for protein synthesis and cell growth. Concurrently, the accumulation of metabolic byproducts such as lactate and hydrogen ions creates a unique environment that enhances satellite cell proliferation and muscle regeneration (Hedt *et al*., 2022) [3].

BFR also promotes vascular adaptations, including increased capillary density and angiogenesis. These changes improve muscle perfusion and may contribute to enhanced recovery and aerobic capacity, particularly in athletes undergoing rehabilitation for lower extremity injuries (De Renty *et al*., 2023) [6].

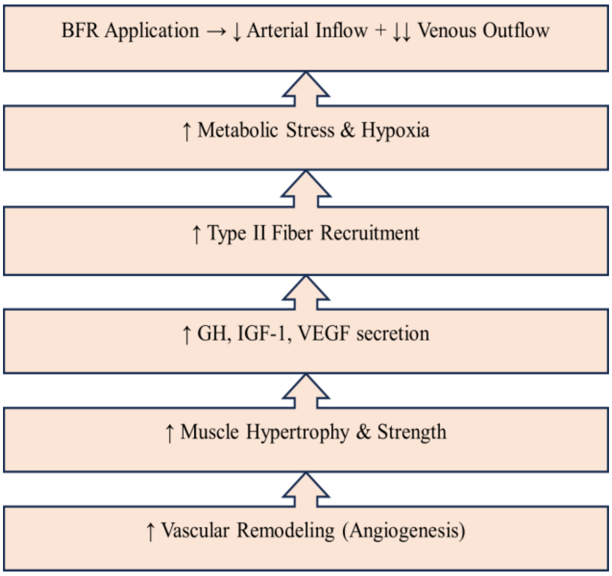


**Fig 1:** Mechanism of Action of Blood Flow Restriction (BFR) Training

**In summary, the primary physiological mechanisms of BFR training include:**

- Recruitment of type II muscle fibers under low-load conditions
- Increased secretion of anabolic hormones
- Cellular swelling and metabolic accumulation
- Enhanced vascular remodeling and angiogenesis

These mechanisms provide a strong scientific basis for incorporating BFR into clinical rehabilitation, especially when tissue loading must be minimized.

## 3. Clinical Applications in Injury Rehabilitation

### 3.1 Blood Flow Restriction in ACL Reconstruction

Anterior cruciate ligament reconstruction (ACLR) is one of the most common orthopedic procedures among athletes. Postoperative recovery is often challenged by quadriceps weakness, muscle atrophy, and delayed return to sport (RTS). Traditional rehabilitation methods involving high-load resistance training may pose risks of graft strain and joint discomfort, especially in the early postoperative phase. In this context, blood flow restriction (BFR) training has been explored as a low-load yet effective alternative for preserving and enhancing muscle function following ACLR.

A randomized controlled trial by Jack *et al*. (2023) [4] investigated BFR therapy combined with low-load resistance training in patients undergoing ACLR with bone-patellar tendon-bone autograft. Over a 12-week postoperative period, patients in the BFR group maintained lower extremity lean mass and bone mineral density (BMD), while the control group experienced significant reductions in both parameters. Moreover, time to RTS was significantly shorter in the BFR group (6.4±0.3 months) compared to the control group (8.3±0.5 months), with no reported complications. These findings suggest that BFR can facilitate early anabolic preservation and potentially accelerate functional recovery.

A systematic review by Koc *et al*. (2022) [10] further corroborates these outcomes, reporting that low-load BFR training post-ACLR leads to greater improvements in quadriceps strength and mass compared to non-BFR protocols. Additionally, pain reduction and comparable ACL graft integrity were observed, indicating that BFR does not compromise graft stability. Li *et al*. (2023) [11] found that BFR at higher occlusion pressures (80% AOP) produced superior gains in quadriceps peak torque and muscle thickness, enhancing side-to-side symmetry and knee function during mid-term recovery.

Despite these benefits, Colapietro *et al*. (2023) [8] caution that the overall strength of evidence supporting BFR post-ACLR remains limited and inconsistent, with effect sizes ranging from trivial to large depending on the protocol. Nonetheless, recent trends support individualized, milestone-based rehabilitation incorporating BFR as a bridging strategy between early mobilization and high-intensity training (Jenkins *et al*., 2022) [9].

Collectively, the literature indicates that BFR is a safe, efficient, and clinically viable method to combat muscle loss and expedite recovery after ACL reconstruction in athletic populations.

### 3.2 Blood Flow Restriction in Tendon and Muscle Injury Rehabilitation

Tendon and muscle injuries are frequently encountered in athletic populations and often require prolonged rehabilitation to restore function, strength, and tissue integrity. While high-load resistance training is a standard approach for promoting tendon and muscle adaptation, it may be unsuitable in the presence of pain, partial tears, or early-phase post-surgical recovery. Blood flow restriction (BFR) training has emerged as a promising adjunct to conventional protocols for treating such injuries due to its ability to stimulate muscular and connective tissue adaptations at low mechanical loads.

A recent scoping review by Burton and McCormack (2022) [12] synthesized findings from 13 studies evaluating the use of BFR in tendon rehabilitation, including tendinopathy, tendon rupture, and healthy tendon adaptations. The review highlighted that BFR training can positively affect tendon pain, strength, function, and morphological characteristics, such as thickness and mechanical stiffness. Although outcomes were varied, improvements in tendon-loading tolerance and neuromuscular performance were consistently noted across different protocols.

In the context of patellofemoral pain (PFP), a randomized controlled trial by Constantinou *et al*. (2022) [13] compared hip and knee strengthening programs with and without BFR. While both groups improved over time, the BFR group demonstrated greater isometric strength of the knee extensors at the two-month follow-up, suggesting that BFR may enhance rehabilitation outcomes without adding joint stress. This is particularly relevant for conditions where mechanical loading may aggravate symptoms, as BFR allows for a therapeutic hypoalgesic effect alongside strength gains.

Furthermore, BFR has shown potential in treating hamstring and rotator cuff muscle injuries by facilitating early loading in the rehabilitation phase, improving metabolic conditioning, and minimizing disuse atrophy (Lorenz *et al*., 2021) [5]. In athletes unable to engage in traditional strength protocols due to pain or surgical precautions, BFR may serve as an intermediate strategy to maintain muscle activation and tendon health.

Despite these promising outcomes, Burton and McCormack (2022) [12] emphasized the heterogeneity in BFR protocols, including variation in occlusion pressure, exercise type, frequency, and duration. These inconsistencies limit the generalizability of results and highlight the need for standardized guidelines tailored to specific tendon and muscle pathologies.

In conclusion, BFR training holds significant therapeutic value in tendon and muscle injury rehabilitation, particularly for athletes who require strength restoration without high mechanical loading. Its use may optimize return-to-play timelines and reduce the burden of recurrent injury through early and progressive tissue stimulation.

### 3.3 Blood Flow Restriction in Postoperative and Load-Compromised Scenarios

In the early postoperative phases of orthopedic rehabilitation or in cases where patients cannot tolerate high mechanical loads, maintaining muscle mass and joint function becomes especially challenging. Conditions such as total knee arthroplasty (TKA), arthroscopic surgeries, or fracture recovery often require load restrictions, which can compromise rehabilitation efficacy. In such settings, blood flow restriction (BFR) training offers a compelling solution by enabling low-load exercise to stimulate anabolic responses similar to high-intensity resistance training.

A clinical review by De Renty *et al*. (2023) [6] evaluated BFR use following TKA and emphasized that low-intensity exercise with BFR not only preserves muscle mass and strength but also reduces pain and inflammation, thereby accelerating functional recovery. The authors noted that BFR may serve as a bridge to more intensive strength training by reducing the barrier posed by pain or post-surgical movement restrictions. This is particularly relevant in older adults, where joint integrity and cardiopulmonary limitations further restrict rehabilitation options.

Similarly, Hedt *et al*. (2022) [3] discussed BFR's role in enhancing rehabilitation after surgical procedures through what they described as the "proximal performance paradox." BFR applied distally during exercise was found to improve proximal limb strength and neuromuscular control, suggesting a systemic or cross-education effect. These findings are relevant for postoperative athletes, particularly in scenarios where full weight-bearing or joint articulation is temporarily contraindicated.

Moreover, BFR has shown promise in prehabilitation-conditioning an athlete prior to surgery to reduce postoperative losses in strength and mobility. This approach may help optimize surgical outcomes and facilitate earlier return to function by building a reserve of muscle mass and strength before the catabolic postoperative period.

Despite its benefits, care must be taken to assess individual contraindications such as thromboembolic risk, uncontrolled hypertension, or peripheral vascular disease. Monitoring cuff pressures, session duration, and patient response is critical to ensuring safety, especially in early rehabilitation stages (Lorenz *et al*., 2021) [5].

Overall, BFR presents an effective strategy in postoperative and load-compromised scenarios, allowing clinicians to initiate early therapeutic exercise without compromising tissue integrity or patient safety.

## 4. Pain Modulation and Exercise-Induced Hypoalgesia

Pain is a significant barrier to effective rehabilitation in athletes recovering from musculoskeletal injuries. It not only limits exercise intensity and volume but also contributes to fear-avoidance behaviors, delayed return to sport, and reduced quality of life. Blood flow restriction (BFR) training has been increasingly recognized for its role in exercise-induced hypoalgesia (EIH) a phenomenon wherein physical activity reduces pain sensitivity during and after exercise.

The hypoalgesia effects of BFR appear to be mediated by a combination of local and systemic mechanisms. Locally, the metabolic stress induced by ischemia during BFR enhances the release of endogenous opioids, endocannabinoids, and serotonin, all of which modulate nociceptive transmission in peripheral and central pathways. Systemically, BFR may activate descending inhibitory pathways from the brainstem that suppress pain signaling (Cervini *et al*., 2023) [2].

Emerging evidence supports the application of BFR as a pain-modulating adjunct in both acute and chronic injury settings. Cervini and Colleagues (2023) [2] conducted a narrative synthesis of potential mechanisms by which BFR contributes to EIH. They highlighted that low-load resistance training with BFR can reduce both resting and movement-evoked pain, even in conditions typically resistant to mechanical loading, such as tendinopathy and patellofemoral pain syndrome. These analgesic effects may allow athletes to engage in earlier or more aggressive rehabilitation protocols without exacerbating symptoms.

In postoperative populations, pain reduction from BFR has been observed as a secondary benefit to strength gains. For instance, in ACL reconstruction recovery, several studies have reported reduced joint pain during exercise and daily activities when BFR was integrated into the rehabilitation protocol (Koc *et al*., 2022) [10]. Such effects are not only clinically meaningful for adherence and functional progress but may also attenuate the risk of chronic pain development through improved mobility and psychosocial confidence.

Importantly, these hypoalgesic benefits are achieved without increasing joint load, making BFR particularly valuable in athletes who are unable to tolerate traditional weight-bearing or high-impact activities. This makes BFR an appealing option in early-stage rehabilitation, chronic overuse injuries, and post-surgical care, where controlling pain while preserving function is critical.

In summary, BFR training not only facilitates muscle adaptation but also contributes to pain reduction via neurophysiological mechanisms. Its ability to induce exercise-induced hypoalgesia broadens its clinical utility and underscores its relevance in multidisciplinary rehabilitation settings.

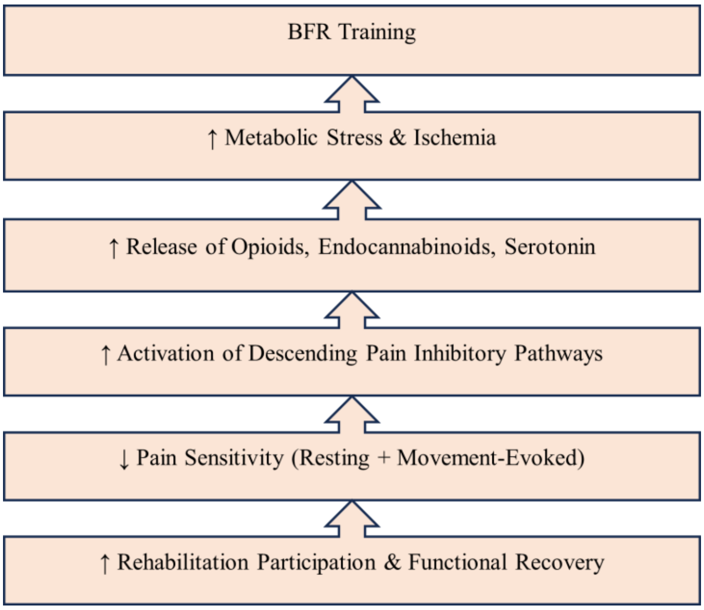


**Fig 2:** Pain Modulation Mechanism of Blood Flow Restriction (BFR) Training

## 5. Safety Considerations and Contraindications

While blood flow restriction (BFR) training is gaining widespread acceptance in musculoskeletal rehabilitation, its application must be approached with appropriate safety precautions and clinical judgment. BFR involves the deliberate restriction of venous return and partial arterial inflow using pneumatic cuffs or elastic bands, which introduces unique physiological stressors. Therefore, understanding its risk profile, contraindications, and safe implementation guidelines is essential for sports clinicians and rehabilitation specialists.

### 5.1 General Safety Profile

The current body of literature supports the general safety of BFR training when applied by trained professionals using controlled protocols. Commonly reported side effects are minor and transient, including limb discomfort, muscle soreness, and petechiae (Lorenz *et al*., 2021) [5]. Serious complications such as venous thromboembolism (VTE), rhabdomyolysis, or nerve injury are exceedingly rare and often linked to improper use, excessive pressures, or prolonged occlusion durations.

Jack *et al*. (2023) [4] reported no major adverse events during a 12-week BFR intervention following ACL reconstruction, emphasizing that with standardized pressure monitoring (e.g., 80% of arterial occlusion pressure) and supervision, the intervention remains safe even in postoperative scenarios. Additionally, the review by Colapietro *et al*. (2023) [8] identified no consistent complications across multiple trials assessing BFR post-ACL reconstruction.

### 5.2 Contraindications
Despite its favorable safety profile, BFR is contraindicated in individuals with specific vascular, cardiovascular, or hematological conditions. Absolute contraindications include:

- Uncontrolled hypertension
- Severe peripheral arterial disease
- History of deep vein thrombosis (DVT) or pulmonary embolism
- Sickle cell anemia
- Active infection or open wounds in the occlusion area

Relative contraindications may include diabetes with neuropathy, recent surgical incisions, and pregnancy, where close supervision and individualized risk-benefit assessment are advised (Lorenz *et al*., 2021) [5].

### 5.3 Monitoring and Implementation Considerations
Effective and safe BFR implementation requires careful attention to:

- Cuff width and limb size: Wider cuffs require lower pressures to achieve the same occlusive effect.
- Occlusion pressure calibration: Use of Doppler or automated systems to determine limb-specific arterial occlusion pressure (AOP).
- Training intensity and volume: Common protocols include 20–30% of one-repetition maximum (1RM) with 4 sets (30-15-15-15 reps).
- Session duration and recovery: Avoid prolonged occlusion; typically, sessions last 15–20 minutes per limb with full reperfusion between exercises.

Education of both clinicians and patients on symptom monitoring (e.g., excessive pain, numbness, or swelling) is crucial to prevent overuse or misuse. Most adverse outcomes in the literature have occurred due to non-standardized, unsupervised application. In summary, BFR training is a low-risk intervention when executed with proper screening, individualized pressure calibration, and supervised progression. Knowledge of contraindications and diligent monitoring are essential to maximize therapeutic benefit while safeguarding athlete safety.

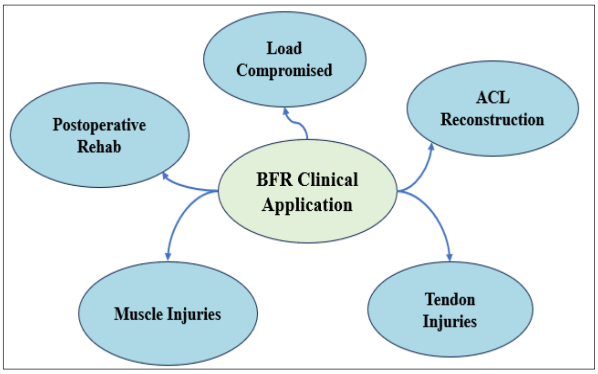


**Fig 3:** Clinical Applications of Blood Flow Restriction (BFR) Training

## 6. Limitations of Current Evidence and Research Gaps
Despite the growing body of research supporting blood flow restriction (BFR) training in the rehabilitation of musculoskeletal injuries, several limitations constrain its widespread adoption and evidence-based optimization. These limitations relate to methodological variability, limited generalizability, incomplete mechanistic understanding, and the need for longer-term outcomes in athletic populations.

### 6.1 Heterogeneity in Protocols
One of the primary challenges in interpreting BFR literature is the lack of standardization in training protocols. Studies differ substantially in terms of cuff width, occlusion pressure (ranging from 40% to 80% AOP), exercise modalities, session duration, and frequency. For example, Li *et al*. (2023) [11] observed enhanced quadriceps outcomes using 80% AOP, whereas other trials reported sufficient effects at lower occlusion levels. This heterogeneity hampers direct comparison of findings and makes it difficult to establish optimal dosage guidelines across injury types and phases of recovery.

### 6.2 Small Sample Sizes and Limited Diversity
Many clinical trials and pilot studies involving BFR have relatively small sample sizes, often limited to a single site or athletic subgroup. This restricts the statistical power and limits generalizability to broader populations such as female athletes, older individuals, or patients with comorbidities (Colapietro *et al*., 2023; Koc *et al*., 2022) [8, 10]. Additionally, many trials are not blinded or do not include long-term follow-up, leaving questions about sustained benefits and reinjury risk.

### 6.3 Inconsistent Outcome Measures
Studies utilize a wide array of outcome measures—ranging from muscle cross-sectional area and peak torque to subjective pain ratings and functional tests. While this reflects BFR's multifaceted benefits, it complicates meta-analyses and consensus building. Moreover, few studies assess return-to-sport timelines using standardized readiness criteria or biomechanical evaluations, which are critical in sports rehabilitation (Burton & McCormack, 2022) [12].

### 6.4 Limited Mechanistic and Safety Data
Although several hypotheses exist about BFR's effects on muscle, tendon, and pain pathways, few studies explore the underlying molecular and cellular mechanisms in depth. Understanding long-term vascular, neural, or metabolic adaptations is essential for optimizing BFR's use in elite athletic rehabilitation. Similarly, although safety has been established in short-term trials, longitudinal safety data, particularly in high-frequency use or in athletes with prior vascular injury, is still lacking (Lorenz *et al*., 2021) [5].

### 6.5 Research in Understudied Injury Types
Most of the existing BFR research is focused on ACL reconstruction and lower limb injuries. Less attention has been given to upper extremity injuries, chronic tendinopathies, or multi-joint trauma common in sports like gymnastics, combat sports, and CrossFit. Expanding the evidence base to a wider array of musculoskeletal conditions and athletic disciplines is necessary for broader clinical translation.

In conclusion, while BFR training holds promise as a low-load, high-benefit intervention in musculoskeletal rehabilitation, further research must aim to:

- Standardize protocols
- Expand participant diversity
- Include long-term outcomes and mechanistic studies
- Develop sport- and injury-specific guidelines

## 7. Conclusion and Recommendations

Blood flow restriction (BFR) training has emerged as a promising and versatile intervention in the rehabilitation of athletes with musculoskeletal injuries. By leveraging low-load exercise under controlled vascular occlusion, BFR enables the activation of anabolic pathways that support muscle hypertrophy, strength gains, and functional recovery without imposing excessive mechanical stress on healing tissues. This characteristic makes it especially valuable in scenarios where traditional high-load resistance training is contraindicated, such as in the early postoperative period or during the management of tendon and joint pathologies.

Evidence from recent clinical trials and systematic reviews demonstrates that BFR can help preserve muscle mass and bone mineral density following anterior cruciate ligament reconstruction, improve quadriceps torque and tendon function in mid-phase rehabilitation, and reduce pain through mechanisms of exercise-induced hypoalgesia. Additionally, its application in prehabilitation and postoperative care has shown potential to accelerate return-to-sport timelines in athletic populations.

However, despite these advantages, limitations in the current literature including protocol variability, small sample sizes, and limited mechanistic data underscore the need for further research. To facilitate widespread adoption and integration into sports medicine, future studies should aim to:

- Establish standardized guidelines for BFR dosage, pressure settings, and training frequency across injury types.
- Include long-term outcomes and return-to-play criteria to assess sustained benefits.
- Investigate BFR's applicability in understudied injuries and diverse athlete populations, including females and para-athletes.
- Conduct cost-effectiveness analyses and safety audits to inform clinical practice guidelines.

In conclusion, BFR training represents a clinically effective, physiologically sound, and adaptable tool for musculoskeletal rehabilitation in athletes. When applied with appropriate precautions and individualized programming, it can bridge the gap between early protective rehabilitation and high-performance training, offering athletes a safer and more efficient pathway back to full function and competition.

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