JHWCR

Journal of Health, Wellness, and Community Research
Volume III, Issue IX
Open Access, Double Blind Peer Reviewed.
Web: https://jhwcr.com, ISSN: 3007-0570
https://doi.org/10.61919/9f8shd25

A Narrative Review

Comparative Efficacy of Blood Flow Restriction Training and Traditional Resistance Training in Post-Surgical Muscle Hypertrophy and Strength Recovery: A Narrative Review

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Author Contributions: Concept: MKH, SS; Design: MNB, ZUN; Data Collection: HAS; Analysis: MMH; Drafting: MKH
Cite this Article | Received: 2025-05-11 | Accepted 2025-07-16
No conflicts declared; ethics approved; consent obtained; data available on request; no funding received.

ABSTRACT

Background: Post-surgical muscle atrophy and delayed strength recovery are common complications following orthopedic procedures such as anterior cruciate ligament (ACL) reconstruction and total knee arthroplasty (TKA). High-load resistance training (HL-RT) is the conventional strategy for restoring muscle mass and function; however, early postoperative application is often limited by pain, inflammation, and mechanical loading constraints. Blood flow restriction (BFR) training has emerged as a low-load alternative capable of eliciting comparable hypertrophic and strength adaptations without imposing excessive stress on healing tissues. Objective: To compare the physiological mechanisms, clinical outcomes, safety profiles, and integration strategies of BFR and HL-RT in post-surgical rehabilitation. Methods: This narrative review synthesized findings from randomized controlled trials, meta-analyses, and clinical guidelines published between 2019 and 2024, focusing on muscle hypertrophy, strength recovery, functional outcomes, and adverse event profiles associated with BFR and HL-RT in post-surgical populations. Results: BFR demonstrated comparable effects to HL-RT in preserving muscle mass and enhancing early strength in patients undergoing ACL reconstruction and TKA. BFR was associated with reduced pain and higher adherence in early rehabilitation phases. HL-RT, while more effective for long-term strength development, is better suited for later-stage recovery. Both modalities, when appropriately phased, contribute significantly to functional restoration. Conclusion: BFR is a safe and effective early-phase intervention in post-surgical rehabilitation, offering clinically meaningful benefits when HL-RT is contraindicated. A phased, evidence-based integration of both modalities optimizes outcomes and accelerates functional recovery.
Keywords: Blood flow restriction, resistance training, post-surgical rehabilitation, muscle hypertrophy, ACL reconstruction, total knee arthroplasty.

INTRODUCTION

Post-surgical muscle atrophy presents a significant challenge in physical rehabilitation, particularly following orthopedic procedures such as anterior cruciate ligament (ACL) reconstruction or total knee arthroplasty (TKA). These surgeries are often associated with pain, inflammation, and joint immobilization that limit early postoperative loading and delay functional recovery. High-load resistance training (HL-RT), traditionally defined as exercise performed at ≥65–70% of one-repetition maximum (1RM), has been well established as an effective modality to stimulate muscle hypertrophy and restore neuromuscular function in rehabilitation contexts (1). However, in the early stages of recovery, the application of high mechanical stress to healing tissues may increase the risk of complications and hinder adherence to rehabilitation protocols (2). To address these limitations, Blood Flow Restriction (BFR) training has emerged as a viable alternative, allowing patients to perform low-intensity exercises while still achieving significant muscular adaptations. BFR involves the application of controlled vascular occlusion to the proximal limb during low-load resistance training (typically 20–30% of 1RM), which creates a hypoxic and metabolically stressful environment that mimics the physiological responses elicited by HL-RT (3). Recent clinical and experimental findings suggest that BFR may offer a safe and effective strategy for enhancing early muscle recovery and improving functional outcomes without imposing excessive joint stress.

This narrative review aims to provide a comparative evaluation of HL-RT and BFR training in the context of post-surgical rehabilitation. It will explore their underlying physiological mechanisms, summarize clinical evidence across various surgical populations, and discuss practical considerations for integrating both modalities into rehabilitation protocols.

PHYSIOLOGICAL MECHANISMS

High-Load Resistance Training (HL-RT)

HL-RT induces muscle hypertrophy, and strength gains primarily through the application of mechanical overload, which stimulates intramuscular signaling pathways responsible for protein synthesis and cellular remodeling. The primary mechanism involves mechanical tension and muscle microtrauma that activate the mechanistic target of rapamycin (mTOR) signaling cascade, leading to increased translational efficiency and protein synthesis (4). Additionally, HL-RT enhances recruitment of motor units, particularly type II fibers, and promotes satellite cell proliferation, which contributes to muscle repair and growth (5). These structural and neuromuscular adaptations are dose-dependent, with progressively increased loads leading to superior long-term gains in strength and muscle mass.

Blood Flow Restriction (BFR) Training

BFR training leverages a distinct yet complementary mechanism by inducing metabolic stress through partial occlusion of venous return while maintaining arterial inflow. This is achieved using tourniquets or pneumatic cuffs applied to the proximal portion of the limb. The resultant hypoxic environment accelerates the accumulation of metabolites such as lactate, which in turn stimulates the secretion of anabolic hormones including growth hormone (GH) and insulin-like growth factor-1 (IGF-1) (6). These hormonal responses promote muscle protein synthesis and satellite cell activation even at low mechanical loads. Moreover, BFR facilitates earlier recruitment of fast-twitch muscle fibers due to oxygen deprivation, replicating the effects of high-load training despite using significantly lighter weights (7). Thus, while HL-RT relies on mechanical loading to initiate muscle adaptation, BFR elicits similar outcomes via metabolic and hormonal pathways, offering a viable option in clinical populations where joint loading must be minimized.

EVIDENCE IN POST-SURGICAL MUSCLE RECOVERY

After Anterior Cruciate Ligament (ACL) Reconstruction

Recovery following ACL reconstruction often involves significant quadriceps atrophy and delayed strength restoration. High-load resistance training (HL-RT) remains the gold standard for regaining neuromuscular performance, but early postoperative limitations such as joint swelling and pain can hinder its application. In contrast, Blood Flow Restriction (BFR) training has demonstrated significant promise in mitigating muscle loss during the initial phases of recovery. In a randomized controlled trial, Hughes et al. (2019) reported that six weeks of BFR training at 30% 1RM yielded quadriceps hypertrophy comparable to traditional HL-RT at 70% 1RM. Similarly, Okoroha et al. (2023) found that perioperative BFR use resulted in superior early strength gains and improved functional scores, including enhanced mobility and reduced joint discomfort. A meta-analysis by Zhou et al. (2024) concluded that BFR combined with low-load resistance training significantly outperformed low-load training alone in improving quadriceps cross-sectional area and isometric strength in the early stages of ACL rehabilitation.

After Total Knee Arthroplasty (TKA)

Patients undergoing TKA often experience prolonged periods of reduced mobility and muscle weakness, particularly in the quadriceps. Implementing HL-RT is frequently delayed due to surgical precautions and pain. Evidence suggests that BFR can be safely introduced earlier in the rehabilitation process and may accelerate strength recovery and functional improvements. Tramer et al. (2022) observed that early-stage BFR training significantly reduced quadriceps atrophy, improved mobility, and alleviated pain in TKA patients. Another clinical trial by Sgromolo et al. (2020) demonstrated that BFR-enhanced protocols led to measurable improvements in gait speed, stair navigation, and quality of life metrics when compared to standard physiotherapy alone. These findings underscore the role of BFR as a transitional method to preserve function and prepare patients for later high-load resistance phases.

Other Surgical Populations

Beyond ACL and TKA rehabilitation, BFR training has shown beneficial effects in other orthopedic and musculoskeletal surgeries. For example, Butt and Ahmed (2024) evaluated BFR in patients recovering from rotator cuff repair and reported significant improvements in shoulder muscle activation and range of motion. Jung et al. (2022) demonstrated enhanced quadriceps strength and balance in patients following patellar fracture repair. Moreover, Kilgas et al. (2019) documented long-term functional gains with BFR training initiated even months after ACL surgery, suggesting that delayed implementation can still yield substantial neuromuscular benefits. Collectively, these studies highlight the versatility of BFR as an adjunct or alternative to traditional resistance training during critical postoperative periods. Its ability to promote hypertrophy and functional recovery with minimal mechanical stress makes it particularly valuable for fragile or pain-limited patients.

Comparative Analysis of Outcomes

Blood flow restriction (BFR) training and high-load resistance training (HL-RT) each offer distinct advantages and limitations in post-surgical muscle rehabilitation, particularly regarding muscle hypertrophy, strength gains, pain, and functional recovery. A critical comparison of their respective outcomes across current literature is essential to guide optimal clinical practice.

Muscle Hypertrophy:

Meta-analyses consistently indicate that BFR training, when combined with low-load resistance exercise, can stimulate muscle hypertrophy comparable to that achieved through HL-RT in untrained and clinical populations (18, 4). While HL-RT typically produces the most robust increases in muscle cross-sectional area in healthy, trained individuals, BFR approaches these effects in patients unable to tolerate high mechanical loads during early recovery phases. This makes BFR especially valuable during the acute and subacute stages of rehabilitation when tissue healing constraints exist.

Strength Gains:

HL-RT remains the most effective modality for maximizing absolute strength gains, attributable to the high levels of mechanical tension applied to muscle and connective tissue (4). However, BFR training has demonstrated considerable efficacy in enhancing strength during periods when HL-RT is not feasible. Studies reveal that patients engaging in BFR protocols early postoperatively exhibit significantly greater improvements in isometric and dynamic strength than those performing low-load resistance training alone, and in some cases, these gains approximate those seen with HL-RT once heavier loading becomes possible (19, 11).

Pain and Exercise Tolerance:

An important advantage of BFR training is its favorable pain and tolerance profile. The use of lighter loads results in reduced peri-exercise discomfort, allowing patients with pain or joint restrictions to participate in strength training without exacerbating symptoms (13). Consequently, adherence to rehabilitation protocols is often higher among patients undergoing BFR, which may indirectly facilitate superior overall outcomes in the early postoperative period.

Functional Performance:

Functional improvements, including gait speed, stair climbing ability, and balance, have been consistently documented in patients undergoing BFR-enhanced rehabilitation (14, 16). While HL-RT ultimately provides greater potential for long-term neuromuscular adaptation, BFR is especially effective at expediting the restoration of basic mobility and activities of daily living during the initial phases of recovery. While HL-RT is superior for achieving maximal strength and muscle mass in the later stages of rehabilitation, BFR offers a unique, evidence-based solution for the early promotion of hypertrophy, strength, and functional gains when high mechanical loading is not yet appropriate. The integration of both modalities—tailored to individual recovery timelines—may offer the most comprehensive strategy for optimizing post-surgical rehabilitation outcomes.

Table 1: Empirical Outcomes of BFR vs. HL-RT in Post-Surgical Rehabilitation

Study / Source	Population / Surgery Type	Intervention	Load Intensity (%1RM)	Duration	Key Outcomes
Hughes et al., 2019	ACL Reconstruction (n=44)	BFR vs. HL-RT	30% vs. 70%	6 weeks	Quadriceps hypertrophy: BFR = HL-RT (↑~7–8% CSA)
Okoroha et al., 2023	ACL Reconstruction (RCT)	Perioperative BFR	30%	6 weeks	Early strength ↑26% (BFR) vs. 15% (Control); Lysholm score ↑
Zhou et al., 2024 (Meta-analysis)	Multiple ACL Trials	BFR + Low Load vs. Low Load Alone	20–30%	4–8 weeks	Significant ↑ in quadriceps CSA ($p<0.01$); Isometric strength ↑
Tramer et al., 2022	TKA (n=30)	BFR during early rehab	20–30%	8 weeks	Pain ↓ by 33%; Strength ↑ by 19% (vs. 7% in standard care)
Sgromolo et al., 2020	Acute TKA	BFR + PT vs. PT alone	30%	6 weeks	Gait speed ↑15%, Stair ascent time ↓20%, QoL scores ↑
Vieira de Melo et al., 2022	Meta-analysis (n=621)	BFR vs. HL-RT	20–30% vs. ≥65%	Varied	Muscle hypertrophy: BFR = HL-RT (ES = 0.58); Strength: HL-RT > BFR
Pan et al., 2021	Knee OA (Pilot)	BFR vs. HL-RT	30% vs. 70%	4 weeks	Pain VAS score: BFR ↓3.5 points vs. HL-RT ↓1.9 points
Kilgas et al., 2019	Post-ACL (older adults)	Late BFR Training	20–30%	6 weeks	Strength ↑17%; Mobility tests improved by 12–18%
Watson et al., 2022	Safety Review	BFR Protocols	50–80% limb occlusion pressure	—	VTE risk negligible with proper screening and cuff calibration
Nakajima et al., 2020	Systematic Review	BFR Pressure Settings	50–80% LOP	—	Recommended safe occlusion: 50% (upper limb), 80% (lower limb)

Abbreviations: ACL (Anterior Cruciate Ligament), TKA (Total Knee Arthroplasty), CSA (Cross-Sectional Area), PT (Physical Therapy), ES (Effect Size), QoL (Quality of Life), VAS (Visual Analog Scale), LOP (Limb Occlusion Pressure), VTE (Venous Thromboembolism)

SAFETY AND PRACTICAL CONSIDERATIONS

Initial apprehensions regarding the safety of blood flow restriction (BFR) training—particularly concerning risks of venous thromboembolism, nerve injury, and cardiovascular complications—have largely been mitigated by recent high-quality studies and clinical reviews (20). When applied according to standardized protocols, BFR training has proven to be a safe and well-tolerated intervention for most post-surgical patients. Key elements that ensure safety include the use of individualized occlusion pressures, gradual progression of exercise intensity, and close clinical monitoring. Current guidelines recommend determining limb occlusion pressure (LOP) for each

 https://doi.org/10.61919/9f8shd25

patient, typically setting BFR cuffs at 50–80% of LOP for the lower extremities and slightly lower for upper limbs to reduce the risk of nerve irritation (12). Exercise protocols commonly involve four sets (30-15-15-15 repetitions) at 20–30% of one-repetition maximum, performed two to four times per week under supervision (12, 11). Strict adherence to these parameters significantly decreases the likelihood of adverse effects.

Despite its favorable safety profile, BFR is not universally appropriate. Contraindications include a history of deep vein thrombosis, uncontrolled hypertension, peripheral vascular disease, or other conditions that could be exacerbated by restricted blood flow (20, 12). Careful pre-exercise screening is therefore essential. Additionally, patient education regarding the sensation of limb pressure and early signs of adverse events—such as excessive numbness or unusual discomfort—is crucial to ensure compliance and minimize complications. In clinical practice, BFR should be administered or at least initiated under the supervision of a trained rehabilitation professional familiar with the technique and safety monitoring. Regular reassessment of limb perfusion, cuff placement, and exercise response is recommended to optimize outcomes and mitigate risk. For HL-RT, the primary safety consideration remains the timing of introduction post-surgery, as excessive early loading can jeopardize tissue healing and increase the risk of re-injury. In summary, both BFR and HL-RT are safe when applied judiciously within the confines of established protocols and with appropriate patient selection. The growing evidence base underscores the importance of individualized assessment, protocol standardization, and interdisciplinary communication to fully realize the benefits of these modalities while minimizing potential harm.

INTEGRATION INTO REHABILITATION PROGRAMS

The successful integration of blood flow restriction (BFR) training and high-load resistance training (HL-RT) into post-surgical rehabilitation programs requires a phased, individualized approach that aligns with tissue healing, patient tolerance, and evolving clinical goals. Evidence supports the use of a progressive framework, transitioning from lower-intensity modalities to more demanding resistance exercises as the patient advances through recovery.

In the early phase (typically the first 6 weeks post-surgery), the primary objectives are to minimize muscle atrophy, preserve neuromuscular activation, and restore joint mobility while protecting healing tissues. During this period, BFR training is particularly advantageous, as it allows for meaningful muscular stimulation at very low loads (such as straight leg raises or unloaded knee extensions) without compromising surgical repairs (3, 11). This approach is especially relevant when traditional high-load exercises are contraindicated due to pain, swelling, or weight-bearing restrictions. The mid-phase (approximately weeks 6–12) is characterized by improved tissue integrity and increased tolerance to mechanical loading. Here, a gradual transition can be made by combining BFR with progressively increased resistance, allowing patients to bridge the gap between low-load and traditional HL-RT. This combination supports ongoing hypertrophy and strength development while reducing risk of overloading vulnerable tissues (15, 10). Clinicians should adjust exercise intensity and volume based on ongoing assessments of pain, range of motion, swelling, and functional progress. In the late phase (after 12 weeks), once healing is sufficient and foundational strength has been established, patients may progress primarily to HL-RT to maximize muscle strength, power, and functional return. HL-RT at this stage is well tolerated and provides the necessary stimulus for advanced neuromuscular and structural adaptation, supporting return to pre-injury activity levels and reducing risk of reinjury (10, 15).

Throughout all phases, close monitoring and individualized progression are essential. Factors such as comorbidities, surgical complexity, and baseline physical condition should inform the selection and sequencing of training modalities. Interdisciplinary communication among surgeons, physical therapists, and patients is vital to ensure safe transitions and maximize rehabilitation outcomes. In summary, the phased integration of BFR and HL-RT—tailored to the patient's clinical status and recovery timeline—enables clinicians to leverage the complementary benefits of each modality, thereby optimizing muscle hypertrophy, strength restoration, and functional recovery following surgery.

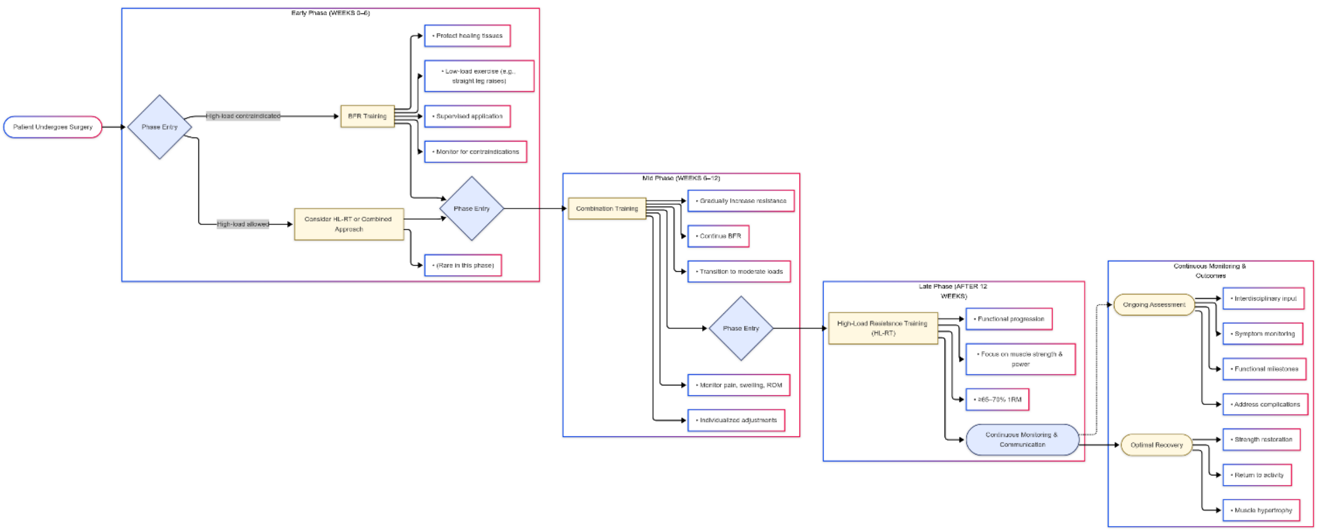

Figure 1 Study Flowchart

The flowchart begins with the patient's entry into the rehabilitation process immediately following surgery. The first major decision point occurs at the phase entry, where the clinician evaluates whether high-load resistance training is appropriate in the early phase of recovery. If high-load resistance is contraindicated—which is common in the first few weeks due to tissue healing constraints—the patient is placed on a BFR training protocol. This phase emphasizes protection of healing tissues, use of low-load exercises like straight leg raises, close clinical supervision, and regular monitoring for any contraindications or complications. This approach aligns with the typical demands of the early rehabilitation phase (Weeks 0–6), where joint stress must be minimized. In the less common case where high-load training is deemed safe at this stage, clinicians may consider introducing HL-RT or a hybrid approach; however, this is noted as rare in the early phase due to potential surgical vulnerability. After completing this stage, the patient proceeds to another decision point marking entry into the mid-phase of rehabilitation (Weeks 6–12).

During the mid-phase, the emphasis shifts toward combination training, which involves continuing BFR while gradually introducing moderate resistance. This phase supports a safe progression in exercise intensity, helping bridge the gap between early-stage recovery and traditional strength training. The protocol includes stepwise increases in resistance, ongoing application of BFR, and careful monitoring of symptoms such as pain, swelling, and range of motion. Importantly, individualized adjustments are made based on clinical feedback and patient tolerance. Upon successful completion of the mid-phase, the patient enters the late rehabilitation phase (After 12 weeks). At this point, full healing and foundational strength allow for the introduction of high-load resistance training (HL-RT). The focus here is on restoring maximal muscle strength, power, and functional capacity. HL-RT exercises are now performed at ≥65–70% of the patient's one-repetition maximum, supporting neuromuscular remodeling and advanced performance goals such as return to sport or demanding physical activity.

Throughout all phases, the model incorporates a parallel stream of continuous monitoring and communication. This includes ongoing assessment of symptoms, functional milestones, and interdisciplinary input from therapists and physicians. If complications arise or milestones are not achieved, feedback loops allow clinicians to adjust or regress the training strategy. Ultimately, the flow concludes at the optimal recovery outcome, characterized by restored muscle hypertrophy, strength, and the patient's safe return to daily activities or sport.

LIMITATIONS AND FUTURE DIRECTIONS

While the current evidence strongly supports the use of both blood flow restriction (BFR) and high-load resistance training (HL-RT) in post-surgical rehabilitation, several limitations warrant consideration. Firstly, a substantial proportion of the available literature focuses on short- to medium-term outcomes, with relatively few studies extending beyond 6 to 12 months post-intervention. As such, the long-term sustainability of strength gains, muscle hypertrophy, and functional outcomes following BFR training remains inadequately explored. Future studies should prioritize longitudinal designs that assess durability of results, recurrence of muscle weakness, and impact on reinjury rates.

Another limitation is the population bias in current research. The majority of trials have centered on lower limb surgeries—most notably ACL reconstruction and total knee arthroplasty—leaving a significant gap in evidence for upper extremity surgeries, spinal procedures, and non-orthopedic postoperative scenarios. Expanding the application of BFR into diverse surgical populations could clarify its broader utility and safety profile. Furthermore, most published studies are conducted in controlled clinical settings, which may not fully replicate real-world rehabilitation environments. Therefore, pragmatic trials that assess BFR effectiveness and adherence in community or home-based rehabilitation are needed. There is also ongoing concern regarding the standardization of BFR protocols. Variability in cuff width, limb occlusion pressure, exercise selection, and frequency makes direct comparisons between studies difficult and limits clinical translation. To optimize both safety and effectiveness, a consensus is needed on dose-response parameters, including pressure calibration methods and progression models. Additionally, patient selection criteria—including screening for vascular disease, clotting risk, and individual tolerance—should be more rigorously defined and validated across populations. Another underexplored area is the cost-effectiveness of BFR training relative to traditional modalities. While BFR may reduce time to functional recovery and physical therapy visits, the initial investment in equipment and professional training must be considered. Economic evaluations comparing BFR-integrated protocols with standard care could guide reimbursement strategies and inform adoption in resource-constrained settings.

Lastly, future research should explore the combined and sequential use of BFR and HL-RT in periodized models tailored to individual recovery phases. This approach holds promise for optimizing outcomes while minimizing risks, but high-quality randomized controlled trials are needed to validate its efficacy. Investigating biomarkers, imaging correlates, and neuromuscular adaptations specific to BFR may also help refine treatment algorithms and personalize care. In conclusion, while the current body of evidence affirms the therapeutic value of BFR and HL-RT in post-surgical rehabilitation, important gaps remain. Addressing these through focused research efforts will be essential to enhance protocol standardization, safety, and broad clinical applicability.

CONCLUSION

Post-surgical muscle rehabilitation presents unique challenges, particularly in the early stages when tissue healing, pain, and joint protection limit the application of traditional resistance training. This review highlights that both blood flow restriction (BFR) training and high-load resistance training (HL-RT) offer significant therapeutic benefits, but their effectiveness depends largely on timing, patient status, and clinical context.

High-load resistance training remains the cornerstone of long-term muscle strength and hypertrophy development due to its capacity to generate substantial mechanical tension and neuromuscular activation. However, in the early postoperative period—when high mechanical loading may be unsafe or intolerable—BFR training emerges as a viable and effective alternative. By simulating the metabolic and hormonal environment of HL-RT through low-load exercise under controlled vascular occlusion, BFR enables patients to initiate rehabilitation earlier, preserve muscle mass, and improve functional outcomes without jeopardizing healing structures.

When applied in a phased, evidence-based framework, BFR and HL-RT can complement each other across the rehabilitation continuum. BFR is ideally suited for early to mid-stage recovery, offering a low-risk strategy to combat disuse atrophy and support neuromuscular reconditioning. As healing progresses, transitioning to HL-RT enables patients to build on these foundational gains and fully restore strength, endurance, and physical function. Importantly, safety considerations—such as individualized occlusion pressure, contraindication screening, and supervised implementation—must be rigorously followed to minimize risk and enhance adherence. The integration of these two modalities, tailored to the patient's surgical profile and functional goals, holds considerable promise for optimizing recovery trajectories. Future research should continue to explore long-term outcomes, broader surgical populations, protocol standardization, and cost-benefit analyses. In clinical practice, the strategic combination of BFR and HL-RT—applied at the right time and intensity—can accelerate recovery, improve patient satisfaction, and support earlier return to activity or sport.

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