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ROLE OF BIOACTIVE SCAFFOLD AND BLOOD FLOW RESTRICTION TRAINING IN MUSCLE STRENGTH, HEALING AND PROPRIOCEPTION AMONG PATIENT WITH ACL RECONSTRUCTION: A NARRATIVE REVIEW

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Abstract

Anterior cruciate ligament (ACL) injuries pose significant challenges in orthopedic and sports medicine, particularly in restoring full function, muscle strength, and proprioception. Traditional surgical reconstruction, while widely practiced, often fails to achieve complete recovery, resulting in low return-to-sport rates and persistent neuromuscular deficits. Emerging interventions, such as Blood Flow Restriction Training (BFRT) and bioactive scaffold-assisted repair, offer promising advancements in regenerative rehabilitation. BFRT employs low-load resistance exercises combined with vascular occlusion to enhance muscle hypertrophy and strength without placing excessive stress on healing tissues, making it especially effective during early rehabilitation. Meanwhile, bioactive scaffolds, such as those utilized in Bridge-Enhanced ACL Repair (BEAR), create a biologically active environment that supports ligament regeneration, preserves native mechanoreceptors, and improves proprioception. Together, these approaches address both the mechanical and biological aspects of recovery. Integrating BFRT with scaffold-based repair may provide synergistic benefits accelerating muscle strength restoration, enhancing neuromuscular control, and promoting intrinsic healing, thereby facilitating a safer and more effective return to function.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are a common orthopedic condition, especially among young athletes, with approximately 200,000 ACL reconstructions performed annually in the United States. These injuries typically occur in high-impact sports that involve deceleration, jump landings, or sudden changes in direction.(1) Sport recovery rates following anterior cruciate ligament reconstruction (ACLR) are low, with only 31% of patients recovering within one year, 41% recovering after two years, and 63% returning to their pre-injury performance levels. Although surgical reconstruction is the standard treatment, achieving full functional recovery continues to pose a significant

challenge.(2)Key domains affected by ACL injury and reconstruction include healing, proprioception, and muscle strength.

The anterior cruciate ligament (ACL), similar to the meniscus, cartilage, and tendons, possesses a limited intrinsic healing capacity due to its location within the synovial joint. The presence of synovial fluid inhibits stable blood clot formation at the injury site, which disrupts the natural healing cascade and restricts tissue regeneration. Consequently, untreated ACL injuries often lead to joint instability, meniscal damage, and early-onset osteoarthritis.(1)

ACL injuries result in significant neurophysiological changes that disrupt the sensorimotor control of the knee. The anterior cruciate ligament (ACL) is not merely a passive stabilizer; it functions as an active sensory organ integrated with the central nervous system (CNS). This integration contributes to the dynamic regulation of knee movements through a dense network of mechanoreceptors. These sensory receptors provide essential proprioceptive feedback, informing the CNS about joint position, tension, and motion, and coordinating neuromuscular responses to protect the knee from excessive loading. When the ACL is injured, this intricate sensorimotor system is compromised, leading to deficits in proprioceptive accuracy, delayed muscular reflexes, and altered motor control strategies.(3)

Quadriceps and hamstring weakness is another frequent sequela post-ACL reconstruction, driven by pain, inflammation, disuse, and disrupted proprioceptive signaling. (4)

METHODOLOGY:

This narrative review aimed to explore and synthesize recent evidence on the role of bioactive scaffolds and blood flow restriction (BFR) training in enhancing muscle strength, tissue healing, and proprioception in patients undergoing anterior cruciate ligament (ACL) reconstruction. A comprehensive literature search was conducted to identify relevant studies published between January 2020 and March 2025. The following electronic databases were used: PubMed, CINAHL, and Google Scholar. The search strategy included combinations of keywords such as "bioactive scaffold," "blood flow restriction training," "ACL reconstruction," "muscle strength," "proprioception," and "tissue healing." Boolean operators (AND, OR) were employed to refine the search.

A total of **22 studies** were included in this review based on the following **inclusion criteria**:

- Published in English between 2020 and 2025
- Peer-reviewed articles
- Studies involving human subjects who underwent ACL reconstruction
- Articles focusing on the application or outcomes of bioactive scaffolds and/or BFR training
- Research evaluating outcomes such as muscle strength, proprioception, or tissue healing

Exclusion criteria included:

- Studies involving animal models only
- Non-peer-reviewed literature
- Articles focusing on unrelated rehabilitation methods or other surgical techniques

The selected studies were independently screened for relevance based on titles and abstracts, followed by full-text review. As this is a narrative review, a qualitative synthesis of the literature was performed without statistical meta-analysis. The findings were categorized thematically under the roles of bioactive scaffolds and BFR training, and their combined influence on rehabilitation outcomes post-ACL reconstruction.

MANAGEMENT AND REHABILITATION:

Effective management of ACL injuries necessitates personalized protocols that address proprioception, neuromuscular coordination, and muscle strength. While conservative management may be appropriate for some patients, surgical intervention is the standard approach for cases involving instability or meniscal pathology. Rehabilitation progresses through distinct phases that emphasize pain control, muscle strengthening, proprioception restoration, and functional retraining. Additionally, psychological support is essential for alleviating

emotional consequences such as anxiety and reduced confidence.(5)

Blood Flow Restriction Training (BFRT):

Innovative rehabilitation techniques, such as Blood Flow Restriction Training (BFRT) and bioactive scaffolds, are gaining traction as complementary therapies to conventional protocols. BFRT involves low-intensity resistance exercises performed under partial vascular occlusion, promoting muscle hypertrophy and strength gains while minimizing stress on the joints. This approach is particularly beneficial during the early recovery phases when patients may struggle to tolerate high-load training. Preliminary studies indicate that BFRT enhances both isokinetic strength and functional performance, although outcomes can vary among individuals.(6)

BFRT has demonstrated potential for patients recovering from ACL reconstruction by applying pressure to the proximal limbs during exercise, which enhances metabolic stress and muscle activation. These mechanisms lead to significant increases in muscle strength and size, even without heavy loading. (7, 8). As such, Blood Flow Restriction Training (BFRT) is particularly suitable for the early stages of rehabilitation. Although some research indicates that high-load resistance training (HL-RT) yields superior strength improvements,(9, 10, 11), others report comparable or even superior effects of BFR-RT, especially in terms of early-phase muscle adaptation(12)

Numerous studies support the incorporation of Blood Flow Restriction Training (BFRT) in anterior cruciate ligament (ACL) rehabilitation, highlighting increased quadriceps strength and hypertrophy compared to traditional rehabilitation protocols. Additionally, BFRT is linked to improved patient-reported outcomes, including reduced pain and enhanced knee function.(13, 14, 15, 16)

Although further evidence is needed, BFRT appears to be a safe, effective, and adaptable strategy for early rehabilitation, capable of improving muscle strength and proprioception with minimal joint strain.

Bioactive Scaffold-Based Repair:

Bioactive scaffolds address the biological limitations associated with anterior cruciate ligament (ACL) healing. Techniques such as Bridge-Enhanced ACL Repair (BEAR) employ matrices infused with growth factors or cells to facilitate ligament regeneration and preserve mechanoreceptors. These methods produce biomechanical outcomes comparable to those of graft-based repairs while providing proprioceptive advantages.(17)

Scaffold-based repair represents a paradigm shift by fostering native tissue regeneration without the need for tendon graft harvesting, thus reducing donor-site morbidity.(18, 19, 20) Notably, this method retains native mechanoreceptors, vital for proprioceptive integration and neuromuscular control. (20)

Clinical studies indicate that scaffold-based repair provides joint stability and functionality comparable to conventional techniques, while also offering additional proprioceptive benefits. Although direct enhancements in strength are still being investigated, it is likely that reduced surgical trauma promotes earlier muscle activation and diminishes postoperative inhibition.(21)

These scaffolds promote vascularization and cellular integration, accelerating recovery and generating high-quality regenerated tissue. Their minimally invasive nature and ability to preserve joint function make them particularly appealing, especially for active individuals seeking a swift return to their activities.(22)

In summary, scaffold-based anterior cruciate ligament (ACL) repair enhances proprioception, supports natural healing, minimizes complications, and may accelerate early muscle recovery providing a physiologically aligned alternative to graft reconstruction.

CONCLUSION

Combining Blood Flow Restriction Training (BFRT) with bioactive scaffold-based anterior cruciate ligament (ACL) repair addresses both the mechanical and biological aspects of ACL rehabilitation. BFRT enhances muscle strength and neuromuscular activation during the early stages of recovery, while bioactive scaffolds facilitate ligament healing and proprioception by preserving native structures. This dual approach mitigates muscle atrophy, restores functional capacity, and may reduce the risk of re-injury and long-term joint degeneration.

RECOMMENDATIONS

Clinicians should consider integrating Blood Flow Restriction Training (BFRT) early in rehabilitation, particularly for patients who are unable to engage in high-load training, as it can enhance muscle strength with minimal stress. Similarly, the use of Biologic Enhanced Augmentation Repair (BEAR) and other scaffold-based methods should be implemented for appropriate candidates to promote natural healing and preserve proprioceptive pathways. A multidisciplinary approach that includes orthopedic surgeons, physiotherapists, and sports scientists is essential. Further research is needed to evaluate the long-term outcomes of combined BFRT and scaffold repair on joint stability, function, and the recurrence of injuries.

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