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Research Article

Optimizing Rehabilitation for Quadriceps Tendon Anterior Cruciate Ligament Reconstruction: A Focused Approach

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Abstract

Anterior cruciate ligament (ACL) injuries are prevalent in the active and athletic communities, with over 200,000 reconstructions performed annually in the United States. While the bone-patellar tendon-bone (BTB) autograft is historically regarded as the "gold standard," its complications, including anterior knee pain and increased osteoarthritis risk, have prompted the exploration of alternative grafts. The quadriceps tendon (QT) autograft has emerged as a promising alternative, offering comparable outcomes in knee stability, functional performance, and patient satisfaction. Despite growing use, rehabilitation protocols specific to QT autografts remain underdeveloped. Existing guidelines, such as those by the American Physical Therapy Association and the Multicenter Orthopaedic Outcomes Network, primarily address BTB and hamstring tendon autografts, leaving a gap in QT-specific postoperative management. This manuscript reviews current evidence on the biomechanical properties and clinical outcomes of QT autografts and identifies unique rehabilitation considerations. Key modalities, including cryotherapy, neuromuscular electrical stimulation (NMES), open kinetic chain exercises, and blood flow restriction training, are evaluated for their role in optimizing early recovery. Special emphasis is placed on quadriceps activation strategies and progressive loading tailored to QT-specific needs. Recommendations aim to bridge current gaps and facilitate evidence-based, graft-specific rehabilitation protocols. This review underscores the importance of advancing personalized rehabilitation approaches to improve outcomes for patients undergoing ACL reconstruction with QT autografts.

Keywords: Quadriceps tendon autograft; ACL reconstruction; Rehabilitation; Open kinetic chain exercises; Neuromuscular electrical stimulation; Blood flow restriction training

Introduction

Anterior Cruciate Ligament (ACL) injuries are among the most common sports-related injuries, with an estimated 200,000 ACL reconstructions (ACLR) performed annually in the United States [1]. Traditionally, the bone-patellar tendon-bone (BTB) autograft has been regarded as the "gold standard" for ACLR due to its favorable clinical and functional outcomes [2,3]. Internationally, the most common graft source is the hamstring tendon autograft (HS) [4]. However, BTB autografts are associated with several risks, including patellar or anterior knee pain, patellar fractures, and an increased likelihood of developing patellofemoral osteoarthritis [5]. HS autografts are associated with increased laxity and increased re tear rate in young athletes and patients with high grade laxity [6,7].

In recent years, the quadriceps tendon (QT) autograft has gained attention as a promising alternative, demonstrating comparable outcome scores, return-to-play rates, and re-tear rates to the BTB autograft [8-10]. Additionally, QT autografts have shown improved re-tear rates compared to HS.8,11 This growing body of evidence supports the QT autograft as a viable option for ACLR, offering potentially fewer complications without compromising surgical outcomes.

Despite the increasing use of QT autografts, significant gaps remain in our understanding of their rehabilitation, particularly during the acute phase. Most of the current rehabilitation guidelines and protocols were either written without inclusion of QT autograft, such as the Multicenter Orthopaedic Outcomes Network (MOON), or without consideration of specific graft types such as the American Physical Therapy Association (APTA) guidelines. These guidelines are based on research relevant to BTB and HT autografts [12-14]. Consequently, there is a need to assess whether these guidelines are fully applicable to patients undergoing ACLR with QT autografts. Furthermore, the American Academy of Orthopaedic Surgeons (AAOS) Clinical Practice Guidelines (CPG) on ACLR provide no specific guidance regarding the use of QT autografts [15]. This lack of specific guidance is concerning given the trajectory of QT autograft use [6].

Additionally, it is crucial to recognize that different graft types exhibit distinct biomechanical properties due to variations in tendon characteristics and fixation techniques.16 These differences, coupled with the potential impact on the harvest site, suggest that a "one size fits all" approach to rehabilitation may not be appropriate. Particularly concerning is the ongoing debate over quadriceps muscle weakness following ACLR with QT autografts, with studies yielding mixed results. While some research indicates persistent quadriceps weakness, other studies report comparable quadriceps strength to that seen with other graft types [17,18]. This uncertainty underscores the need for graft-specific rehabilitation protocols.

Despite advances in QT autograft harvesting techniques and its increasing use, rehabilitation protocols specific to QT autografts have received little attention. The purpose of this manuscript is to: (1) review specific exercises and modalities relevant to recovery following ACLR with a QT autograft, and (2) provide evidence-based recommendations for acute phase rehabilitation following QT autograft ACLR. Ultimately, this review aims to serve as a precursor to future randomized studies that will develop specific protocols and clinical practice guidelines tailored to QT autograft ACLR.

Biomechanics

Anatomy of the Quadriceps Tendon

The QT is made up of fibers from the vastus medialis, vastus lateralis and rectus femoris anteriorly [19-22]. Additionally, the deepest portion of the QT is formed by the vastus intermedius. Furthermore, the superficial layer of the QT has been described as originating from the thickening of the deep fascia posterior to the rectus femoris, the middle layers originating from the thickening of the fascia posterior to the vastus lateralis and vastus medialis, and the deep layer is formed by the anterior thickening of the deep fascia just anterior to the vastus intermedius [23]. The tendon itself ranges in width from 2.5 to 3 cm and averages approximately 6-8 cm in length from the superior pole of the patella to the myotendinous junction [19-21]. Height is the greatest predictor of QT length [24].

The rectus femoris is the most superficial muscle of the quadriceps group and inserts on superior third of the anterior surface of the patella [22]. The intermediate layer of the QT, made up of the vastus lateralis and vastus medialis form a continuous aponeurosis that inserts into the base of the patella. This insertion is just posterior to the insertion of the rectus femoris, while also continuing laterally and medially to insert into the sides of the patella [22]. The vastus intermedius makes up the deepest layer of the QT and has an intimate origin with the vastus lateralis proximally and the lateral intermuscular septum distally [22,25].

The vascular supply of the QT stems from three arteries which consist of the lateral circumflex femoral artery, branches of the descending geniculate artery, and the medial and lateral superior geniculate arteries.19,25 The blood supply to the superficial aspect of the tendon has complete vascular networks that extend from the patella to the myotendinous junction.25 The deep portion of the tendon has an avascular portion 10 mm proximal to the border of the patella that measures about 30mm x 15mm [19,25].

Biomechanics of the Quadriceps Tendon

Historically, QT grafts for ACLR were considered biomechanically inferior to HT and BTB grafts, but biomechanical differences may have been due to inferior graft harvesting techniques and fixation devices [19]. Recent studies have shown that the biomechanical properties of the QT autograft are similar to those of the native ACL and compared similarly with BTB and HT [20,21,26]. Woo et al. demonstrated through a cadaveric study that the ultimate load to failure of the native ACL was 2,106N.27 The QT autograft demonstrated an ultimate load to failure of 2,185 N and stiffness of 466 N/mm, compared to the BTB autograft, which had an ultimate load to failure of 1,580 N and stiffness of 278 N/mm.28 It should also be noted that HT autografts have consistently demonstrated the highest load to failures at 4,000N when compared to BTB and QT autografts.

Additionally, Adams et al. found that harvesting a partial-thickness 10-mm wide central free tendon graft from the QT reduces its tensile strength by approximately one third. However, the postharvest strength of the QT was still higher than that of the intact patellar tendon [16]. These findings highlight the biomechanical advantages of using the QT for ACLR.

Given these findings, the QT is an appropriate autograft choice for ACLR. Furthermore, clinical outcomes following ACLR using the QT autograft have been promising with studies showing similar or superior results in terms of knee stability, functional outcomes, and patient satisfaction scores when compared to other graft types [29-31].

Cryotherapy

Cryotherapy has been a long-standing modality in the recovery of post-operative ACLR. A systematic review by Glattke et al in 2021 recommends cryotherapy as an effective pre and post-operative analgesic. This recommendation is in agreement with the vast amount of literature on this topic [32-39].

An interesting finding on cryotherapy is it may decrease arthrogenic muscular inhibition of the quadriceps in the short term after surgery or after a bout of swelling [40-43]. With quadriceps activation being a primary goal in immediate post-operative recovery, this is an important variable to consider in regard to cryotherapy. We strongly recommend the use of cryotherapy as it has demonstrated benefits for pain, ROM, and quadriceps function in the early stages of ACL recovery.

Open Kinetic Chain

Open kinetic chain (OKC) exercise has been a topic of contention for many years. The primary fear around OKC exercise is creating graft laxity if initiated too early in the rehab process. However, quadriceps strength recovery is difficult for all graft types, and OKC exercise is the only way to isolate the quadriceps. Strength recovery of the quadriceps has been shown to be particularly challenging with QT grafts [18]. With the unique anatomy of the QT graft, strong biomechanical properties, and stable fixation techniques as previously discussed – we believe that early and aggressive OKC exercise is safe and essential to a proper rehab program post QT ACLR.

Beynon et al showed that OKC exercise between 90°-45° puts little to no strain on the ACL [44]. While an excellent review from Escamilla et al in 2012 shows that a full ROM OKC knee extension without weight up to 10lbs of resistance showed similar or less ACL strain than many typical ADLs and common rehab exercises [45]. Beynnon et al, also demonstrated that a full ROM OKC knee extension without resistance places 2.8% total strain on the ACL [44]. This value is less than a Lachman test which is typically performed intraoperatively and in the early post-operative follow ups. For these reasons, we believe isometrics and unweighted full ROM knee extension can be performed immediately in the rehab process as anterior knee pain permits.

There is evidence to support progressive loading of OKC exercise, and that is safe and effective when done appropriately. Traditional rehab exercises that are initiated early in rehab show similar strain values as OKC knee extension exercise [45]. For example, stationary bike, walking, step ups and squatting produce anywhere from 2-4% total strain on the ACL. While, as stated above, unweighted up to 10lbs of OKC knee extension produces from 2.8-3.8% total ACL strain [44]. Interestingly, level ground walking produces 355N of shear force on the ACL while a 12-repetition max of OKC knee extension produces 248N of shear force on the ACL [46,47]. This evidence demonstrates that it is safe to thoughtfully use progressive overload for OKC exercise just as is used with other typical therapy exercises early on in therapy. OKC should be used early and often particularly when considering the unique biomechanical properties of the QT ACLR.

Finally, an excellent paper from Solie et al in 2023 makes some recommendations for rehab implications specific to post QT ACLR [48]. Beyond early quad activation and OKC initiation, performing strengthening in hip neutral positions is an important consideration. Due to the location and size of the QT graft, it is important to address all layers of the quad muscle group as much as possible. Performing OKC quad isolation exercises in hip neutral will target the rectus femoris, the most superficial layer of the quadriceps [48]. Another consideration is training the quadriceps in deeper knee flexion angles during OKC exercise. Training in greater knee flexion angles will preferentially target the QT. This can be progressed carefully, while being mindful of the graft harvest site as to not increase irritability to the healing tissue [48]. These are two important considerations for OKC rehab post QT ACLR that may be helpful for successful quadriceps recovery (Table 1).

Phase	Exercise	Progression and Notes
Weeks 0–1	Isometric knee extensions (90–45°), no-load full-ROM knee extensions	Begin as early as graft site pain allows. Focus on pain-free ROM.
Weeks 2–3	Continue isometrics and progress to weighted knee extensions (1–2 lbs increments)	Ensure previous exercises can be performed pain-free through full ROM before progressing weight.
Weeks 4–5	Weighted OKC knee extensions through full ROM, 12+ rep sets	Maintain good control. Perform exercises in hip-neutral positions to target all layers of the quadriceps.
Week 6+	Use knee extension machine with pad at mid-shin; progress pad distally as tolerated	Gradual increase in weight and ROM while avoiding high-load, low-repetition exercises for six months.

Table 1: Exercise progression acute phase rehabilitation of quadriceps tendon autograft. ROM = Range of Motion, BFR = Blood Flow Restriction, NMES = Neuromuscular Electrical Stimulation, OKC = Open Kinetic Chain, LOP = Limb Occlusion Pressure, 1RM = One-Repetition Maximum.

BFR

The use of Blood Flow Restriction (BFR) training has gained significant popularity as a rehabilitation technique for addressing common impairments following ACLR. BFR involves the application of cuffs or bands placed proximally on the lower extremity to partially restrict arterial inflow and completely restrict venous outflow during exercise. Early implementation of BFR acutely after ACLR has been shown to mitigate muscle atrophy caused by reduced muscle protein synthesis following QT ACLR [49-53]. While evidence supports these benefits, recent findings, such as those by Colombo et al., highlight variability in outcomes depending on protocols and patient populations. Although BFR has demonstrated improvements in muscle strength and patient-reported outcome measures (PROMs), its superiority to traditional methods in enhancing muscle size and strength gains is not universally consistent. These findings emphasize the importance of tailoring BFR protocols to individual patient needs and recovery stages to optimize rehabilitation outcomes [54].

Nakajima et al. showed that BFR enhances cell swelling, causing stretch stimulation of osmosensors in the cell membrane, which triggers anabolic and anti-catabolic processes to increase muscle protein synthesis [55]. Passive BFR application without exercise, using 100% limb occlusion pressure (LOP) with a 5-minute occlusion and 3-minute reperfusion protocol, has been shown to reduce muscle atrophy, and this effect may be further enhanced when combined with neuromuscular electrical stimulation (NMES) [56-58]. Once patients can tolerate OKC exercises, BFR can be applied with 80% LOP using a set and repetition scheme to failure, most commonly 30-15-15-15. For QT ACLR, traditional low-load BFR protocols can be introduced earlier in rehabilitation compared to standard ACL protocols, using weights up to 20-30% of the one-repetition maximum (1RM), which may be calculated from preinjury or the non-surgical leg [54,56-58].

Hughes et al. (2017) demonstrated that low-load BFR training was superior to low-load resistance training alone for improving muscle mass and strength gains [59]. However, Colombo et al. emphasize the need for standardized methodologies, as variability in cuff pressures, exercise regimens, and occlusion methods can affect the efficacy of BFR. While BFR is generally considered safe, clinicians must remain vigilant about rare but serious complications such as deep vein thrombosis or nerve injury [54]. When compared to heavy-load training, however, low-load BFR training remains inferior for achieving maximum strength gains [59,60]. Thus, BFR should be viewed as a bridge toward heavier loading (Table 2). The advantages of QT ACLR in facilitating earlier OKC resistance training may contribute to reduced muscle atrophy and improved strength outcomes during the rehabilitation process.

Phase	Exercise	Progression and Notes
Weeks 0–3	Passive BFR at 100% LOP, 5-minute occlusion, 3-minute reperfusion cycles	No exercise required during this phase. Focus on mitigating muscle atrophy.
Weeks 4+	BFR with OKC exercises at 80% LOP, 30-15-15-15 rep scheme	Gradual progression to 20–30% 1RM resistance. Avoid graft site irritation and monitor patient tolerance.

Table 2: Blood flow restriction guidelines for acute phase rehabilitation of quadriceps tendon autograft. ROM = Range of Motion, BFR = Blood Flow Restriction, NMES = Neuromuscular Electrical Stimulation, OKC = Open Kinetic Chain, LOP = Limb Occlusion Pressure, 1RM = One-Repetition Maximum.

NMES

NMES plays a vital role in overcoming muscle inhibition, which is common following ACLR. NMES facilitates muscle recruitment by stimulating motor units that may be inhibited due to pain or joint effusion. It enhances muscle activation by increasing both motor unit recruitment and firing rate (rate coding), making it a valuable tool in post-operative rehabilitation [61]. Since the early 1990s, NMES has been studied in ACLR rehabilitation as an adjunct to traditional therapeutic exercises, particularly for its ability to promote quadriceps strength recovery and maintain muscle function.

Despite its known benefits, high-level evidence investigating the use of NMES specifically in QT autograft ACL rehabilitation is limited. Among the literature available, only a few studies mention NMES as part of the rehabilitation protocol. For example, Guney Deniz et al. reported that subjects a knee proprioception study followed a post-operative program focused on progressive quadriceps strengthening, which was augmented with NMES. This program also included therapeutic exercises designed to restore neuromuscular control, a crucial aspect of rehabilitation [62].

Solie et al. highlighted the potential benefits of early NMES implementation, particularly when combined with BFR during quadriceps exercises when the QT autograft was utilized. Their findings suggest that early use of NMES may enhance neuromuscular recruitment, reduce thigh muscle atrophy, and improve muscle size and strength throughout the rehabilitation process [48].

However, Zhang et al. pointed out inconsistencies in the application of NMES across ACLR rehabilitation protocols. This lack of standardization, alongside other adjuncts like motion-controlled braces and cryotherapy, underscores the variability in how NMES is applied post-operatively [63]. These inconsistencies suggest that, while NMES has demonstrated potential benefits, further research is needed to establish high-level evidence for its specific use in QT ACL rehabilitation.

While there is limited high-quality evidence for NMES in QT-specific ACL rehabilitation, the broader ACLR literature strongly supports its use. According to the 2017 clinical practice guidelines on knee ligament sprains, NMES is recommended for 6 to 8 weeks following ACLR to augment quadriceps strengthening exercises and improve short-term functional outcomes [12]. This A-grade evidence emphasizes the importance of NMES in promoting strength recovery.

Culvenor's systematic review of 16 randomized controlled trials (RCTs) further supports NMES, particularly when applied two to six times per week within the first 4 to 12 weeks post-operatively. The review found a large effect size for NMES in improving quadriceps strength during early recovery phases, providing moderate-certainty evidence for its effectiveness [64].

At the cellular level, Toth et al. demonstrated that early NMES use can reduce muscle fiber atrophy, particularly in type II fibers, while preserving contractility in type I fibers. These findings provide cellular-level evidence for the beneficial effects of NMES in modifying skeletal muscle maladaptation following ACLR [65]. This body of evidence indicates that while more research is needed for NMES in QT-specific rehabilitation, its effectiveness in general ACLR rehabilitation is well-established.

In summary, while NMES has demonstrated significant benefits in general ACL rehabilitation, there remains a lack of high-quality research specifically investigating its use in QT autograft procedures. The current literature highlights the potential for NMES to enhance muscle strength, reduce atrophy, and improve functional outcomes, but inconsistencies in its application across studies underscore the need for more standardized protocols (Table 3). Future research should focus on determining the optimal intensity, timing, and duration of NMES in quad autograft ACL rehabilitation to maximize its effectiveness and provide stronger evidence for its use in clinical practice.

Phase	Exercise	Progression and Notes
Pre-Op	NMES during isometric exercises	Use 3 x 5-inch pads, ≥400 microseconds pulse width, 50–75 pulses per second.
Weeks 0–6	NMES during OKC exercises	Parameters: 2-second ramp-up, 10-second contraction, 50-second rest; perform 2–6 sessions weekly for 6–8 weeks.
Weeks 6+	NMES with advanced resistance exercises	Adjust intensity as needed for strength recovery; ensure proper patient comfort.

Table 3: Neuromuscylar electrical stimulation guidelines for acute phase rehabilitation of qudariceps tendon autograft. ROM = Range of Motion, BFR = Blood Flow Restriction, NMES = Neuromuscular Electrical Stimulation, OKC = Open Kinetic Chain, LOP = Limb Occlusion Pressure, 1RM = One-Repetition Maximum.

Conclusion

In conclusion, we recommend tailoring ACL rehabilitation to the autograft source, particularly when utilizing the QT autograft. The acute phase, defined as the first 6-8 weeks, is a critical window for quadriceps activation. The unique biomechanical properties of the remaining QT and the autograft allow for increased loading during this period.

OKC exercises should begin immediately, starting with isometric exercises between 90–45° and no-load, full-ROM knee extensions as early as graft site pain allows within the first week. As strength, ROM, and pain improve, progression should follow typical overload principles, while high-load, low-repetition strength work should be avoided until six months post-operatively.

To mitigate muscle atrophy, passive BFR application without exercise (100% LOP with a 5-minute occlusion and 3-minute reperfusion protocol) is recommended during the initial three weeks. Once patients can tolerate OKC exercises, BFR with exercise at 80% LOP using the 30-15-15-15 repetition scheme should be introduced, with gradual progression to 20–30% 1RM resistance.

Additionally, NMES should be initiated pre-operatively and continued post-operatively to enhance muscle activation. NMES should be dosed to at least 50% of maximum voluntary isometric contraction (MVIC) using 3 x 5-inch pads, with parameters of ≥400 microseconds pulse width and 50–75 pulses per second for pulsed current, or 1000 Hz "Australian" or 2000 Hz "Russian" alternating current bursts modulated at 50–75 bursts per second. Sessions should include a 2-second ramp-up, 10-second contraction, and 50 seconds of rest, performed 2-6 times per week for 6-8 weeks.

These recommendations emphasize the importance of structured rehabilitation strategies tailored to the QT graft (Table 4), underscoring the need for further research to refine and standardize these approaches. Remaining rehabilitation phases should follow current guidelines provided good quadriceps activation and recruitment. Further research is needed to refine and standardize these approaches, ensuring optimal recovery and functional outcomes for patients.

	Quadriceps tendon autograft open chain kinetic exercise recommendations	Current open chain kinetic exercise recommendations
Weeks 0-1	Quad sets SLR Variable degree knee extension isometrics (90°/60°/45°) effort as tolerated Full OKC knee extension unweighted range as tolerated NMES for all above exercises strongly encouraged Additionally, consider performing in hip neutral positions to target all layers of quad	No OKC exercise recommended before 4 weeks in any CPG
Weeks 2-3	Continue with quad sets, SLR, and variable degree isometrics Progress OKC knee extension as tolerated. Can begin adding ankle weights weight in 1-2lbs increments. Should not progress weight until previous exercise can be performed full range and pain free Continue use of NMES during exercise	No OKC exercise recommended before 4 weeks in any CPG
Weeks 4-5	Continue to progress weighted OKC knee extension through full ROM with good control Recommend 12 rep sets or higher Work in hip neutral as tolerated Continue use of NMES as needed	May initiate OKC exercise in limited range from 90-45 degrees at week 4 No OKC exercise recommended before 6 weeks per MOON protocol
Week 6+	Can begin use of weighted knee extension machine with pad at mid shin level When able to perform through full ROM, begin to move pad distally and increase weight as tolerated through full ROM	May initiate OKC at week 6 per MOON protocol

Table 4: Specific open chain kinetic exercise progression, updated progression versus current recommendations. ROM = Range of Motion, OKC = Open Kinetic Chain, NMES = Neuromuscular Electrical Stimulation, SLR = Straight Leg Raise, VAS = Visual Analog Scale, CKC = Closed Kinetic Chain.

1. Current recommendations are based on the clinical practice guideline systematic review from 2020 by Andrade et al. Referenced within this text are the published clinical practice guidelines widely available to PTs and ATs
2. We recommend avoiding graft site pain >2/10 VAS with all listed exercises
3. CKC recommendations can follow typical exercise progressions reported in CPGs

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