ENHANCING NEUROMUSCULAR FUNCTION POST ACL RECONSTRUCTION

INSIGHTS AND INTERVENTIONS

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INTRODUCTION

Following any knee injury or surgery, there is commonly a phase of reduced activity and disuse that leads to muscle atrophy[1], diminished strength, and anterior knee pain[2]. After an anterior cruciate ligament (ACL) injury, patients might experience a decrease of 20% to 33% in their quadriceps muscle volume from the moment of injury up to three weeks post-ACL reconstruction (ACLR)[2,3]. The decline in muscle mass and strength can be a source of pain, functional limitation, and decreased physical fitness[4]. These persistent muscle weaknesses after surgery can result in functional deficits lasting up to 3 years postoperatively[5]. Periods of reduced mobility before and after surgery, vascular ischemia[6], and inability to perform high load strength training preoperatively and in the early postoperative period contribute to these early losses[7].

An extensive amount of research after ACLR indicates that a significant proportion of patients fall short of meeting adequate levels of strength, function and performance as recommended at the time of return to sport (RTS)[8,9]. Approximately 35% of athletes fail to return to sport (RTS) at their preinjury level[10] and are at a high risk of reinjury in the 24 months after RTS[11]. The long term health and future injury risk of the operated knee might be reduced if they meet established discharge criteria[12] or achieve strength symmetry[13].

With the ultimate objective of regaining or even surpassing the patient's previous level of performance and protecting them from future injuries in mind, the rehabilitation team must guide the patient through an extensive recovery journey and adeptly devise interventions. These interventions are aimed at rectifying deficits in strength and functional performance by precisely targeting the underlying mechanisms that result in muscle atrophy and impaired neuromuscular activation.

STRENGTH DEFICITS

The exact mechanisms leading to quadriceps weakness remain unclear; however, neurological and morphological changes that have been observed are considered the primary factors contributing to the decline in knee extensors strength[14]. The following sections will outline some of these mechanisms and propose potential interventions aimed at enhancing neuromuscular function.

NEUROLOGICAL FACTORS

As a direct consequence of trauma to the knee, some patients develop substantial neuromuscular impairments of the quadriceps muscle, known as arthrogenic muscle inhibition (AMI)[15]. Joint swelling, inflammation, pain and structural damage that occur after knee injury or knee surgery are the major drivers of this process. They contribute to the disturbance of the sensory system and the modification of proprioceptive input from the knee joint, triggering reflex responses that result in decreased excitability of motor neurons supplying the quadriceps and hamstrings.

Furthermore, the immediate neural adaptations within the nervous system resulting from an ACL injury can lead reductions in muscle fiber conduction velocity and spontaneous fiber discharge which are indirect markers of denervated fibers in the muscle groups surrounding the knee[16]. This disruption in neural pathways can decrease the muscle's capability for contraction, making it challenging to activate the muscle during exercise and the subsequent development of weakness[17].

Identifying and minimizing AMI early in rehabilitation is vital to optimize strength development throughout the rehab process. Without addressing AMI with targeted interventions, patients may struggle to perform exercises effectively, leading to compensatory movement patterns and persistent strength deficits.

MUSCLE MORPHOLOGY

Morphological factors such as fiber type composition and muscle architecture influence the size and contractile capacity of the muscle[18]. In a study investigating which factors determine maximum isometric knee torque, Trezise et al[19] found muscle size (cross sectional area of the quadriceps) as well as fascicle length were the strongest predictors explaining approximately 50% and about 20% of the variability respectively.

It has been reported that patients who have undergone ACLR, demonstrate decreased quadriceps muscle volume and cross-sectional area[20]. There are observed selective reductions in type IIA (fast oxidative glycolytic) muscle fibers cross-sectional area and frequency[21]. While these changes can only partially explain the quadriceps weakness observed after ACLR, it is essential to emphasize these findings as it will enhance our comprehension of the issue.

It is important to highlight that the muscle atrophy seen following a traumatic joint injury like an ACL rupture, differs in its underlying causes from the muscle atrophy that results from disuse. In cases of traumatic joint injury, neurological changes appear to play a significant role in causing a rapid reduction in muscle mass[17]. Because the injury leads to a range of factors that contribute to muscle atrophy, traditional strength training approaches might not be effective if the underlying neurological changes are not addressed first. Instead, personalized interventions that are more targeted and adapted to the individual's morphological and neurological deficits are necessary.

TREATMENT MODALITIES AND EARLY PHASE INTERVENTIONS

In the Aspetar clinical practice guidelines on rehabilitation after ACLR[22] a range of modalities have been proposed to enhance strength outcomes and promote muscle activation. In the following section we cover the practical aspect of neuromuscular electrical stimulation (NMES), Surface Electromyography (EMG) biofeedback and blood flow restriction (BFR).

NEUROMUSCULAR ELECTRICAL STIMULATION

NMES is a therapeutic modality commonly used to address muscle disuse atrophy after ACLR. Interventions utilizing NMES 4 to 6 weeks after ACLR have been shown to aid in the recovery of quadriceps strength and functional performance, outperforming rehabilitation without NMES[22]. Furthermore, recent studies underscore the advantages of promptly initiating NMES after ACL injury and subsequent surgery, as it effectively mitigates skeletal muscle atrophy and contractile dysfunction[23]. However, it is noteworthy that other ACLR-related studies have reported contrasting results, failing to demonstrate any advantage in postoperative strength attributable to NMES interventions implemented within similar temporal parameters[24]. The use of NMES is encouraged, starting as early as the second day of ACLR, unless contraindicated[22,24].

According to the recently published *Aspetar Clinical Practice Guideline on Rehabilitation after ACLR*[22], it is recommended to use NMES together with active functional exercises, as it provides superior results in restoring quadriceps strength and force symmetry when compared to NMES alone. Moreover, the literature suggests that the use of NMES after ACLR can lead to a significant reduction in knee joint swelling during the early phase of rehabilitation and a moderate reduction in the intermediate and advanced phases[24]. Some examples of exercises that we use at Aspetar during the early phase are together with NMES are: isometric quadriceps at different angles of knee flexion, static quads contraction, straight leg raise, isometric open kinetic chain exercises in various degrees of knee extension, and isometric wall squat.

Figure 1: NMES early post-ACLR rehabilitation phase

Regarding volume, the literature suggests a frequency from 2-5 times per week to daily[24]. Considering that the use of NMES is safe even in the early stages of ACLR rehabilitation, at Aspetar we use it every session, preferably during warm-up, reaching the maximum tolerable intensity by the patient, aiming for a minimum of 100mA within 6 weeks after the surgery, for 20 minutes with the electrodes being placed proximal and distal to the targeted muscle (quadriceps for BPTB and QT grafts; Quadriceps and Hamstrings for HT graft).

The use of NMES may offer its most pronounced benefits during the early stages of recovery, gradually diminishing in effectiveness as patients regain strength and the ability for voluntary muscle activation improves[25]. A summary of Aspetar's NMES recommendations (frequency, dosage, intensity, electrode placement, muscle groups and goals) can be found in the Modalities Table (Table 1).

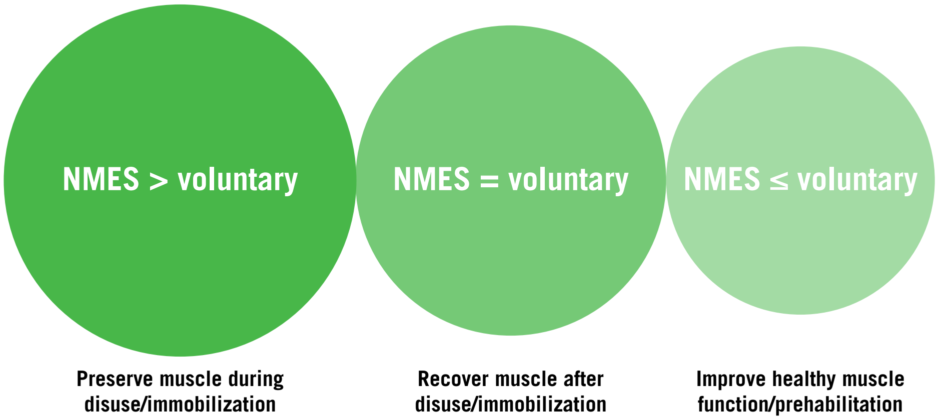

Figure 2: Main uses and effectiveness of NMES (re)training programs[26].

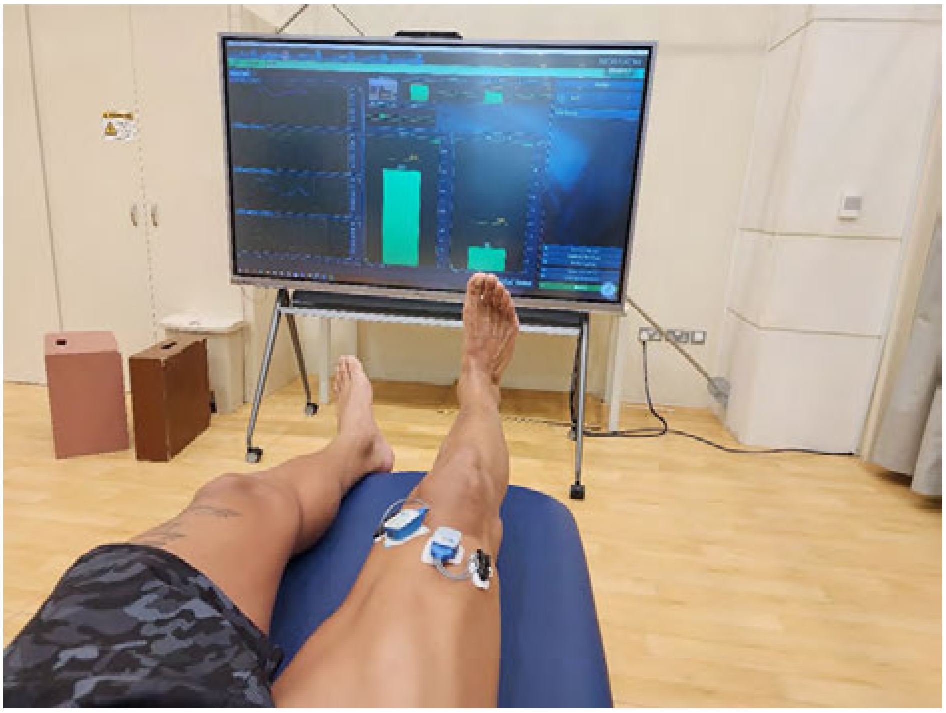

Figure 3: Using EMG visual feedback to focus on enhancing vastus medialis activation and minimizing hamstring activity during isometric knee extension holds.

EMG BIOFEEDBACK

Surface electromyography serves as a valuable modality utilized by both clinicians and researchers to investigate human motion. Its primary purpose is to gain insights into the intricate process through which our nervous system manages our movements by orchestrating the complex patterns of muscle activation and deactivation. With modern technology, these muscle action patterns can be turned into visual or auditory signals that can be observed by the clinicians and be used as feedback by their patients.

It has been shown that patients with ACLR display an altered muscle activity pattern during jumping and cutting/change-of-direction tasks[27,28], even though they are capable to return to sport[29]. This is also seen in functional tasks like running where ACLR patients show neuromuscular alterations during different phases of running with a reduced medial hamstring activity in stance phase[30]. Altered EMG muscle signals have been found in relation to the contralateral limb and between first time ACLR and secondary ACLR[31]. These changes might have implications for the return to sport as the patient develops a more long-term protective mechanism to minimize knee loads[32].

Within the scope of ACL rehabilitation, EMG biofeedback interventions have three primary objectives: addressing muscle hypoactivity, muscle hyperactivity, and employing a combined approach focused on coordination training. Improved motor learning is an additional benefit achieved by providing external visual feedback of effort as the athlete works to determine the most effective strategy. As an illustration, one method to enhance quadriceps engagement involves instructing the patient to increase EMG amplitude to reach a specified threshold on the display, while hamstring relaxation is encouraged by maintaining EMG activity below a designated target marker.

While the evidence supporting the effectiveness of EMG biofeedback in improving active knee extension and quadriceps strength[33] is currently limited, it does show promise. Additional research is necessary to establish precise clinical practice recommendations. However, it is important to note that EMG biofeedback is a safe, low cost and non-invasive intervention. It can be seamlessly integrated into standard rehabilitation protocols during regular activation and strengthening exercises or motor learning sessions.

We recommend the implementation of EMG biofeedback in each session during the early phase of ACLR rehabilitation. Emphasis should be placed on activating the inhibited muscles, while addressing muscle hyperactivity. Additionally, real-time biofeedback can be utilized during functional tasks such as single-leg stance/squat, with a focus on targeting knee extensors or flexors. The goal of the intervention is for the patient to increase their maximum EMG amplitude during each session.

BLOOD FLOW RESTRICTION TRAINING

BFR training has been shown to have beneficial effects addressing muscle atrophy after ACLR[34]. The primary use case is to improve muscle growth, muscle strength, and improve overall clinical outcomes[35]. During BFR, a cuff is placed proximally on the leg of the affected side. The cuff is inflated to a set pressure which will restrict the arterial inflow (the oxygenated blood flowing to the muscle) and minimize the venous return (the deoxygenated blood flowing from the muscle)[36], fostering an anaerobic setting. This environment facilitates muscle growth through enhanced cell signaling, increased protein creation, and stimulated myogenic proliferation[37].

BFR combined with low load resistance training (20%–30% 1RM) has shown better results in increasing muscle volume and strength after ACLR, when compared to isolated low load resistance training and similar to high load resistance training[2,38]. In the early phase after ACLR, where the patient can be load-compromised by having restrictions with limited range of motion, weight bearing, and/or swelling and pain.", traditional heavy strength training may not be feasible[2]. BFR training can offer an effective alternative solution to achieve some of the same responses as heavier progressive strength training while minimizing the mechanical load of the knee joint[4,39,40].

In the existing literature, there is considerable variability concerning the frequency, volume, cuff width and limb occlusion pressure (LOP) of BFR training[41]. An extensive review of methodologies[2], recommended BFR with a frequency of 2-3 session per week when interventions lasting longer than three weeks or 1-2 session per day when lasting less than three weeks[3,36]. When applying BFR, a submaximal percentage (40%-80%) of total LOP is desired. This method allows for appropriate progression of the pressure, similar to progressive loading resistance training[42]. A common LOP used as starting point is usually above 200mmhg, and from this point the pressure is gradually reduced to achieve a 40-80% occlusion. BFR is a method to facilitate getting the muscle to fatigue or "chasing the pump", which can effectively be achieved at several percentage levels of LOP. Personalized LOP's have been suggested to be more efficient in achieving optimal clinical outcomes in a safer manner[43].

Figure 4: BFR during knee extensors strengthening exercises.

Our recommendations are to start with BFR as soon as possible after ACLR, with a minimum of 2 to 3 times per week for a block of 8 to 14 weeks. Our protocol for isolated muscles consists of 4 sets of 30-15-15-15 repetitions (20-30% of 1RM) aiming for a LOP of 80%, if possible[2,36,44-47]. Another practical way to apply BFR is to use it during warm-up/cardio exercises such as elliptical trainer, walking or cycling. In cycling, we encourage our patient to keep a pace of 90-100 RPM. Furthermore, BFR could also be used to target desired muscle groups or as a session "finisher" to stress muscle fibers that may have not been sufficiently stressed during the training session.

When applying BFR, some precautions must be taken into consideration as most studies have stringent inclusion/exclusion criteria, leaving limited data on individuals with comorbidities frequently seen in rehabilitation clinics[32]. Delayed onset muscle soreness (DOMS) is one of the most reported symptoms after BFR[48], and the one we are looking for in our targeted muscles. Numbness is another commonly reported symptom after BFR, probably due to inappropriately high tourniquet pressures, thus resulting in peripheral nerve compression[49]. Therefore, appropriate selection and application of the cuff (size, site, pressure) is essential for preventing peripheral nerve irritation[34]. A 'traffic light' approach is suggested to screen the patient for eligibility for BFR (Figure 4).

Figure 4: "Traffic light" approach to screen the patient.

CLINICAL CASE STUDIES

Case 1

A 25-year-old soccer player presented with anterior knee pain and severe quadriceps weakness three-months post ACLR and patella repair. The patient was unable to follow the regular rehabilitation routine because exercises aimed at strengthening the muscles were causing pain, leading to a fear of movement.

During isometric knee extension strength testing, it was found that there was a 50% asymmetry in the strength of the knee extensor muscles. Additionally, the patient exhibited a compensatory movement pattern during a double-leg squat, exhibiting 30% higher ground reaction force on the non-injured side. He also had difficulty squatting beyond 60-degrees knee flexion during single leg squat and showed 40% higher impact force during a step-down test indicating lack of eccentric control during the task.

For the initial assessment, EMG sensors were applied over vastus medialis (VMO), vastus lateralis (VL), and rectus femoris (RF) muscles and asked the patient to perform regular exercises such as straight leg raises, double leg squat, isometric contractions at various knee flexion angles. A significantly reduced activation of VMO muscle was observed during the test.

Our team utilized EMG feedback cues to enhance the activity of the VMO and improve the ratio of VMO to VL activation. Due to the motor learning benefits of EMG biofeedback, within the initial session observable improvements were evident with the patient succeeded in activating his VMO during exercises that had previously no/minimal activation during testing.

Following the initial assessment, we integrated EMG biofeedback into the patient's rehabilitation sessions, with a primary focus on enhancing quadriceps activation, particularly emphasizing the VMO. In addition to EMG, the patient started every session with NMES to facilitate quadriceps activation followed by 10 minutes bicycle using BFR. During the session, leg extension with BFR protocol consisting of 30-15-15-15 reps was added. Over a two-week period consisting of six sessions, the patient experienced a notable reduction in pain and was able to execute open chain quadriceps strengthening and compound exercises without symptoms facilitating the opportunity to increase the strength training stimulus and adaptation. He also reported a much-improved sensation of quadriceps activity and muscular exertion with observable normalized activation patterns compared to the contralateral limb. These sessions seemed to instill in the patient a sense of empowerment and confidence, eventually enabling him to achieve the strength and functional criteria to progress to the advanced phase of his rehabilitation program.

Case 2

A 28-year-old professional football player, 3 months post-ACLR (hamstring graft), experiencing significant difficulty activating medial hamstrings during his rehabilitation. The athlete faced a challenge, as his rehabilitation was hampered by persistent pain and weakness in the medial hamstrings, hindering the execution of conventional strengthening exercises and functional training. He displayed an apparent avoidance behavior during hamstring strength testing, exhibiting a 45% strength deficit compared to the uninjured limb.

Recognizing the need for a more comprehensive evaluation and intervention, the athlete was brought into our specialized Assessment and Movement Analysis Lab (AMAL). Here, we employed the advanced EMG system, which provided feedback on co-contraction and activation patterns of lower limb muscles. This evaluation revealed significantly reduced EMG activity on the medial hamstrings and helped identifying patterns and exercises that specifically enhance medial hamstring activation, decrease lateral hamstring hyperactivity, and promote the patient's motor-control learning process. Remarkably, after a single session, the athlete demonstrated the ability to retain and apply the enhanced activation patterns. Transitioning back to the clinic, his rehabilitation program involved a portable 2-channel EMG device used daily, incorporating engaging exercises and "games" to promote muscle activation.

In tandem with the EMG advancements, we integrated NMES and BFR interventions following Aspetar protocols. The NMES, offered direct stimulation to the hamstring muscles, promoting increased muscle activation together with active exercises.

BFR, executed according to Aspetar's protocol, was introduced during low-intensity resistance and isometric exercises. This integration induced muscle hypertrophy and strength gains at reduced exercise

Table 1

Neuromuscular Electrical Stimulation	*Frequency: In every rehab session as early as possible after ACL (safe from the 2nd day) 2-5 times per week to daily use.* *Dose: 20 minutes.* *Intensity: Max tolerable aiming for 100mA (200 energy) within 6 weeks after ACLR.* *Electrode placement: Proximal and distal to the muscle.* *Muscle groups: Quadriceps for Bone-Patella Tendon- Bone (BPTB) and Quadriceps Tendon (QT) grafts* *Quadriceps and Hamstrings for Hamstring (HT) graft.* *Goals: Prevent muscle atrophy, facilitation of voluntary muscle contraction, improve range of motion, swelling reduction.*
EMG biofeedback	*Frequency: In every rehab session at the initial phase of the rehabilitation (6 weeks+ as required).* *Muscle groups: Knee extensors and/or flexors.* *Goals: Increase EMG amplitude on targeted muscles, decrease EMG amplitude of hyperactive muscles, enhance motor control.*
Blood flow restriction training	*Frequency: In every rehab session as early as possible after ACLR using the traffic light approach. Minimum 2-3 sessions per week for block of 8 to 14 weeks.* *Dose: Commonly used protocols 4 sets of 30-15-15-15 repetitions aiming for 20-30% of 1RM. In addition, BFR for warm up or session finisher.* *Intensity: 40%-80% of total limb occlusion pressure.* *Muscle groups: Quadriceps for BPTB and QT grafts Quadriceps and Hamstrings for HT graft.* *Goals: promote hypertrophy with low mechanical load.*

Table 1: Modalities table: Aspetar recommendations to target AMI.

intensities, as evidenced by the enhanced muscle pump and metabolic stress.

Over a meticulously planned 6-week block, the athlete made significant strides in his rehabilitation. The combination of advanced EMG technology, and the NMES and BFR protocols, helped the patient to increase his medial hamstring activity and reduce his strength deficit to 20%. The athlete reported a significant reduction in pain and a renewed confidence in his hamstring's capacity - a critical advancement for the dynamic and explosive movements integral to football.

This case exemplifies the intricate and multidimensional approach required for a holistic post-ACLR rehabilitation. The focused attention beyond the customary emphasis on the quadriceps, unveils a comprehensive pathway for athletes and clinicians navigating the complex landscape of post-ACLR rehabilitation.

SUMMARY

The utilization of modalities such as NMES, EMG and BFR presents promising avenues for enhancing knee muscle function subsequent to ACLR. During the initial stages of rehabilitation, NMES can minimize muscle atrophy and contractile dysfunction. EMG provides valuable biofeedback enabling patients to acquire essential muscle control skills and enhance quadriceps engagement. BFR offers a solution for promoting muscle growth, particularly in scenarios where compromised knee load-bearing due to restricted range of motion or weight-bearing limitations, or hindered muscle activation caused by AMI is a concern. By embracing these modalities, muscle function (in particular the quadriceps and hamstrings) can be optimized in the early stages of rehabilitation setting a solid platform for progression to more traditional strength training strategies in the later phases optimizing knee function and successful recovery following ACLR.

References
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