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Effectiveness of Neuromuscular Electrical Stimulation on Quadriceps Strength After Anterior Cruciate Ligament Reconstruction

Matthew Larsen
Bethel University

EFFECTIVENESS OF NEUROMUSCULAR ELECTRICAL STIMULATION ON QUADRICEPS STRENGTH AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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MATTHEW LARSEN

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MATTHEW LARSEN

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Approvals:

Project Advisor: Janet Johnson, DPT, LAT, ATC

Project Advisor Signature:

Dean of Business, Leadership, Health, and Social Sciences: Chad Osgood, Ed.D., LAT, ATC

Dean of Business, Leadership, Health, and Social Sciences Signature:

Athletic Training Program Director: Chad Osgood, Ed.D., LAT, ATC

Athletic Training Program Director Signature:

Abstract

Background/Purpose: With anterior cruciate ligament (ACL) injuries becoming increasingly common in individuals of all ages, it's important to understand how to best treat the patient after surgery. The purpose of this study is to critically review and evaluate the effectiveness of Neuromuscular Electrical Stimulation (NMES) on quadriceps strength after anterior cruciate ligament reconstruction (ACLr).

Problem: Many articles look to evaluate how effective the use of NMES is in increasing quadriceps strength after ACLr, but the current literature does not fully agree on the extent of effectiveness. Therefore, it is necessary to conduct a critical review of the literature to see what the general consensus is regarding NMES use. The question being asked is as follows: Does the addition of NMES, when utilized post-ACLr, enhance quadriceps strength?

Methods: 20 articles were found using PubMed, Google Scholar, and CLICsearch. Of those 20, 17 were randomized controlled trials, two were systematic reviews, and one was a case series. The year of publication for the studies used in this critical review range from 1987 to 2019. Studies that used NMES to increase quad strength after ACLr or total knee arthroplasty (TKA) were used to draw a conclusion.

Results: Of the 20 articles used, 16 found that NMES was effective in regaining quadriceps strength after ACLr, while the remaining four concluded that NMES, while it would not have a negative effect on the patient, was not necessary for strengthening after ACLr. The studies that found no significant difference between groups were of lower quality compared to the studies that found a significant difference.

Conclusion: This critical review supports the use of NMES after ACLr to increase quadriceps strength with 15 studies advocating for the use and 5 against the use of NMES. Additional research is necessary to evaluate the long term strength gains that can come from NMES use, and how it can affect return to play in athletes.

Implications for Practice: With the goal of rehabilitation being to get the patient back to full activity, regaining function should be the main long term focus. After ACLr, patients will experience weakness and asymmetry in the involved leg. Using NMES to regain quad strength can assist in getting the involved leg back in accordance with the uninvolved leg, making the patient more functional and returning them to pre-morbid activity levels sooner.

Keywords: Anterior Cruciate Ligament, ACL, Anterior Cruciate Ligament Reconstruction, ACLr, Neuromuscular Electrical Stimulation, NMES, Quadriceps, Strength

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Chapter 1 - Introduction

Purpose of this Study

The purpose of this study is to perform a literature review evaluating the effectiveness of neuromuscular electrical stimulation (NMES) on quadriceps strength after anterior cruciate ligament replacement (ACLr). The anterior cruciate ligament (ACL) is one of the most commonly injured ligaments in the knee and one of the most common injuries among the athletic population (Hauger et al., 2017). After ACLr, it is common for the quadriceps to be inhibited due to effusion in the knee joint (Nyland et al., 2016). Because of this inhibition, the quadriceps are unable to optimally perform knee extension (Nyland et al., 2016).

NMES is the use of electrical currents to elicit a muscle contraction via stimulation of the motor unit. Currently, NMES is used for muscle reeducation, strengthening a muscle contraction, decreasing muscle spasm and edema, and preventing disuse atrophy (Knight & Draper, 2013). Because NMES can facilitate muscle reeducation, it is thought that NMES may be able to help increase quadriceps strength and keep the musculature from atrophying after surgery thereby maintaining quadriceps function during the period of immobilization (Kim, Croy, Hertel, & Saliba, 2010). While there are plenty of reviews that look at ACL rehabilitation, few review how NMES can be effectively utilized in ACLr recovery. This critical review of the literature will assist in answering the following clinical question. Does the addition of NMES, when utilized post-ACLr, enhance quadriceps strength?

Knee Anatomy and ACLr

The ACL is attached to the anteromedial intercondylar eminence of the tibia inferiorly and inserts on the medial wall of the lateral femoral condyle superiorly (Starkey & Brown, 2015). The function of the ACL is to prevent excessive anterior tibial translation, internal and external rotation of the tibia on the femur, and hyperextension of the tibiofemoral joint (Starkey & Brown, 2015). The mechanism of injury (MOI) for an ACL tear or sprain is typically noncontact. The injury will usually result from a pivot, cut, or turn while running. Starkey and Brown (2015) say that apart from torsional stresses, an ACL injury can also occur from a force causing anterior displacement of the tibia or posterior forces on the femur. Individuals who have an ACL tear may feel or hear a popping sensation upon injury (Starkey & Brown, 2015). After an ACL tear, both hamstring and quadriceps strength will decrease significantly due to pain, edema, and muscle guarding, but quadriceps strength may decrease by up to three times more than hamstring strength (Kim et al., 2016). This weakness can last up to 7 years in extreme cases (Thomas et al., 2013).

ACL surgery consists of replacing the ACL utilizing three different methods: allograft, bone-patellar tendon-bone graft (BPTD), a hamstring graft using the semitendinosus, or the gracilis (van Grinsven et al., 2010). Post ACL tear, there are three generally accepted rehabilitation options: accelerated post-op, conservative post-op, or nonsurgical (Houglum, 2016). Factors that may determine whether or not a patient undergoes surgery include age, activity level, desire to return to full participation, and knee instability (Houglum, 2016). Houglum (2016) says the majority of patients who choose to undergo surgery include younger individuals, those who would like to return to high level activity, and those with severe instability. Following surgery, the accelerated post-op plan requires 5-6 months for the individual to return to full participation; the conservative post-op plan takes 6-9 months for return to play (Houglum, 2016). While both of those plans are viable options after an ACLr, the choice of plan utilized is based on tissue healing, regaining strength, type of surgery, type of graft and fixation used, other injuries that may have occurred with the ACL injury, and psychological readiness.

Rehabilitation After ACLr

Van Grinsven et al. (2010) performed a systematic review which led to designing an optimal accelerated ACL rehabilitation program along with the goals for each stage of rehabilitation. They identified that the most important goals after ACLr surgery are to reduce pain, swelling, inflammation, and regain active range of motion (AROM), passive range of motion (PROM), strength, and neuromuscular control. The researchers divided the rehabilitation plan into 4 phases over 22 weeks. Phase 1 begins 1 week post-surgery and focuses on controlling pain and inflammation, obtaining ROM of 0º-90º, regaining muscle control in open and closed kinetic chains, and improving gait pattern. Phase 2 is weeks 2-9 and focuses on controlling pain or swelling after sessions, working toward full ROM, walking without crutches and improving the gait pattern, isometric and isotonic strengthening specifically for the quadriceps and hamstrings, and starting neuromuscular training. Phase 3 is weeks 9-16 and focuses on obtaining and maintaining full ROM, optimizing muscle strength and endurance, and neuromuscular training focusing on dynamic stability and plyometrics. Phase 4 is weeks 16-22 and focuses on maximizing muscle strength, endurance, and neuromuscular control emphasizing jumping, agility training, and tasks specific to the individual's sport. Using this rehabilitation plan outline, we can look at the goals of each phase to identify where NMES would be most effective (usually in the early stages of rehabilitation to prevent muscle atrophy) in producing the desired effects of this modality.

In a non-accelerated or conservative rehabilitation program, the goals remain the same, but are introduced at different phases of the program (Houglum, 2016). Immediately post-op through week 3 (Inflammation stage), the goals are to relieve pain and spasm, reduce edema and ecchymosis, protect the repair, and prevent deconditioning of unaffected body segments (Houglum, 2016). Week 3 through week 9 (early proliferation stage), the goals are to have no pain, edema, or spasm, full knee ROM (weeks 6-8), normal gait pattern, and increased strength of deficient muscles and muscle groups (Houglum, 2016). Week 9 through 18 (late proliferation stage) aims to have the patient maintain normal ROM, normal running gait, and achieve 85%-90% normal strength, which will be compared to the unaffected knee (Houglum, 2016). Week 20 though 36 (remodeling stage) aims to have normal strength of all muscles, and return to normal performance. (Houglum, 2016). Again, knowing the rehabilitation plans and associated goals, allows the physical therapist or athletic trainer working with the injured individual to know the appropriate timing and parameters of using NMES.

Neuromuscular Electrical Stimulation (NMES)

NMES involves placing electrodes on the skin above the muscle where the contraction is desired. The electrodes are then connected to the NMES device. Electrode placement requires having one electrode on the muscle belly and the other at the distal or proximal end of the muscle (Knight & Draper, 2013). Using a bipolar electrode placement is effective when the goal is for a more generalized muscle contraction (Knight & Draper, 2013). This can be used in an attempt to isolate a muscle group. However, for the quadriceps, a more common electrode placement involves using four electrodes, known as quadripolar electrode placement. Two electrodes are placed on the medial and lateral side of the superior thigh and two are placed on the medial and lateral side of the inferior thigh a couple inches above the knee (Starkey, 2013). While quadripolar electrode placement is usually used when targeting agonist and antagonist muscle groups, it can also be used for larger muscle groups like the quadriceps (Starkey, 2013). NMES depolarizes the alpha motor neurons in the muscle causing involuntary contractions (Knight & Draper, 2013). The muscle contraction brought on by NMES initiates neuromuscular re-education, assisting the patient in feeling and visualizing a muscle contraction. Once they are able to contract independently, the patient is instructed to isometrically contract the muscle(s) each time the muscle is stimulated by the NMES unit in order to improve strength (Knight & Draper, 2013). The following parameters are recommended for muscle reeducation using NMES: pulse duration of 20-300µsec (Starkey, 2013), 50-70pps or 20-50hz (Doucet, Lam & Griffin, 2012), bipolar or quadripolar electrode placement, 10:50 duty cycle to 10:30 then 10:10 as rehabilitation progresses, 2-3s on/off ramp, 20 minutes daily (Knight & Draper, 2013). As quadriceps control improves, the individual can progress through the ROM by placing a foam roller or bolster under the knee and performing active knee extension (Knight & Draper, 2013).

Significance to Athletic Training and Rehabilitation

After ACLr, there may be ROM deficits specifically with achieving terminal knee extension (TKE). This may be due to extensor lag, the condition in which there is full passive extension, but the patient is unable to go into active TKE (Houglum, 2016). This can be because of pain, swelling, stiffness, or weakness, all things that are present after ACLr. Along with ROM deficits, there are strength deficits. After ACLr, quadriceps strength may be limited for up to two years (Houglum, 2016). Because of quadriceps asymmetry and deficits, individuals who underwent ACLr may have altered movement patterns that can affect how they perform in activities of daily living (ADLs) and athletic events leading to an increased risk of reinjury (Lepley, Wojtys, & Palmieri-Smith, 2015). According to Schmitt, Paterno, & Hewett (2010), active individuals with a greater quadriceps femoris (QF) deficit after ACLr were shown to have decreased function and performance ability while those with a smaller QF deficit had similar performance levels compared to uninjured, active individuals. A study analyzing the trends between professional soccer players and their return to sport rates after ACLr shows that while 85.8% of professional soccer players were still playing soccer after surgery, only 65% of them were playing at the same level (Waldén, Hägglund, Magnusson, & Ekstrand, 2016). Age differences may affect return to play, making it important to recognize more effective treatments for quadriceps strengthening that may be achieved using NMES, and thus decrease the time to return to play.

Need for Review

Van Grinsven et al. (2010) and Houglum (2016) identified ACLr rehabilitation programs and protocols, but they do not mention the use of NMES as a tool for muscle reeducation and muscle strengthening. Because of this, a review of the current literature is necessary to see how the existing rehabilitation programs align, and how the use of NMES to increase quadriceps strength after ACLr could improve overall recovery.

Chapter 2 - Methods

Introduction

This chapter will describe the methods that were used to find and critically review the literature regarding the use and effectiveness of NMES after ACLr to reeducate the quadriceps and increase knee extensor strength. Search strategies, inclusion and exclusion criteria, the number of studies selected for review, and the criteria used for evaluating the research studies will be included.

Description of Search Strategies

The studies used in this paper evaluated the effectiveness of electrical stimulation, specifically NMES, for increasing quadriceps strength after ACLr surgery. A search was conducted on various databases including PubMed, Google Scholar, Center for Leading Innovation and Collaboration (CLICsearch), BioMedCentral, and EBSCOhost. The years of studies used range from 1987 to 2020. The search keywords that were used to identify potential research studies included: electrical stimulation or e-stim, neuromuscular electrical stimulation or NMES, anterior cruciate ligament or ACL, anterior cruciate ligament reconstruction or ACLr, and quadriceps strength, or quad strength.

Inclusion and Exclusion Criteria

Inclusion criteria for this study included studies that evaluated quadricep strength after anterior cruciate ligament reconstruction or studies that compared the effectiveness of electrical stimulation compared to other modalities in increasing quadriceps strength after ACLr. Studies were only included if there was full text available. Articles with only abstracts available were excluded from the study. The studies were randomized controlled trials (RCT), parallel longitudinal studies, prospective studies, systematic reviews, or case series. Systematic reviews were not ideal for this review, but they were used if they included studies that were not full text accessible online. Studies were excluded if they evaluated ACL deficient knees or if they evaluated the effectiveness of percutaneous electrical stimulation. While percutaneous e-stim may be an effective way to stimulate the quadriceps directly by sticking a needle into the muscle, percutaneous electrical stimulation is not typically done in an athletic training setting and was therefore excluded. Articles that did not use electrical stimulation after ACLr were not ideal, but were included to add more support to the clinical question. Other knee surgeries like total knee arthroplasty (TKA) were included as long as the study assessed the effectiveness of NMES on quadriceps strength during rehabilitation. Lastly, articles that looked at the effectiveness of electrical stimulation in rats or other animals were excluded.

Summary of Studies Selected

Using PubMed, 54 articles were found. After narrowing the search to only articles that were full text available, 13 articles remained. Of those 13 articles, seven were on the topic of ACL reconstructive surgery that used electrical stimulation in rehabilitation for quadriceps strengthening. 12 other articles were found using Google Scholar or CLICsearch through the Bethel University (St. Paul, MN) library. In total, 20 articles were used for this literature review. Of those 20 articles, 17 were RCTs, two were systematic reviews and one was a case series.

Systematic reviews were included in this study as they provided additional supportive information.

Evaluation Criteria

For the evaluation of the research studies, critical appraisal tools were used to evaluate the quality and level of each study. The tool used was based on which type of study design was used. For the systematic reviews, four questions were asked about the article to determine its quality (Raab & Craig, 2016, p. 81). These questions were: 1) Is the clinical question focused? 2) Was the literature search thorough and exhaustive? 3) Are the included studies of high quality and valid? 4) Is the selection of the included studies reproducible? Also used for the systematic reviews was the CASP systematic review checklist. The PEDro scale was used for RCTs and parallel longitudinal studies. Studies with a score of 9-10 were considered excellent quality, 6-8 were good, 4-5 were fair, and anything below 4 were considered poor quality (Hariohm, Prakash, Saravankumar, 2015). Throughout this study, if studies were found to be of excellent or good quality, they were categorized as a study of high quality. If studies were found to be of fair or poor, they were categorized as a study of low quality. This was strictly for the sake of simplicity. Along with using the PEDro scale, articles were also evaluated based on their testing protocol and age. Articles that were considered low quality were studies that had a lower amount of participants, did not use a control group, were older than 15 years, used NMES parameters that had low intensities, or used participants that were immobilized in a full cast that didn't allow for any movement. The high quality articles will help determine the effectiveness of NMES on quadriceps strength after ACLr.

Summary

This chapter discussed the description of the search strategies, inclusion and exclusion criteria for the studies, the amount and types of studies used, and how each study was evaluated using a critical appraisal tool. The next chapter will critically evaluate the studies as well as discuss the description and results of the studies to show if NMES is effective in strengthening the quadriceps after anterior cruciate ligament reconstruction.

Chapter 3 - Literature Review and Analysis

Synthesis of Matrix

A matrix format was used to evaluate the research regarding the effectiveness of NMES on quadriceps strength after ACLr. In total, there are 20 articles included in the matrix. Of those 20, 17 are randomized controlled trials, two are systematic reviews, and one is a case series. Systematic reviews were used if they reviewed studies that were not free, full text accessible online.

The PEDro Scale was used to critically appraise the randomized controlled/clinical trials. Four questions were used to critically appraise the systematic reviews (Raab & Craig, 2016, p.81). They are as follows: is the clinical question focused? Was the literature search thorough and exhaustive? Are the included studies of high quality and validity? And is the selection of the included studies reproducible? While these questions were used to evaluate the systematic reviews, age was also taken into account. In general, if the study was 15 years or older, it would be considered lower quality depending on how it scored on the appraisal checklist. The three-minute checklist (Chan & Bhandari, 2011) was used to critically appraise the case series.

The matrix method used was an evidence synthesis matrix that included the APA citation, purpose of the study, sample, study design, measurements used, results/conclusions of the study, recommendations going forward, and the level and quality of the evidence. The matrices can be found in the Appendix.

Synthesis of Major Findings

The following section will provide a brief synopsis of the studies utilized to evaluate the use of NMES on quadriceps strength after ACLr. The studies are divided according to the quality of the study. The level of quality is based on how many participants were included in the study, the year the study was conducted or published, whether or not they included a control group, and which interventions NMES was compared against. Sorting these studies in this manner demonstrates how many studies support or do not support the use of NMES and the level of quality of the supportive or non-supportive studies.

Studies of High Quality that Support the Use of NMES

Feil, Newell, and Minogue (2011) conducted a randomized controlled trial comparing the effectiveness of standard NMES using electrodes versus Kneehab, a wearable NMES unit, in regaining quadriceps strength, improving performance measures, and decreasing recovery time after ACLr. It was expected that the Kneehab unit would lead to greater compliance due to its ease of use, thereby facilitating increased strength gains. Threegroups were used to test the effectiveness of NMES on quadriceps strength after ACLr: KH (Kneehab group) (n=33 at completion of study), PS (Polystim/wired stimulation group) (n=29 at completion of study), and CO (control group) (n=34 at completion of study). The two groups that received NMES by either route (KH or PS) were instructed to isometrically contract their quadriceps during every stimulation. The control group was similarly instructed but did not have electrical stimulation. The NMES groups completed treatment for 20 minutes per session, 3 sessions per day, 5 days per week for 12 weeks. Feil et al. (2011) measured quadriceps strength, a single leg hop for distance, and a timed shuttle run (6.3m x 4). Tests were completed at 6, 12, and 24 weeks post-op. Feil et al. (2011) found the greatest compliance to treatment came from the control group, followed by the Kneehab group, and then the polystim group. In all tests, the KH group showed the greatest increase in strength,distance for single leg jumps, and decrease in shuttle run times, with the control group and PS group being close in scores, which may have been due to participant compliance with the PS group. Feil et al. (2011) concluded that although all groups improved in the 24 week testing period in strength and performance measures; improvements slowed after the 12th week. Of the three groups, the KH group had the greatest compliance of all measured outcomes (Feil et al., 2011). While it is not always financially feasible for clinics or schools to have Kneehab units, this study shows that NMES is still effective in the earlier stages of rehabilitation after ACLr. On the PEDro scale, this article scores 8/11.

Fitzgerald, Piva, and Irrgang (2003) used a modified NMES protocol in order to help patients who had a bone-patellar tendon-bone autograft (BPTB) after finding that electrically stimulated contractions at high flexion angles caused pain at the donor site. Because of this finding, Fitzgerald et al. (2003) decided to modify their approach and apply NMES while the knee was in full extension to keep the donor site from experiencing pain during treatment. Amplitude was applied at the patients' maximal tolerated level. Using this modified approach, Fitgerald et al. (2003) wanted to test the effectiveness on improving quadriceps strength and physical function after ACLr. They used 43 total participants who received NMES treatment (n=21) or no NMES (n=22); both groups received a standard post-op ACLr treatment plan. Treatment for both groups occurred twice per week. Testing was completed at week 12 and 16 where patients performed a maximal quadriceps contraction against a dynamometer 3 times. The highest of the 3 attempts was taken as the participants' score. The Knee Outcome Survey - Activities of Daily Living Survey (ADLS) was also taken to assess functional activities throughout treatment. At 12 weeks, the NMES group achieved greater quadriceps strength compared to the control group. The results were statistically significant. At 16 weeks, the

NMES group's mean scores appeared higher than the comparison group, but the difference was not statistically significant. ADLS scores at 12 and 16 weeks were statistically significant with the NMES group showing greater scores than the comparison group. Fitzgerald et al. (2003) concluded that using this modified NMES protocol can be effective in strengthening the quadriceps and increasing functional activity scores after ACLr for clinics that don't have access to dynamometers or for patients who don't tolerate NMES with isometric resistance well while in knee flexion. This article scores 8/11 on the PEDro scale.

Hasegawa et al. (2011) conducted a RCT to assess the effectiveness of electrical stimulation (EMS) on muscle atrophy prevention in the early stages of rehabilitation after ACLr. In this study, 20 patients were split into a control group that used a standard post-op ACL rehabilitation plan (n=10) and an EMS group (n=10). The EMS group used EMS as an adjunct to the standard rehabilitation plan. The EMS unit provided was a handheld device that was designed to use co-contractions in the lower extremity to keep the joint from moving. A parameter of 20hz, 250 pulse width, and 5 seconds of stimulation and 2 seconds of rest were used (Hasegawa et al., 2011). They also used an exponential climbing pulse to get deeper into the muscle. Muscle thickness of the rectus femoris (RF), vastus lateralis (VL), vastus intermedius (VI), and calf muscles were measured pre-op and 4 weeks and 3 months post-op. Also measured was the isometric knee extension strength at the same time as the muscle thickness and lower extremity function using the Lysholm Score that was taken at pre-op and 6 months post-op. Hasegawa et al. (2011) found that EMS helped prevent atrophy in the four muscles they tested. Using EMS also resulted in hypertrophy of the VL and calf muscles (Hasegawa et al., 2011). Lysholm scores showed no significant differences between groups. At

3 months post-op, the EMS group was stronger than the control group. It is believed that this is because the control group experienced more atrophy than the EMS group giving the EMS group a head start of sorts (Hasegawa et al., 2011). In conclusion, Hasegawa et al. (2011) found that 20hz EMS was effective in preventing atrophy and weakness and should be used in treating post-op ACLr patients. This article scores 8/11 on the PEDro scale.

Hauger et al. (2017) conducted a systematic review to determine if NMES with physical therapy (PT) was more effective in improving quadriceps strength after ACLr compared to standard PT. In this study, 11 randomized controlled trials were reviewed. Studies that were included used NMES as an adjunct to PT, had a control group that didn't use NMES as a modality, participants had ACL surgeries, participants were 13 years of age or older, the primary outcome measures were isokinetic or isometric torque output or self-reported performance measures. The articles reviewed scored in the range of 3/10-7/10 on the PEDro Scale. Hauger et al. (2017) concluded that quadriceps strength was significantly increased following the use of NMES and PT as compared to only using standard PT. They also found that self-reported physical function had improved, but the improvement only lasted for about 6 weeks. After the 6 week follow-up, self-reported physical function was neither affected nor influenced by NMES use. While the research could have been more thorough and exhaustive, Hauger et al. (2017) met the rest of the criteria and is still a recently published article making it high quality.

Labanca et al. (2018) tested the effectiveness of NMES superimposed with sit-to-stand-to-sit (STSTS) exercises on quadriceps strength after ACLr. Using the STSTS exercise allowed quadriceps to work in the concentric and eccentric phases. Labanca et al. (2018) thought that doing this with NMES would allow for the muscle to rehabilitate in a more functional manner. 63 patients were split up into 3 groups: NMES+STSTS (n=21), STSTS only (n=21), and the no additional treatment (NAT) group (n=21). In the NMES+STSTS group, participants performed the STSTS exercise in 8 seconds once the NMES kicked in then they had an 8 second rest. The STSTS protocol for both groups (NMES+STSTS and STSTS only) started with the participants doing 3 sets of 6 reps with 4 seconds of concentric and 4 seconds of eccentric movement. As the training continued, the number of reps increased, the time spent in the concentric phase decreased, and the time spent in the eccentric phase increased. The NAT group received a standard post-op ACLr rehabilitation plan. Outcomes measurements of this study included: knee flexor (hamstring) and extensor (quadriceps) strength, knee joint pain, lower limb loading symmetry using a squat jump on a force plate, and knee and thigh circumferences. Labanca et al. (2018) found that knee extensor and flexor strength increased in all groups, but strength increased the most in the NMES+STSTS group compared the STSTS only and NAT groups at 60 and 180 days post-op. The same was found with limb symmetry. At 60 and 180 days, all groups were found to have increased limb symmetry, but the NMES+STSTS group had the biggest increase (Labanca et al., 2018). Knee joint pain was not shown to have a significant difference between groups, but pain levels did decrease in all groups due to healing. Vertical force limb symmetry increased over time with the NMES+STSTS group having the highest percentages at the 15th, 30th, and 180th day of testing, but the STSTS only had the highest percentages at the 60th day with the NMES+STSTS having the second highest percentage of the three groups (Labanca et al., 2018). Thigh and knee circumference differences decreased as treatment went on and all groups improved, but the NMES+STSTS group showed a significantly lower difference than the STSTS only and NAT groups at 30 days (Labanca et al., 2018). Labanca et al. (2018) concluded by stating the use of the STSTS exercise is an effective way to diminish post-op atrophy, strengthen the quadriceps and improve bilateral lower limb loading compared to the standard isometric contraction. Using the STSTS exercise is a more functional exercise and superimposing NMES on STSTS allows for the patient to increase their quadriceps strength in a functional way after ACLr (Labanca et al., 2018). This article scores 10/11 on the PEDro scale.

Moran, Gottlieb, Gam, and Springer (2019) compared the use of NMES with functional electrical stimulation (FES). FES uses NMES in a functional setting. For example, NMES can be used during a single leg or double leg squat when the patient is using a table for balance. This type of electrical stimulation stimulates the quadriceps to contract as the patient is doing exercises to help the patient contract while doing a movement. In this study, Moran et al. researched 23 total patients who had ACLr surgery using a randomized controlled pilot study. Of those 23, 10 were in the FES group and 13 were in the NMES group. The protocol had the patients do FES while walking or NMES 10 minutes per day for 3 days per week along with their standard rehabilitation protocol. Moran et al. measured gait speed, gait symmetry, quadriceps isometric peak strength ratio, and peak strength symmetry 2 weeks pre-op and 4 weeks post-op. Gait measurements were also performed 1 week post-op. It was concluded that while gait speed and symmetry did not differ between groups, FES did have a greater recovery of quadriceps strength and symmetry 4 weeks post-op than NMES. While both modalities were said to be effective in this case, Moran et al. (2019) recommend studying the long term effects of FES compared to NMES and using a larger sample size to get a more accurate result. On the PEDro scale, this article scores 8/11.

Ross (2000) sought to examine the effectiveness of the addition of NMES with closed kinetic chain exercises (CKC) on anterior tibiofemoral knee joint laxity and performance measures including unilateral squat, .10m lateral step-ups, and anterior reach. Ross used 20 participants divided into two groups. There were ten participants in the NMES+CKC group and ten in the CKC only group. Both groups completed the same basic rehabilitation plan. The NMES+CKC group began NMES treatment one week post-op and used NMES while squatting five days per week for the second through fourth week and three days per week for the fifth and sixth week. Sessions were 30 minutes long with squats being performed for 15 seconds and a 35 second rest time. During the rest period, participants would alternate between heel to toe raises or walking with weight shifting for the allotted time. NMES was conducted at 50pps, 15:30 duty cycle with a 3s ramp. Anterior joint laxity was measured using an arthrometer. Performance measures included a squat for depth, lateral step-ups performed for 15 seconds and max reps, and an anterior reach test where participants stood on one leg and reached as far forward as they could with the non-weight bearing leg for balance. Ross (2000) found that there was a significant difference between the NMES+CKC group and the CKC only group when it came to unilateral squats and lateral step-ups. Between the two groups, there was less strength loss in the NMES+CKC group leading to less performance loss (Ross, 2000). Ross (2000) concluded by saying that NMES with CKC exercise is effective for unilateral squat and lateral step-ups, but the between group differences was not significant when it came to the anterior reach test or joint laxity. Open kinetic chain (OKC) exercises should be used to isolate the weakened muscles, but more research is needed (Ross, 2000). This study scores 8/11 on the PEDro scale.

Snyder-Mackler, Delitto, Bailey, and Stralka (1995) conducted a prospective, randomized clinical trial to test the effectiveness of electrical stimulation in the early post-op phase after ACLr. 110 total participants were split into four different groups: high intensity NMES (n=31), low intensity NMES (n=25), a combination of low and high intensity NMES (n=20), and high level volitional exercise (n=34). All patients were seen 3 times per week for the first 6 weeks for intensive exercise rehabilitation. The high level NMES group was treated 3 times per week consisting of 15 isometric contractions at 2500hz, 75pps, and an 11:120 duty cycle (11 second contraction, 120 second rest). The high level exercise group was also seen 3 times per week performing 3 sets of 15 contractions at max effort where each contraction was held for 8 seconds. The low intensity NMES group used a portable device that was conducted at 300 microseconds at a frequency of 55pps at 15:50 duty cycle. They performed the low intensity NMES for 15 minutes per session, 4 sessions per day, and five days per week. The patients in the combo group received the same treatments as the high and low intensity NMES groups. Testing was performed after four weeks of treatment. Quadriceps strength was tested using an electromechanical dynamometer and each participant had a stimulator superimposed on their quadriceps that would deliver a supramaximal stimulus to test if the participant was performing a true maximal contraction. If a true maximal contraction was performed, an increase in torque would not be seen. Gait was also tested using a motion-analysis system. Snyder-Mackler et al. (1995) found that there was no significant difference between the high intensity NMES group and the combo group, but there was a significant difference between the groups treated with high intensity NMES and the low intensity and volitional exercise groups. They also found that the groups that used high intensity NMES with their rehabilitation had 70% recovery of the quadriceps (compared bilaterally) at 6 weeks post-op while the low intensity NMES group was at 51% and the exercise group was at 57% (Snyder-Mackler et al., 1995). The patients who were treated with high intensity NMES also had a more normal gait pattern after treatment compared to the other groups, which is probably due to the increased strength in the quadriceps (Snyder-Mackler et al. 1995). It was concluded that high intensity NMES with isometric contractions will improve the strength of the quadriceps leading to improved function after ACLr (Snyder-Mackler, 1995). This article scores 8/11 on the PEDro scale.

Taradaj et al. (2013) compared the effectiveness of NMES on quadriceps strength and circumference/muscle girth using a randomized controlled trial on 80 professional soccer players who had ACLr surgery. This study used two groups of 40 soccer players per group. Both groups received the same rehabilitation exercise protocol, but only one group received NMES as a treatment method. The protocol for the NMES group called for 3 treatments daily, 3 days per week, with 3 hours between treatments. Treatment was done bilaterally in order to see how the surgical side compared to the non-surgical side in increasing quadriceps strength and girth. Taradaj et al. measured strength using a tensometer and muscle girth using a tailor tape measure 10cm above the patella. Measurements were taken before the first day of therapy and after the last day of therapy. After the last day of therapy, measurements were again taken at a 1 month and a 3 month follow up appointment. For the NMES group, the strength of the operated and non-operated side increased from 645.9 N to 893.4 N and 840.1 N to 1089.8 N respectively. For the NMES group, the circumference of the operated side and non-operated side increased from 56.5cm to 57.9cm and 58.1cm to 59.3cm respectively. For the control group, the operated and non-operated side strength increased from 648.6 N to 669.8 N and 840.4 N to 885.2 N respectively. Lastly, for the control group, the operated and non-operated side circumference increased from 56.2cm to 57.1cm and 57.7cm to 58.2cm respectively. Taradaj et al. concluded that NMES was effective in increasing quadriceps strength and restoring mass and strength in soccer players. This study scores 9/11 on the PEDro scale.

Studies of High Quality that Do Not Support the Use of NMES

The phrase, "do not support" may be a little misleading in this context. All studies included in this and the "Studies of Low Quality that Do Not Support the Use of NMES" section were not against the use of NMES on quadriceps after ACLr,instead however; the studies did not find a significant difference between their groups, concluding that NMES was not necessary for ACLr rehabilitation to regain strength. The researchers do not state in any of the studies that NMES will have a negative effect on the patient receiving treatment.

Lieber, Silva, and Daniel (1996) conducted an RCT to compare the effectiveness of NMES versus voluntary contractions to see which method is more effective in quadriceps strengthening after ACLr. They attempted to match muscle tensions or intensities between groups to see a more accurate result. There were 40 participants who were split into two groups: NMES (n=20) and voluntary muscle contraction (VMC) (n=20). In order to match the intensity of the NMES group, the VMC group trained at progressively increasing torque levels that were equal to 15%-45% (increased through treatment) of the uninjured limbs max torque. Contract and relax cycles lasted for the same amount of times between groups at 10 seconds contract, 20 seconds to relax or 10:20 duty cycle with a 2 second ramp on and off for patient comfort, leading to 60 total contractions in a treatment session. The NMES group used a stimulation intensity that they were able to tolerate for 30 minutes. Treatment was done for 30 minutes per day, 5 days per week for 4 weeks. Participants of both groups also did at home therapy exercises. Knee extension torque was the main measurement, which was measured at 6, 8, 12, 24, and 52 weeks post-op. Lieber et al. (1996) measured knee extension torque at 90°. The results indicated there were equal strength gains between groups, meaning there was no significant difference between groups even up to 1 year post-op. However, the VMC group performed about 30% greater torque production compared to the NMES group (332.1nm/min for VMC, 252nm/min for NMES). Lieber et al. (1996) recommended more studies with carefully controlled intensities to resolve the differences in the results of the literature and see the true effect of NMES versus VMC for regaining quadriceps strength after ACLr. While both treatment methods are effective in regaining strength after ACLr, NMES is not necessary when using VMC at matching intensities. This study scores 8/11 on the PEDro scale.

<u>Studies of Low Quality that Support the Use of NMES</u>

Currier et al. (1993) conducted a pilot study to test the effects of using NMES with a pulsed electromagnetic field on thigh girth, knee extensor strength, and pain scores on patients after ACLr. There were three groups used in this study: control (n=4), NMES (n=7), and NMES+PEMF (n=7). All groups received a standard rehabilitation plan along with their modality if they were in an experimental group. PEMF was used to help increase the muscle contraction concurrently with NMES giving the patient a stronger contraction than the NMES only group without the increased pain that may be caused with NMES. The parameters for the NMES group were as follows: 2500hz, 50pps, 15:50 duty cycle with a 5 second ramp on. The NMES group completed 10 contractions during their session at an intensity that they could tolerate, but contractions at 50% of their maximal voluntary contraction was the goal. The parameters for the NMES+PEMF group were as follows: 1.5 Tesla, 60 cosine pps, 10:50 duty cycle. Patients completed 3 sessions per week for 6 weeks total. Currier et al. (1993) found decreased total thigh girth loss between the three groups with the NMES group having the least amount of girth loss of the three groups with the NMES+PEMF group close behind. Currier et al. (1993) also found that some of the participants of the NMES+PEMF group maintained or increased their extensor torque, while others actually decreased. However, this decrease in torque is less compared to other studies (Currier et al., 1993). Torque scores were not available for the NMES or control groups because of the time restraints of their rehabilitation program. In conclusion, Currier et al. (1993) decided that NMES+PEMF and NMES alone are both effective in decreasing thigh girth losses after ACLr. Despite being an older study, this is in agreement with current literature. This study scores 5/11 on the PEDro scale.

Kim, Croy, Hertel, and Saliba (2010) conducted a systematic review of RCTs that assessed the effects of NMES on quadriceps strength, functional performance, and self-reported function after ACLr surgery. In their study, eight RCTs were reviewed. Seven assessed strength outcomes, one assessed function test scores, and one assessed self-report functional outcomes. The seven studies that assessed strength outcomes showed mixed results. Three of the studies showed clear effectiveness in regards to strength gains whereas three also showed the results to be inconclusive of NMES being effective in regaining quadriceps strength. The three studies that showed strength gains also had the least amount of treatment sessions of any of the RCTs used in this study. Kim et al. (2010) states, “NMES appears to result in no added benefit to weight-bearing exercise for functional performance tests in patients post-ACL reconstruction.” The researchers were careful to point out that their results may not be sufficient enough to draw a conclusion on whether NMES was effective for increasing functional test scores after ACLr. This study had a low PEDro score scale of 3 which may indicate why these conclusions were drawn. The one study that evaluated self-reported functional outcomes used the Knee Outcome Survey to evaluate how the patient perceived their function when doing activities of daily living (ADLs). Kim et al. (2010) came to the conclusion that self-reported functional outcome scores were moderately improved when using NMES after ACLr. They also concluded that NMES is effective for use after ACLr in terms of strength and there is a positive effect on self-reported functional outcome scores, but functional test scores were inconclusive in determining the effectiveness of NMES after ACLr. More tests and clinical trials were recommended to determine effectiveness and parameters for treatment. This study is considered to be of low quality because they only included eight studies and the average PEDro score for the articles was considerably low.

Lepley, Wojtys, and Palmieri-Smith (2015a) examined how NMES could be used with eccentric (ECC) exercises to improve sagittal knee and quadriceps symmetry in patients who had ACLr. 36 patients were split up into 4 treatment groups: NMES+ECC (n=8), NMES only (n=10), ECC only (n=8), and standard of care (n=10). There was also a healthy participants control group (n=10). The study lasted about 3 months. In the first 6 weeks, the NMES+ECC and NMES only groups received NMES while the ECC only group received no ECC or NMES treatment. At the same time, the standard of care group received the standard ACL rehabilitation plan of the university at which the study was conducted. During the second 6 weeks, the NMES+ECC and ECC only groups started ECC training which occured 2 times per week while the NMES only group received no ECC or NMES treatment and the standard of care group continued on with the standard ACL rehabilitation plan. When the groups were not receiving their specified type of intervention, they were all receiving the same treatment based on a basic ACL rehabilitation protocol. To measure strength, Lepley et al. (2015a) used an isokinetic dynamometer similar to a leg extension machine. Each participant performed 3 maximal knee extensions maximal voluntary isometrics (MVIC). The maximal knee torque was then normalized to each participant's body weight for a comparison of strength to body weight. Strength was tested bilaterally for a healthy baseline for each participant. Single-leg landing was also tested by having each patient jump onto a force plate from a predetermined distance based on each participant's leg length. Lepley et al. (2015a) found that there was greater limb symmetry in the NMES+ECC group compared to the ECC only group which made the NMES+ECC group more comparable to the healthy group. It was suggested that the more symmetrical the strength in the quadriceps, that post-ACLr functional knee performance should improve, which is why the NMES+ECC group had the greatest limb symmetry index on the single-leg landing test. This study is not without limitations. The basic rehabilitation protocol used on each patient may have differed leading to some potential differences in goals or treatment methods that may be better used for rehabilitation than other methods. Also, the low sample size may not be representative of the whole population. However, even though it was not statistically significant, the NMES+ECC group had the earliest RTP date of any of the treatment groups. Like many other researchers, Lepley et al. (2015a) recognize that future studies need to be conducted in order to see the true effects of NMES+ECC exercises as a treatment method for ACLr rehabilitation. This study scores 5/11 on the PEDro scale.

Paternostro-Sluga, Fialka, Alacamliogliu, Saradeth, and Fialka-Moser (1999) conducted a study that set out to determine if adding NMES to rehabilitation would be more effective than rehabilitation alone, and how much does NMES actually affect strength compared to just being used as an analgesic effect. To test this, they used 3 groups: NMES (n=16), Transcutaneous Electrical Nerve Stimulation (TENS) (n=14), and exercise alone (n=17). Strength was tested at post-op week 6, 12, and 52 using isometric and isokinetic testing of leg extension. Strength was tested bilaterally for three reps with a 5 second hold and 10 seconds rest between reps and the peak torque was taken. Standard rehabilitation was performed for all patients. The NMES and TENS group used their respective type of stimulation one time per day for 7 days per week. Both groups used a portable, battery powered unit. The NMES protocol consisted of two sets. Set 1 was 4 sets of 12 contractions at 30hz with a 5 second hold, 1 second ramp time, and a 15 second off time. Set 2 was 2 sets of 12 contractions at 50hz with a 10 second hold, 2 second ramp time, and a 50 second off time. Between each set, there was a 6 minute break. Patients were told not to perform a voluntary contraction while the contraction was produced by the e-stim unit. The TENS group used a pulse duration of 220 microseconds at 100hz and elicited no muscular contraction. Sessions lasted 30 minutes. During testing, Paternostro-Sluga et al. (1999) found that there was no significant difference between groups when it came to isometric and isokinetic torque of the quadriceps. However, there was still a tendency in favor of the use of NMES for quadriceps strength recovery after ACLr. They found that after 6 weeks, the involved knee of the NMES group was at 69.1% isometric strength of the involved limb while the TENS group was at 65.6% and the exercise group was at 60.7% (Paternostro-Sluga et al., 1999). The NMES group still ended up stronger at the end, therefore, there was no significant difference in terms of strength gains between groups. This study scores 10/11 on the PEDro scale, but because it is over 20 years old, the quality is lowered.

Snyder-Mackler, Delitto, Stralka, and Bailey (1994) compared the dosage of electrical stimulation and quadriceps strength after ACLr in order to establish a dose-response curve. 110 subjects were used, a subsample group of 52 participants that were focused on in this study. Of those 52, 31 used a clinical stimulator and 21 used a portable stimulator. Participants used the stimulators for 4 weeks and completed a rehabilitation play from weeks 2 through 6 with treatment occurring 3 times per week. In the clinical stimulator group, treatment consisted of 15 isometric contractions with the knee in 65º flexion on an electromechanical dynamometer with the stimulator set at the highest intensity the participant could tolerate and adjusted as the participant adapted to the intensity. The torque of the isometric contraction was measured and compared bilaterally. In the portable stimulator group, the participants used the modality four times a day for 15 minutes per session 5 days per week. The duty cycle was set at 15:50 (15 seconds on, 50 seconds off). After the 4 weeks of treatment, the MVIC was taken for each group. Snyder-Mackler et al. (1994) found that there was a linear response between training intensity and quadriceps strength meaning the higher the training intensity, the more symmetrical the quadriceps strength compared to the uninvolved side. This correlates with previous research regarding the effectiveness of NMES on quadriceps strength after ACLr since NMES is typically more intense than TENS or IFC electrical stimulation (Knight & Draper, 2013). A critique of this study is that, to the reader's knowledge, they did not have a baseline group receiving standard post-op ACL rehabilitation without NMES. A baseline helps the researchers to see the effectiveness of a given modality. Without a baseline group, the true effects are difficult to interpret. One may still be able to get accurate results without a baseline group, but the true effects are unknown without the comparison. Also, this study used portable stimulators which are not capable of producing the required intensity to see a strength change. Snyder-Mackler et al. (1994) suggest that in order for there to be a change, the training contraction intensity has to be at or above 10% of the uninvolved limb maximal voluntary contraction. This 10% is the threshold for muscular adaptation in this case. Participants who were not able to train at this intensity (portable stimulator group) did not see as great of increases in maximal voluntary contraction compared to the the clinical stimulator group who could train at this threshold (Snyder-Mackler et al., 1994). This study scores 9/11 on the PEDro scale, but because of its age, lack of control group, and use of a portable stimulator, it is considered to be low quality.

Stevens, Mizner, and Snyder-Mackler (2004) assessed the effectiveness of NMES on quadriceps after TKA. In this case series, 8 participants were split up into an NMES group (n=5) and an EX group (n=3). Treatment started 3-4 weeks after TKA and was done 3 times per week for 6 weeks. For treatment, the NMES group completed 10 isometric contractions at 2500hz at 50pps with a 2-3 second ramp at a 10:80 duty cycle. This was done at the maximal tolerated intensity for each individual patient. Quadriceps strength and activation was assessed at the initial evaluation (3rd week), at mid-training (6th week), post-training (9th week), 3-month follow up (12th week), and at the 6-month follow up (24th week). Quadriceps strength and activation was measured using an electromechanical dynamometer with their knees flexed to 75º. The participants warmed up by performing a voluntary isometric contraction that they thought was 50-75% of their maximal effort. The participants then performed a 3-5 second MVIC. During the contraction, a 135-V, 10-pulse, 100pps train was delivered to assess whether or not the participant was maximally activating their quadriceps. Three MVICs were performed with a 5 minute rest between contractions to make sure that the participant had enough time to rest and avoid muscle fatigue. Measurements were taken for both legs. Stevens et al. (2004) found that the weak NMES legs showed more improvements in quadriceps strength (221-451%) compared to the strong NMES legs (50-152%), weak EX legs (41-148%), and the strong EX legs (30-71%). Improvements in the weak leg strength was seen through the 6-month follow up. Because of the small sample size, Stevens et al. (2004) could not determine a dose-response relationship, but they did conclude that high intensity NMES can be used to increase quadriceps strength after TKA. While TKA is a different procedure that ACLr, the end goal of recovering quadriceps strength is the same as that of ACLr, which is why it is included in this study (Stevens-Lapsley et al., 2012). Based on the three-minute checklist (Chan & Bhandari, 2011), this study scores 6/8. However, because this study looks at the use of NMES on TKA instead of ACLr, it is included as a low quality article for support.

Wigerstad-Lossing et al. (1988) conducted a study to compare the effects of electrical muscle stimulation paired with voluntary muscle contraction to voluntary muscle contraction alone during immobilization after ACLr. 23 participants were split between the 2 groups: EMS+VMC (n=11) and VMC only (n=11). After surgery, participants were immobilized for 3 weeks with a full leg cast and then put in a knee cast for 3 more weeks. All participants began performing VMC on the first post-op day and the EMS+VMC group began EMS on the second day. Parameters for the treatment were as follows: 30hz, 300ms pulse width, 6 seconds stimulation with 10 seconds of rest with a 2 second ramp time, and an amplitude of 65-100mA. Stimulation was performed for 10 minute sets 4 times per day, 3 days per week. Each set had 10 minutes of rest between them. Strength was measured using a Cybex dynamometer per-op and again at 6 weeks post-op. A CT scan was also taken to evaluate muscle size and growth. A muscle biopsy was also taken to view fiber composition and enzymatic activity. Wigerstad-Lossing et al. (1988) found that the EMS+VMC group had significantly less of a decrease of isometric quadriceps strength at testing compared to pre-op, meaning the EMS+VMC group regained more of their strength faster than the VMC only group. There was also a smaller reduction of cross-sectional sizes between the 2 groups with EMS+VMC having less of a reduction than the VMC only group (Wigerstad-Lossing et al., 1988). Wigerstad-Lossing et al. (1988) found that there was a higher ratio of type 2 fast-twitch fibers compared to type 1 slow-twitch fibers in the EMS+VMC group compared to the VMC only group. This is likely due to the stronger, more intense contraction from combining the contraction with EMS. Using EMS+VMC is beneficial when it comes to maintaining muscle characteristics like size and strength and it could be helpful with preparing patients for more intense rehabilitation as they heal and progress through their rehabilitation plan (Wigerstad-Lossing et al., 1988). This study scores 6/11, but because of its age and use of immobilization, it is considered low quality.

Studies of Low Quality that Do Not Support the Use of NMES

Draper and Ballard (1991) conducted a study to test the effects on quadriceps strengthening between electrical stimulation (e-stim) and electromyographic biofeedback. The researchers investigated if there was a difference between the two modalities when it came to recovery rate of peak quadriceps torque and knee ROM during a 6 week training period after ACLr (1991). 30 participants in total were split between the e-stim (n=15) and biofeedback (n=15) group. Each group used their assigned modality while performing quadriceps sets (QS) and straight leg raises (SLR). Patients were asked to use the e-stim or biofeedback units 3 times per day for 30 minutes per session, but were also told to record the amount of sessions they actually completed to evaluate compliance. Participants were also asked to travel to a clinic 3 times per week to perform 3 sets of 10 reps of QS and SLR for the clinicians. The exercises progressed to the point of using ankle weights as the program continued. At 6 weeks post-op, participants reported to the clinic to perform 3 maximal 3 second quadriceps contractions on a dynamometer with a 10 second rest between reps. Participants were tested bilaterally for comparison. Draper and Ballard (1991) found that while there was no AROM difference between the groups, the biofeedback group had greater quadriceps strength gains after the 6 week training period. It was suggested this was due to participant effort put forth during the treatment sessions. When patients are using biofeedback, they have to, "formulate a motor strategy, initiate the muscle contraction, and voluntarily maintain the contraction during the hold time" (Draper and Ballard, 1991). When patients are using e-stim, the contraction is artificially produced so the patient doesn't have to focus to start or maintain the contraction. Because of this potential lack of effort when using e-stim, patients may become passive and not attempt to contract the quadriceps as recovery goes on leading them to have less strength gains and not recover at the same rate. This recovery rate is slower compared to someone putting in effort to contract the quadriceps during e-stim or biofeedback where the individual is forced to make the contraction on their own strength. This makes biofeedback a better option in increasing quadriceps strength and function after ACLr (Draper and Ballard, 1991). This study scores 9/11 on the PEDro scale, but because of its age and use of immobilization, it is considered low quality.

While Lepley et al. (2015b) found that NMES+ECC was useful in restoring quadriceps strength and could help with knee functional performance, earlier that year, Lepley, Wojtys, and Palmieri-Smith (2015b) also published a study talking about using NMES+ECC to improve quadriceps function post-ACLr. There were 36 participants split up into 4 groups: NMES+ECC (n=8), ECC only (n=10), NMES only (n=8), and standard of care (n=10). Those 4 groups were also compared to a healthy group of 10 participants. The same protocol was used with NMES+ECC and NMES only receiving NMES treatment for the first 6 weeks and ECC only receiving a basic rehabilitation protocol. During the second 6 weeks, the NMES+ECC and ECC only group received eccentric exercises while the NMES only group received a basic rehabilitation protocol. The standard of care group received a standard post-ACLr rehabilitation plan used by the institution. In this study, Lepley et al. (2015b) found that eccentric exercise therapy alone was found to have greater improvements in quadriceps activation than just using NMES, which they say is contradicting the literature. However, there was no difference in quadriceps activation or strength between the NMES+ECC group compared to the ECC only group and the restored levels of these two groups were comparable to the healthy group. The results indicated that NMES alone is not as effective in increasing quadriceps strength or activation compared to ECC alone. However, NMES+ECC and ECC only show the same amount of effectiveness and are comparable to healthy adults. Lepley et al. (2015b) stated that for eccentric exercise usage instead of the combination of eccentrics and NMES is better because for NMES to work, it must be delivered at high intensities which clinics may not be able to achieve and additionally the high intensities may not be tolerated well by the patient. In this instance, Lepley et al. (2015b) advocate for using eccentric exercises only to increase patient compliance to therapy after ACLr. This study scores 5/11 on the PEDro scale.

Sisk, Stralka, Deering, and Griffin (1987) conducted a randomized controlled trial to evaluate the effectiveness of electrical stimulation and isometric exercises on quadriceps strength after ACL by comparing the use of e-stim (ES) with exercise to exercise alone. In this study, there were two groups: e-stim+exercise (ES+EX) (n=11) and exercise only (EX) (n=11). All patients were placed in plaster-mold immobilization casts from the ankle to the groin, replaced with a fiberglass cast at week 2, then replaced with a mobile cast/brace at week 4 to allow the patient to move within 45-90° of knee flexion. Patients in the ES+EX group started ES on the 3rd or 4th post-op day and exercises began 2nd post-op day. Exercises were done for 30 reps, 3 times per day. The parameters for ES were as follows: 40hz, 300msec, 10:30 duty cycle with .5 second ramp, rectangular waveform. ES was applied for 8 hours per day, 7 days per week for the first 6 weeks post-op. At the 7th, 8th, and 9th week, knee extensor strength was measured using a dynamometer. Three maximal isometric contractions were performed and the highest score was taken and compared to body weight to adjust for the various body compositions of the participants. Sisk et al. (1987) found that there was a significant difference between testing sessions, but there was no significant difference between groups in terms of strength gains throughout testing. Interestingly, competitive athletes seemed to recover and regain strength faster than the recreational athletes being tested (Sisk et al., 1987). This could be due to the competitive athletes nature of competition and desire to return to play at full strength as soon as possible being higher than recreational athletes. However, there was no significant difference between the competitive athletes in each group (Sisk et al., 1987). Sisk et al. (1987) concluded that there was no significant difference in strength between groups, making ES not necessary for regaining strength following ACLr. This study scores 6/11 on the PEDro scale, but is considered low quality because of its age and use of immobilization.

Strengths and Weaknesses of the Study

The articles used in this study had many strengths. The use of randomized controlled trials contributed to the strength of the arguments. Placing patients in randomly assigned groups eliminated bias involved between the groups. Comparing NMES to patients not using NMES and to other modalities helped strengthen the argument as well. Articles that d compared the use of NMES versus patients who did not use NMES provided the researchers a good comparison group to show the true effects of NMES on quadriceps strength after ACLr. The highest quality articles compared NMES combined with exercises to an NMES only group and to a non-NMES/exercise only group increased the strength of the articles. Using this type of research process allowed the researchers to see how effective NMES was compared to other types of protocols. Studies that took into account patient reported outcome measures gave the participant the ability to evaluate themselves in how they functioned outside of therapy. Using patient reported outcome measures allowed for the researchers to see the patient's functionality and identify if NMES was helping with their functional activities and thus defend the use of NMES in therapy.

A weakness of some of the studies used was the use of plaster mold or full leg immobilization after therapy (Sisk et al., 1987; Wigerstad-Lossing et al., 1988). Using a plaster mold cast instead of a hinged cast caused further atrophy because the patients were not able to move their leg at all. This may have delayed the recovery, therefore affecting the accuracy of the results. Plaster mold casts have also been shown to make joints more stiff post-op along with increasing the risk for bone and cartilage deterioration. Sandberg, Nilsson, and Westlin (1987) showed that a hinged cast/brace actually helped ACL tears heal faster making it the more effective type of protection for ACL injuries and taking away some of the accuracy of the claims of the articles that used plaster mold casts.

Another weakness was that some studies did not utilize a control group making it difficult to see the extent of the effectiveness of NMES. Having a control group allows the researchers to see how the results of the treatment group compare to the results of the control group. This does not give the research as much credibility.

Small sample size also decreased the quality of some of these studies. This can be difficult to do in the health field because researchers need to find participants who, in this case, tore their ACL and had ACLr surgery. The age of some of the studies are weakened as ACL rehabilitation and treatment has changed in the past 20-30 years (Sisk et al., 1987; Wigerstad-Lossing et al., 1988; Draper & Ballard, 1991; Currier, 1993, Lieber et al., 1996; Paternostro-Sluga et al., 1999; Snyder-Mackler et al., 1994; Snyder-Mackler et al., 1995). Lastly, studies that used handheld NMES units were considered to be weaker because these units may not have the capability of producing intensities high enough to create a strong contraction.

Summary

This chapter reviewed the information covered in 20 articles. 17 of the studies were randomized controlled trials and two were systematic reviews. While some of the studies did not see a significant difference when using NMES after ACLr, the majority of the articles supported the use of NMES. However, most of the articles that did not see a significant difference between groups did not necessarily report that clinicians should not use NMES as a treatment method; most of these articles held a neutral stance and said that there were other more effective methods to treat quadriceps weakness after ACLr.

The next chapter will provide details about how the studies included in this chapter can be assimilated to help the practitioner determine if they should include NMES in their treatment protocol.

Chapter 4 - Discussion, Implications, Conclusion

Literature Synthesis

Studies that analyzed the effectiveness of NMES on quadriceps strength after ACLr were used for this critical review. Of the 20 articles that were examined, 16 came to the conclusion that NMES was effective in regaining quadriceps strength after ACLr. Of those 16, nine were considered to be of high quality and seven were considered to be of low quality. Four articles came to the conclusion that NMES, while not doing any harm, was not effective in regaining quadriceps strength after ACLr. Articles that did not advocate for the usage of NMES after ACLr for quadriceps strength, were not against NMES use, but took a neutral stance saying a patient could achieve the same results using other treatment methods. Of those five, one was considered to be of high quality and four were considered to be of low quality.

Articles that were considered high quality were studies that included a higher amount of participants, had a control group for comparison, compared the use of NMES to the control group along with another treatment group, or used NMES in conjunction with OKC or CKC exercises including voluntary isometric quadriceps contractions or squats.

Summary of High Quality Findings that Support the Use of NMES

Moran et al. (2019) found that functional electrical stimulation was more effective in regaining quadriceps strength than normal NMES. These results support Ross's (2000) statements about NMES being effective in regaining quadriceps strength and increasing performance function while using NMES during CKC exercises. Labanca et al. (2018) were in agreement when they used NMES during a sit-to-stand protocol to make the exercise more functional than an isometric quadriceps contraction. They found that quadriceps strength, bilateral strength symmetry, girth, and vertical force all increased in the NMES+STSTS group compared to the other groups (Labanca et al., 2018). Feil et al. (2011) also support this result with their study that evaluated the use of a Kneehab unit compared to the standard polystim unit. Using the Kneehab sleeve may allow the patient to be more functional and move around while using the modality compared to a patient who needs to sit supine on a treatment table while using polystim. Taradej et al. (2013) found that using NMES on professional soccer players helped increase strength and mass on the involved limb, but also found the use of NMES to be effective in strengthening the uninvolved limb. Hauger et al. (2017) and Kim et al. (2010) conducted systematic reviews of randomized controlled trials and both groups came to the conclusion that NMES was effective in regaining quadriceps strength, and also helped improve performance functions. Fitzgerald et al. (2003) found that using a modified NMES protocol involving the patient sitting with their involved leg straight on the table instead of using a dynamometer for resistance showed promising results for increasing quadriceps strength and improving ADL scores. While the previous studies all found strength gains in the quadriceps, Hasegawa et al. (2011) also found gains in the vastus lateralis and calf muscles along with preventing atrophy in rectus femoris, vastus lateralis, vastus intermedius, and the calf muscles. Snyder-Mackler et al. (1995) tested the effects of high intensity NMES, low intensity NMES, a combination of high and low intensity NMES, and high intensity exercise. The results indicated the groups that used the high intensity NMES showed the greatest gains in strength and function in terms of gait patterns.

Summary of Low Quality Findings that Support the Use of NMES

Snyder-Mackler et al. (1994) found a linear response between training intensity and quadriceps strength. The higher the intensity, the greater the quadriceps strength. It was reported that in order to achieve a training effect, the participant must be training at a minimum of 10% of their maximal voluntary contraction of their uninvolved limb. Participants who did not train at this intensity (TENS group) did not see great strength gains, while groups that did (NMES group) showed greater bilateral symmetry (Snyder-Mackler et al., 1994). Leply et al. (2015) used NMES with eccentric exercises and found that the NMES+ECC group was more comparable to the healthy control group when it came to limb symmetry and the NMES+ECC group had a sooner return to play date than the ECC only group. Wigerstad-Lossing et al. (1988) found that the treatment group regained their strength faster than the control group and there was an increase in type 2 muscle fibers at the end of treatment. This increase in type 2 muscle fibers could be due to the more intense contraction from the NMES provided to the treatment group (Wigerstad-Lossing et al., 1988). Currier et al. (1993) used NMES with a PEMF compared to a NMES alone and control group and saw a decrease in total thigh girth loss in the NMES group with the NMES+PEMF group close behind in scores. The NMES+PEMF group also showed a maintenance or increase in quadriceps torque. However, some participants in that group also decreased in torque and torque for the NMES alone group was not available. The decrease in thigh girth is enough to show the atrophy preventing effects of NMES (Currier et al., 1993). Paternostro-Sluga et al. (1999) found no significant difference between groups when it came to isometric and isokinetic quadriceps strength, but the results did tend to favor the NMES group being stronger. Stevens et al. (2004) concluded that NMES was effective in increasing quadriceps strength after TKA. Even though TKA is different from ACLr, the muscles still function the same so this study can support the idea that NMES may increase quad strength after ACLr. However, the greater increase in strength gains may be attributed to the fact that TKAs do not require a graft to be used. The use of a graft may limit initial strength gains after surgery.

Summary of High Quality Findings that are Against the Use of NMES

Only one article that was against the use of NMES was considered to be of high quality. Lieber et al. (1996) found that voluntary muscle contractions were just as effective in regaining quadriceps strength after ACLr compared to NMES as long as the contractions were performed at or close to the same intensity as the NMES. If contractions were performed at the same intensity, NMES was not necessary (Lieber et al., 1996).

Summary of Low Quality Findings that are Against the Use of NMES

Lepley et al. (2015) found that eccentric exercises with NMES was more effective than NMES alone, but just as effective as eccentric exercises alone. NMES alone has to be delivered at higher intensities that may not be tolerable for patients and since NMES+ECC is just as effective as ECC only, it would be better for patient rehabilitation compliance if the treatment just includes eccentric exercises (Lepley et al, 2015). Draper and Ballard (1991) tested NMES versus biofeedback and found that biofeedback had better strength gains after 6 weeks than the NMES group. They believe this to be because with biofeedback, the patient has to contract their quadriceps and maintain the contraction on their own while with NMES, the patient does not need to contract because the unit performs the contraction for them. This makes the patient passive and there is a lack of effort. Since there is no lack of effort with biofeedback, they argue this is the better option for post-op ACLr rehabilitation (Draper & Ballard, 1991). Sisk et al.

(1987) found no significant difference in strength gains between groups after the treatment period making NMES not necessary for regaining strength.

Trends and Gaps in the Literature

Similar trends existed among the literature used for this study. These themes include the use of maximal voluntary isometric contractions (MVIC) as a measurement for quadriceps strength, using CKC and OKC exercises as an adjunct to NMES treatment, and using performance as a measurement tool to assess functional strength during activities of daily living among patients. The majority of the studies tested the patient's quadriceps MVIC. Some tested the patients at full extension (Fitzgerald et al., 2003) while others tested patients under resistance at or around 60º of knee flexion so the patients had more available motion to go into full extension. Fitzgerald et al. (2003) used full extension instead of 60º flexion because of the stress on the graft from using too much resistance while in knee flexion. Being in flexion could cause pain in the joint, causing the patient to not give a maximal contraction and giving the researchers a false result. Studies that used MVIC as a measurement used it because it shows how the strength can recover and how the quadriceps can get stronger throughout treatment.

CKC or OKC exercises were used throughout a majority of the studies. The majority of the studies used OKC during their tests using a dynamometer and others used leg extension machines (Paternostro-Sluga et al., 1999) for their exercises. The distal limb is moving freely making this OKC. Others used CKC exercises like Labanca et al. (2018) and Ross (2000). CKC exercises were used because they are a more functional and safer exercise than OKC due to the patient being weightbearing. Ross et al. (2000) suggest that CKC exercises can and should be used for functional strengthening while OKC exercises can be used for the strengthening of isolated, weakened muscles.

Performance measures are a great tool to assess functional ability after a surgical procedure. Feil et al. (2011), Ross (2000), Kim et al (2010), Hauger et al. (2017), Labanca et al. (2018), Lepley et al. (2015a) and Lepley et al. (2015b) assessed performance throughout treatment after ACLr. This allowed them to see how patients progressed and how they functioned in everyday activities outside of treatment. All except Kim et al. (2010) and Lepley et al. (2015) found increases in performance throughout treatment.

Throughout the research, some gaps were identified. While most of the studies conducted were of high quality and had good experimental protocols, there were some studies that did not utilize a control group. Some of the studies tested NMES against another modality. For example, Draper and Ballard (1991) conducted a study testing NMES versus biofeedback. Moran et al. (2019) tested NMES versus FES with no control group. Synder-Mackler et al. (1994) tested NMES were portable electrical stimulation. Lepley et al. (2015a) and Lepley et al. (2015b) used a healthy population control group that did not have an ACL injury. This also may have negatively impacted some results as the control group was not representative of the participants being tested. As this topic is becoming more common, researchers may have not used a true control group as they believed the effects of NMES are known and it would be more beneficial to test NMES versus other types of modalities. In order for true effects to be seen, researchers need to know how the treatment group differs from the control group, making the control group one of the most important parts of a study.

Implications for NMES Use After ACLr

Based on the evidence of this critical review, the use of NMES after ACLr can increase quadriceps strength if used appropriately. NMES should produce a tetanic contraction and the patient should attempt to produce a voluntary contraction during the NMES produced contraction to get a maximal contraction allowing the patient to relearn the contraction and regain their strength. Previous studies (Labanca et al., 2018; Taradaj et al., 2013; Moran et al., 2019) advocate for the use of NMES after ACLr for quadriceps strength. Only a few reviewed studies reported being against, or took a neutral stance on NMES. The main goal of rehabilitation is to return the patient back to their prior level of function. To reach this goal, patient functionality should be the long term focus. To return to full function, strength and bilateral symmetry must be achieved. Studies that supported the use of NMES showed that patient function increased as treatment continues. This may be due to the increase in strength and symmetry from using NMES with OKC or CKC exercises. Thus, increasing strength increases patient function contributing to their improved quality of life.

Improvement with functional training is likely to come from performing CKC exercises due to the limb being weight bearing instead of freely moving in air and the limb moving in a functional pattern. Labanca et al. (2018) showed how the use of NMES with CKC exercises (STSTS protocol) can help regain strength and symmetry in patients compared to CKC only and control group. Knee flexor and extensor strength and vertical force limb symmetry increased and the difference in thigh girth decreased along with pain levels in the NMES+STSTS group. Using NMES, which has been shown to prevent atrophy (Labanca et al., 2018; Hasegawa et al., 2011) combined with CKC exercises, which are more functional than OKC, can lead to greater strength gains and a sooner return to play (RTP) than using NMES alone.

Snyder-Mackler et al. (1995) compared results of high intensity NMES, low intensity NMES, combination intensity NMES, and exercise only and found similar results as Labanca et al. (2018) showing that the groups that were treated using high level NMES showed greater improvements in quadriceps strength and gait patterns making them more functional. Using a higher level intensity with a maximal quadriceps contraction will produce a maximal contraction leading to increased strength gains and recovery due to the patient's ability to produce and maintain a stronger contraction.

Moran et al. (2019) assessed the effects of NMES compared to FES during walking and analyzed gait and quadriceps strength. At the end of the study, Moran et al. (2019) found that FES had a greater recovery time with strength and gait being more symmetrical after 4 weeks. While the results were not statistically significant, this study shows that FES had a greater recovery time, potentially due to the use of functional exercises instead of OKC exercises. Because of how much walking is done everyday, walking can be considered one of the most functional activities.

Recommendations for Future Research

The critically reviewed studies provided recommendations regarding future study and practice of NMES on quadriceps strength after ACLr. Most of the studies recommended studying the use of NMES for longer lengths of time. The majority of the studies only used NMES for 6 weeks and did not look at the results for much longer. Only two studies looked at the results after 1 year: Paternostro-Sluga et al. (1999) and Lieber et al. (1996). Because of this, more studies are needed that evaluate how NMES can affect quadriceps strength and return to play long term.

Along with conducting extended studies on quadriceps strength after ACLr, more studies need to compare the usage of NMES to a control group and other treatment methods. Few articles tested a control group against a treatment group (NMES), another treatment group (NMES+exercise), and another control group (just exercise). This will allow researchers to see the effects of standard rehabilitation, standard rehabilitation plus NMES, standard rehabilitation with more intense exercise, and standard rehabilitation with NMES and more intense exercise so we can see the true effects of each method. An ideal research study would include a control group for baseline testing, an NMES only group, an NMES group with CKC exercises, and NMES group with OKC exercises, a CKC only group, and an OKC only group. This will allow the researchers to see the results between each group and which method is most effective for increasing quadriceps strength and limb symmetry after ACLr allowing practitioners to use the best method to help their patients and athletes get back to their sports or activities as soon as possible and as close to where they were before their injury, if not stronger.

Conclusion

The findings of this critical review of the literature support the use of NMES to increase quadriceps strength and prevent atrophy after ACLr. 20 articles were researched to find the answer to the clinical question: does the addition of NMES, when utilized post-ACLr, enhance quadriceps strength? Of those 20, 16 supported the use of NMES and four did not see NMES as an effective modality for treatment after ACLr. Two of the studies used were systematic reviews and 17 were randomized controlled trials. The results show that NMES is an effective treatment method when added to post-op ACLr rehabilitation. The best results were seen when NMES was paired with CKC exercises including squats or walking. Using this method will help the patients regain strength and function faster than a standard rehabilitation protocol, exercises alone, or NMES alone allowing the patient to get back to their sport of life as soon as possible, which should be the main goal of a practitioner.

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Appendix

Source: Draper, V., & Ballard, L. (1991). Electrical Stimulation Versus Electromyographic Biofeedback in the Recovery of Quadriceps Femoris Muscle Function Following Anterior Cruciate Ligament Surgery. *Physical Therapy*, *71*(6), 455–461. doi: 10.1093/ptj/71.6.455			
Purpose	Sample, Level/Quality	Design and Measurements	Results
To compare e-stim and biofeedback as adjuncts to quad muscle strengthening. To determine if there are differences between the two when it comes to rate of recovery of peak torque output and knee ROM during 6 week training period after ACLr	30 patients (16 male, 14 female) Age 15-44 Acute ACL tear BPTB Level: 1 Quality: Fair	Randomized Controlled Trial Quad femoris muscle isometric peak torque during 6th post-op week. 3 maximal 3-second contractions at 60º from full ext. Tested BILAT EXT AROM Tools: MyoTrac EMG Biofeedback unit MyoCare Plus E-stim unit Cybex isokinetic dynamometer Goniometer	No difference between e-stim and biofeedback when it came to AROM. Biofeedback produced more quad isometric peak torque than e-stim
Recommendations: E-stim and biofeedback use after ACLr could be effective if used in the same rehab program, but research is needed to prove this.			

Source: Hasegawa, Kobayashi, Arai, Tamaki, Nakamura, & Moritani. (2011). Effect of early implementation of electrical muscle stimulation to prevent muscle atrophy and weakness in patients after anterior cruciate ligament reconstruction. Journal of Electromyography and Kinesiology, 21(4), 622-630.			
Purpose	Sample, Level/Quality	Design and Measurements	Results

Assess the effect of electrical muscle stimulation (EMS) on muscle atrophy prevention in early rehab stages after ACLr	20 patients (16 male, 4 female) Age 13-54 Acute ACL tears, hamstring graft Level: 1 Quality: Good	Randomized control trial Control group (standard rehab plan): 10 patients EMS group (standard rehab plan + handheld ems machine): 10 patients - Used co-contraction to keep joint from moving, rehab started 2 days post-op Pre-op, 4wks post-op, 3mo post-op Muscle thickness of rectus femoris, vastus lateralis, vastus intermedius, and calf muscles Isometric knee ext strength Lower extremity function (Lysholm score)	Decrease is quad peak torque was less in the EMS group compared to the control group at 4wks post-op. Recovery ratio at 3mo post-op was higher in EMS group compared to control group. Muscle strength differences at 3mo were different because of muscle atrophy prevention at 4wks for both groups.
Recommendations: Suggest that EMS with 20Hz with exponential climbing pulse almost immediately after surgery can prevent atrophy and weakness after hamstring graft ACLr			

Source: Lieber, R. L., Silva, P. D., & Daniel, D. M. (1996). Equal effectiveness of electrical and volitional strength training for quadriceps femoris muscles after anterior cruciate ligament surgery. *Journal of Orthopaedic Research*, *14*(1), 131–138. doi: 10.1002/jor.1100140121			
Purpose	Sample,	Design and	Results

	Level/Quality	Measurements	
To compare NMES with voluntary contractions at matching intensities to see which treatment method is more effective in strengthening skeletal muscle	40 men and women (20/group, 15m, 4w) Age 15-44 ACLr within previous 2-6 weeks Ability to put knee in 90º flex Level: 1 Quality: Fair	Randomized control trial Intensity (magnitude of torque) of NMES was intended to be met with volitional group Torque increased each week 10s contraction, 20s relaxation, 2s ramp 30min/day, 5days/week, 4weeks Peak torque Knee extension activity	When treatment activity was matched between groups, identical strength gains were achieved.
Recommendations: Studies with carefully controlled treatment intensities are required in order to resolve discrepancies in the literature.			

Source: Sisk, T. D., Stralka, S. W., Deering, M. B., & Griffin, J. W. (1987). Effect of electrical stimulation on quadriceps strength after reconstructive surgery of the anterior cruciate ligament. The American Journal of Sports Medicine, 15(3), 215–220. https://doi.org/10.1177/036354658701500304			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Assess efficacy of combination e-stim and isometric exercise on isometric quad strength after	22 patients (11/group) Characteristics in table 1 in PDF	Randomized control trial Quad strength of intervention group	No statistically significant strength differences between groups at any test

ACLr	Level: 1 Quality: Fair	was compared with control (just exercise) group Patients were in casts for 6 weeks (2wk plaster, 4wk fiberglass) Rehab began on 2nd post-op day Each exercise done 30 reps, 3x/day. ROM ex started 6th post-op week. ES: 40Hz, 300msec, 10sec contraction, 30sec rest, .5sec ramp Isometric knee ext (quad) strength using isokinetic dynamometer Testing: 3 slight effort contractions, 1 min rest, 3 more practice contractions (last was maximal), 1-2 min rest, 3 maximal contractions	Participants who were competitive athletes were stronger and seemed to regain strength faster than recreational athletes. ES with exercise during post-surgical immobilization had no more effect on quad strength than just exercises.
Recommendations: Level of activity should be considered in future studies. In future studies, compare strength of injured side to uninjured side to test strength symmetry/proportions.			

Source:
Wigerstad-Lossing, I., Grimby, G., Jonsson, T., Morelli, B., Peterson, L., & Renstrom, P. (1988). Effects of electrical muscle stimulation combined with voluntary contractions after

knee ligament surgery. *Medicine & Science in Sports & Exercise*, *20*(1), 93–98. doi: 10.1249/00005768-198802000-00014			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Compare effect of electrical muscle stimulation and voluntary muscle contraction to just voluntary muscle contraction during cast immobilization after ACLr.	23 participants, 16m, 7w 13 exp group, 10 con group Level: 1 Quality: Fair	Randomized control trial 30Hz, 300ms, 2s rise time, 6s stimulation, 10s rest. 65-100mA, contract during stimulation 4x10min, 10 min rest between stimulation, 3x/wk Strength measured pre-op and 6wk post-op Computed tomography Muscle biopsy	Experimental group showed less reduction of iso muscle strength (quad/knee extension) than the control group. Also, significantly smaller reduction in cross-sectional area of quad muscle.
Recommendations: E-stim can be beneficial during immobilization period after ACLr when it comes to maintaining muscle characteristics. Also better prepares patients for rehab following immobilization period.			

Source: Currier, D. P., Ray, J. M., Nyland, J., Rooney, J. G., Noteboom, J. T., & Kellogg, R. (1993). Effects of Electrical and Electromagnetic Stimulation after Anterior Cruciate Ligament Reconstruction. *Journal of Orthopaedic & Sports Physical Therapy*, *17*(4), 177–184. doi: 10.2519/jospt.1993.17.4.177			
Purpose	Sample, Level/Quality	Design and Measurements	Results

Test the effects of using NMES with a pulsed electromagnetic field (PEMF)	18 participants Control (n=4) NMES (n=7) NMES+PEMF (n=7) Level: 2 Quality: Fair	Pilot Study Thigh girth, knee extensor strength, and pain scores	Decreased thigh girth total loss between the three groups. Least amount of loss in NMES+PEMF group NMES+PEMF group maintained/increased extensor torque, other groups decreased NMES+PEMF and NMES alone are both effective in decreasing thigh girth losses after ACLr.
Recommendations: More research is needed, NMES+PEMF may be more tolerable than NMES alone			

Source: Feil, S., Newell, J., Minogue, C., & Paessler, H. H. (2011). The Effectiveness of Supplementing a Standard Rehabilitation Program With Superimposed Neuromuscular Electrical Stimulation After Anterior Cruciate Ligament Reconstruction: A Prospective, Randomized, Single-Blind Study. The American Journal of Sports Medicine, 39(6), 1238–1247. https://doi.org/10.1177/0363546510396180			
Purpose	Sample, Level/Quality	Design and Measurements	Results
To compare effectiveness of NMES (polystim) or garment NMES (kneehab) to standard post-op ACL rehab program (control). Compare quad strength, performance measures, and recovery time	131 participants Level: 1 Quality: Good	Prospective, randomized, controlled, single blind study Quad strength Performance measures Recovery time	Compliance (most to least): control, kneehab, polystim Most outcome measures' improvement slowed after 12 weeks for all groups, showing NMES is more effective earlier on in rehab

			Kneehab was more convenient than polystim Kneehab patients achieved consistently better results, recovered faster, and were more compliant than other groups
Recommendations: NMES should be investigated for a longer time period, NMES effectiveness should be looked at for other surgical procedures involving the knee			

Source: Fitzgerald, G. K., Piva, S. R., & Irrgang, J. J. (2003). A Modified Neuromuscular Electrical Stimulation Protocol for Quadriceps Strength Training Following Anterior Cruciate Ligament Reconstruction. *Journal of Orthopaedic & Sports Physical Therapy*, *33*(9), 492–501. doi: 10.2519/jospt.2003.33.9.492			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Determine effectiveness of using modified NMES training program for improving quadriceps strength and physical function in rehab after ACLr. Find less painful NMES levels for patients with BPTB graft	43 participants Level: 1 Quality: Good	Randomized clinical trial, single-masked Quad torque output and self-reported knee function	Modest increase in quad torque output after 12 weeks and self-reported function scores at 12 and 16 weeks
Recommendations: Good modality for patients who can't tolerate high-intensity NMES			

Source: Hauger, A. V., Reiman, M. P., Bjordal, J. M., Sheets, C., Ledbetter, L., & Goode, A. P. (2017). Neuromuscular electrical stimulation is effective in strengthening the quadriceps muscle after anterior cruciate ligament surgery. *Knee Surgery, Sports Traumatology, Arthroscopy*, *26*(2), 399–410. doi: 10.1007/s00167-017-4669-5			
Purpose	Sample, Level/Quality	Design and Measurements	Results
To determine if NMES with standard physical therapy was more effective in improving quad strength compared to just physical therapy after ACLr.	11 Studies Level: 1 Quality: Good	Systematic Review Studies measuring isokinetic or isometric torque output and self-report performance measures	NMES found to significantly increase quadriceps strength. Self-reported physical function improved, but only for 6 weeks
Recommendations: Longer studies are required to evaluate the effectiveness of NMES on quad strength after ACLr			

Source: Labanca, L. E., Rocchi, J. P., Laudani, L., Guitaldi, R., Virgulti, A., Mariani, P., & Macaluso, A. (2018). Neuromuscular Electrical Stimulation Superimposed on Movement Early after ACL Surgery. Medicine & Science in Sports & Exercise, 50(3), 407-416.			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Test effectiveness on quad strengthening of 6 week training program using NMES superimposed with sit-stand-sit exercise	63 participants 21 participants per group Level: 1 Quality: Good	Randomized single-blind study Quad strength	NMES+STS=higher quad strength NMES patients were strongest of all groups 6 mo after surgery
Recommendations: Double limb functional activities are important early in rehab for limb symmetry and should be used after ACLr.			

Source: Paternostro-Sluga, T., Fialka, C., Alacamlioglu, Y., Saradeth, T., & Fialka-Moser, V. (1999). Neuromuscular Electrical Stimulation After Anterior Cruciate Ligament Surgery. Clinical Orthopaedics and Related Research, 368, 166–175. doi: 10.1097/00003086-199911000-00020			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Test effectiveness of adding NMES to rehab after ACLr compared to rehab alone and test if the effect is analgesic or actual strength gains	NMES: n=16 TENS: n=14 EX alone: n=17 Level: 1 Quality: Fair	Randomized, double-blind, controlled trial Isometric and isokinetic quad strength Tested bilaterally	No significant difference between groups in terms of isometric and isokinetic strength. Results tended to favor towards NMES group, but were not significant enough
Recommendations: Older participants, individuals with less strength, and knee surgery with longer immobilization period need to be researched			

Source: Snyder-Mackler, L., Delitto, A., Stralka, S. W., & Bailey, S. L. (1994). Use of Electrical Stimulation to Enhance Recovery of Quadriceps Femoris Muscle Force Production in Patients Following Anterior Cruciate Ligament Reconstruction. *Physical Therapy*, *74*(10), 901–907. doi: 10.1093/ptj/74.10.901			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Compare e-stim dosage and quad femoris strength recovery after ACLr. Establish a dose-response curve.	110 participants Subsample: 52 (12f, 40m) Level: 1 Quality: Fair	Randomized Clinical Trial Maximal voluntary contraction of quads	Recovery is positively correlated to training contraction intensity Portable stimulators not capable of producing intensity above 10% threshold

Recommendations: 10% of uninvolved quad femoris strength is threshold, must be trained at this level to elicit training effect that increases muscle force production

Source: Snyder-Mackler, L., Delitto, A., Bailey, S. L., & Stralka, S. W. (1995). Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. *The Journal of Bone & Joint Surgery*, *77*(8), 1166–1173. doi: 10.2106/00004623-199508000-00004			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Effectiveness of NMES with intensive rehab post-op ACLr	110 participants 4 groups: High intensity NMES (n=31) Low intensity NMES (n=25) Combo high and low NMES (n=20) Exercise (n=34) Level: 1 Quality: Good	Prospective, Randomized Controlled Trial Quad Strength Gait Analysis	Quad strength and gait improved significantly between groups that received high intensity NMES and groups that did not 70% of quad strength recovery in high intensity NMES, 51% in low intensity, and 57% in exercise
Recommendations: Continued research is needed. Improvements in quad strength will help with gait and other functional activities			

Source: Moran, U., Gottlieb, U., Gam, A., & Springer, S. (2019). Functional electrical stimulation following anterior cruciate ligament reconstruction: a randomized controlled pilot study. *Journal of neuroengineering and rehabilitation*, *16*(1), 89. doi:10.1186/s12984-019-0566-0			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Assess the feasibility	23 total patients who	Randomized	Quadriceps FES with

of functional electrical stimulation on the quadriceps during walking and standing after ACLr. Comparison of quad FES to NMES	would undergo ACLr 10 - FES group 13 - NMES group Level: 1 Quality: Good	controlled pilot study Each group did the e-stim for 10 minutes, 3 days/week along with standard rehabilitation protocol Gait speed, gait symmetry, quad isometric peak strength ratio, peak strength symmetry. Outcomes evaluated 2 weeks before and 4 weeks post-op. Gait outcomes assessment also performed 1 week post-op.	standard rehabilitation was more effective than NMES with standard rehabilitation in regaining quad strength and symmetry 4-wks after ACLr. Gait speed and symmetry did not differ between groups.
Recommendations: Future investigations should investigate different FES protocols. Further study looking at cost-effectiveness is necessary. FES could be used on other body parts where gait can be affected by arthrogenic muscle inhibition (AMI). Further investigations needed to evaluate long-term effectiveness.			

Source: Taradaj, J., Halski, T., Kucharzewski, M., Walewicz, K., Smykla, A., Ozon, M., Slupska, L., Dymarek, R., Ptaszkowski, K., Rajfur, J., Pasternok, M. (2013). The Effect of NeuroMuscular Electrical Stimulation on Quadriceps Strength and Knee Function in Professional Soccer Players: Return to Sport after ACL Reconstruction. *BioMed Research International*, *2013*, 1–9. doi: 10.1155/2013/802534			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Study the efficacy and safety of NMES.	80 professional soccer players	Randomized controlled trial	Useful for increasing strength in soccer

Differences in quad strength between stimulation and control group. Differences in quad circumference and other safety parameters after NMES	Must have undergone similar surgery, received same rehab procedure before NMES trials, provide informed consent, spend 6 months in study, not fit exclusion description. Level: 1 Quality: Good	Subjects received same exercise program. NMES group did treatment 3x/daily 3days/week Strength using tensometer Quad circumference using tailor tape 10cm above patella	players Safe for biomechanics Beneficial for restoring mass and strength **NMES** Strength O-side: 645.9-893.4N Strength NO-side: 840.1-1089.8N O-circumference: 56.5-57.9cm NO-circumference: 58.1-59.3cm **Control** Strength O-side: 648.6-669.8N Strength NO-side: 840.4-885.2N O-circumference: 56.2-57.1cm NO-circumference: 57.7-58.2cm
Recommendations: Study did not investigate early and long-term results. Should be investigated. Pathological changes in the knee function after increasing strength should be studied.			

Source: Kim, K.-M., Croy, T., Hertel, J., & Saliba, S. (2010). Effects of Neuromuscular Electrical Stimulation After Anterior Cruciate Ligament Reconstruction on Quadriceps Strength, Function, and Patient-Oriented Outcomes: A Systematic Review. *Journal of Orthopaedic & Sports Physical Therapy*, *40*(7), 383–391. doi: 10.2519/jospt.2010.3184			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Systematic review or RCTs assessing	8 RCTs	Systematic review of randomized	NMES combined with exercise is more

effects of NMES on quad strength, functional performance, and self-reported function after ACLr	Level: 1 Quality: Fair	controlled trials. Used PubMed, CINAHL, SportDiscus, Web of Science, and Cochrane Collaboration Key words: *ACL, anterior cruciate ligament, ACL reconstruction, anterior cruciate ligament reconstruction* AND *electrical stimulation, neuromuscular electrical stimulation, Russian electrical stimulation, NMES, quadriceps weakness*, and *knee rehabilitation* Strength outcomes using isokinetic and isometric knee extension Functional test scores (1 RCT) Self-reported functional outcomes (1 RCT)	effective than using exercises alone specifically in the first 4 weeks post-op.
Recommendations: Future studies should use RCTs with PEDro score of 8+ Future trials should obtain pre-op knee extensor torque baseline, self-reported function, and functional performance test scores.			

Source: Lepley, L. K., Wojtys, E. M., & Palmieri-Smith, R. M. (2015). Combination of eccentric exercise and neuromuscular electrical stimulation to improve biomechanical limb symmetry after anterior cruciate ligament reconstruction. *Clinical biomechanics (Bristol, Avon)*, *30*(7), 738–747. doi:10.1016/j.clinbiomech.2015.04.011			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Examine capability of combined NMES and eccentric exercises to improve sagittal knee symmetry and quadriceps symmetry after ACLr	36 patients undergoing ACLr (13 female, 26 male), BPTB or hamstring graft for surgical method Between 14 and 30 Undergoing rehab in clinic conducting study Acute ACL injury No previous history or knee surgery No previous ACL injury No known heart condition Level: 1 Quality: Fair	Parallel longitudinal design (RCT) Same rehab plans, but one group did NMES with rehab and other did not NMES+ECC and ECC only groups, ECC done 2x/week for 6 weeks Isokinetic dynamometer, hips flexed to 90º, back supported, testing leg and torso secured to dynamometer 3 maximal knee extension maximal voluntary isometrics, maximal knee extension torque then normalized to body weight and compared bilaterally Single-leg landing on force plate	Greater limb symmetry in NMES+ECC group compared to ECC only group. NMES+ECC produced greater limb symmetry making them more comparable to the healthy group. Greater knee flexion angles and moments over stance related to quad strength, interventions capable of restoring strength can influence sagittal plane knee mechanics, which should improve functional knee performance after ACLr
Recommendations: Future work should study NMES' ability to decrease severity of negative alterations to muscle morphology			

Source: Lepley, L. K., Wojtys, E. M., & Palmieri-Smith, R. M. (2015). Combination of eccentric exercise and neuromuscular electrical stimulation to improve quadriceps function post-ACL reconstruction. *The Knee*, *22*(3), 270–277. doi:10.1016/j.knee.2014.11.013			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Evaluate effectiveness of NMES+ECC to improve quad muscle activation and strength post ACLr	36 patients undergoing ACLr NMES only group NMES+ECC group ECC only group Standard rehab/standard of care group 10 healthy control participants for comparison Level: 1 Quality: Good	Parallel longitudinal design (RCT) Testing sessions: pre-op, 12 weeks post-op, RTP Standard rehabilitation plan along with NMES or ECC NMES and ECC not at same time, 6 week blocks to ensure patient could manage pain, effusion, ROM, and quad function Isokinetic dynamometer, hips flexed to 90º, back supported, testing leg and torso secured to dynamometer 3 maximal knee extension maximal voluntary isometrics, maximal knee extension torque then normalized to body weight and compared bilaterally	Eccentrics were driving force behind quad strength NMES was not effective in improving quad activation function. May be able to improve function at higher intensities

Recommendations: Consider using eccentrics post ACLr to improve quad activation and strength NMES may be effective at higher intensities which may be uncomfortable for patients decreasing compliance

Source: Ross, M. (2000). The effect of neuromuscular electrical stimulation during closed kinetic chain exercise on lower extremity performance following anterior cruciate ligament reconstruction*. *Sports Medicine, Training and Rehabilitation*, *9*(4), 239–251. doi: 10.1080/15438620009512559			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Examine effect of NMES in conjunction with CKC exercises on anterior tibiofemoral joint laxity and performance measures (unilateral squat, .10m lat step up, anterior reach test)	20 patients NMES+CKC (n=10) CKC only (n=10) Level: 1 Quality: Good	RCT Same rehab plans per group. NMES started 1wk post-op Wk 2-4: 5d/wk Wk 5-6: 3d/wk 30 min sessions of NMES+squat. 15 second rep, 35 second rest with alternating heel-toe raises and walking with weight shifting during rests. 50pps, 15:30, 3s ramp Anterior joint laxity (KT-1000 joint arthrometer) (basically anterior drawer test) Unilateral squat	Significant difference between groups for squat and step-up with NMES+CKC showing better results Less strength loss in NMES+CKC group leading to less performance loss

		(deepest point, knee flexion) Lateral step-up test (15s time frame, max reps) Anterior reach test (reach forward with one leg while balancing on other)	
Recommendations: Long term study is needed OKC exercise should be used in order to isolate weak muscle groups.			

Source: Stevens, J. E., Mizner, R. L., & Snyder-Mackler, L. (2004). Neuromuscular Electrical Stimulation for Quadriceps Muscle Strengthening After Bilateral Total Knee Arthroplasty: A Case Series. *Journal of Orthopaedic and Sports Physical Therapy*, 21–29. doi: 10.2519/jospt.2004.0947			
Purpose	Sample, Level/Quality	Design and Measurements	Results
Assess effects of adding high-intensity NMES to strength programs after TKA for rehab	8 participants NMES: n=5 EX: n=3 Level: 4 Quality: Fair	Case series Treatment 3-4 weeks post-op 3 times/week for 6 weeks 2500hz, 50pps, 2-3s ramp, max intensity tolerated, 10:80 duty cycle No voluntary contraction 3rd week (initial eval), 6th week	Quad strength increases were greatest in NMES weak (221%-451%) leg compared to NMES strong (50-152%), EX strong (30-71%), and EX weak (41-148%) Weak legs showed improvement through 6-month follow up

		(mid-training), 9th week (post-training), 12th week (3-month follow up), 24th week (6-month follow up) Quad strength: 3 trials with 5 minute rest between reps, MVIC Quad activation	
Recommendations: More studies required with more participants to find a dose-response relationship Full 6 weeks of treatment may not be necessary due to most improvement took place in the first 3 weeks of treatment			