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Effects of Neuromuscular Electrical Stimulation After Anterior Cruciate Ligament Reconstruction on Quadriceps Strength, Function, and Patient-Oriented Outcomes: A Systematic Review

Postoperative weakness, muscle atrophy, and impaired knee function are common following anterior cruciate ligament (ACL) reconstruction. During the first 4 weeks after surgery, significant quadriceps strength deficits, when compared to the contralateral limb, have been reported.[26,28] Although knee stability is significantly improved, long-term outcomes report knee extensor weakness ranging from 6%[12] to 18%[23] as late as 1 to 6 years following reconstruction. Ernst et al[8] further demonstrated that persistent lower extremity compensations exist following ACL reconstruction and adversely affect single-limb performance, including vertical jump takeoff and landing. Other investigators[12] found that patients following ACL reconstruction who had knee extensor strength less than 80% of the contralateral side had gait kinematics similar to patients with ACL-deficient knees. In the same study, patients with knee extensor strength greater than 90% of the contralateral limb demonstrated gait kinematics similar to healthy individuals without ACL injury.[12] A clear challenge for the rehabilitation specialist treating patients who have undergone ACL reconstruction is the resolution of the quadriceps strength deficit through the safest and most expeditious means available.

• **STUDY DESIGN:** Systematic literature review.

• **OBJECTIVE:** To perform a systematic review of randomized controlled trials assessing the effects of neuromuscular electrical stimulation (NMES) on quadriceps strength, functional performance, and self-reported function after anterior cruciate ligament reconstruction.

• **BACKGROUND:** Conflicting evidence exists regarding the effectiveness of NMES following anterior cruciate ligament reconstruction.

• **METHODS:** Searches were performed for randomized controlled trials using electronic databases from 1966 through October 2008. Methodological quality was assessed using the Physiotherapy Evidence Database Scale. Between-group effect sizes and 95% confidence intervals (CIs) were calculated.

• **RESULTS:** Eight randomized controlled trials were included. The average Physiotherapy Evidence Database Scale score was 4 out of possible maximum 10. The effect sizes for quadriceps strength measures (isometric or isokinetic torque) from 7 studies ranged from –0.74 to 3.81 at approximately 6 weeks postoperatively; 6 of 11 comparisons were statistically significant, with strength benefits favoring NMES treatment. The effect sizes for functional performance measures from 1 study ranged from 0.07 to 0.64 at 6 weeks postoperatively; none of 3 comparisons were statistically significant, and the effect sizes for self-reported function measures from 1 study were 0.66 and 0.72 at 12 to 16 weeks postoperatively; both comparisons were statistically significant, with benefits favoring NMES treatment.

• **CONCLUSION:** NMES combined with exercise may be more effective in improving quadriceps strength than exercise alone, whereas its effect on functional performance and patient-oriented outcomes is inconclusive. Inconsistencies were noted in the NMES parameters and application of NMES.

• **LEVEL OF EVIDENCE:** Therapy, level 1a–.
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• **KEY WORDS:** *ACL, electromodality, postsurgical knee rehabilitation, randomized clinical trials*

Neuromuscular electrical stimulation (NMES) applied to the quadriceps is used in the clinical rehabilitation of quadriceps weakness following ACL reconstruction.[18] Some investigators initiate NMES on the third postoperative day[21] and continue through week 4[27]

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and even through the 12th postoperative week.[21] The primary outcome of NMES treatment is to restore and improve quadriceps function. Investigators have referred to the clinical condition treated as quadriceps weakness,[9] or the rationale to treat as to influence the recovery of the quadriceps muscles[7] or the prevention of muscular weakening.[20] Others have described the expected effect of the treatment as a contraction of sufficient intensity to reeducate the quadriceps muscles or retard muscular atrophy.[19] Thus, in spite of the variable terminology used across studies, the clinical rationale is similar, in that stimulation may aid in restoration or enhancement of quadriceps strength and could be assessed by isometric or isokinetic dynamometry. The intended use of NMES in this review can be operationally defined as its impact upon quadriceps strength, functional performance, and self-reported function. Electrodes are placed over the vastus medialis near the knee and on the proximal thigh over the vastus lateralis in several studies,[7,9,24,25,27] and other studies report placement over the femoral nerve proximally and vastus medialis,[7] or even both the quadriceps and hamstrings simultaneously.[6,28] A wide variety of electrodes have been used, consisting of carbon rubber reusables[31] to self-adhering electrodes[9] of varying sizes.[24,26,28] The intensity of contraction in randomized controlled trials (RCT) has been previously reported to be administered at a patient's maximally tolerable level.[6,19,26,27] Treatment times and durations vary from 30 minutes[13] to 10 hours per day[1] or by performing 15 repetitions[26-28] over a daily or every-other-day regimen. The variability in NMES parameters may have an impact on the clinical outcomes of treatment and exacerbate the challenges of clinicians seeking effective treatments for patients following ACL reconstruction.

The NMES intervention has been proposed to help restore quadriceps strength by facilitating recruitment of the muscle that may be inhibited by pain, effusion, or knee trauma. This phenomenon has been referred to as arthrogenic muscle inhibition and often results in atrophy.[19] The inhibition is suspected to delay the return of quadriceps strength after ACL reconstruction, and NMES is targeted directly at improving strength and minimizing atrophy.[21] However, the magnitude of any clinical benefit of NMES on knee extensor strength, functional performance, or other patient-specific outcomes following ACL reconstruction is presently unclear.

Contradictions and inconsistencies on the effectiveness of NMES versus exercise[32] for patients following ACL reconstruction exist in the literature, and further review is warranted to clarify any clinical benefits of this intervention. Previous systematic reviews on this topic have provided insight into the reported effects of NMES[3,22] and have made suggestions for future research; however, no systematic review has compared the relative effect sizes (ESs) of between-group differences following a course of NMES for quadriceps strength, functional performance, or self-reported function. Our primary purposes were to summarize the outcomes of NMES versus control treatments by calculating the ESs and associated 95% confidence intervals (CIs) for the outcome measures of (1) quadriceps strength, (2) self-reported function, and (3) functional performance, as well as to present evidence-based clinical recommendations and suggestions for treatment parameters

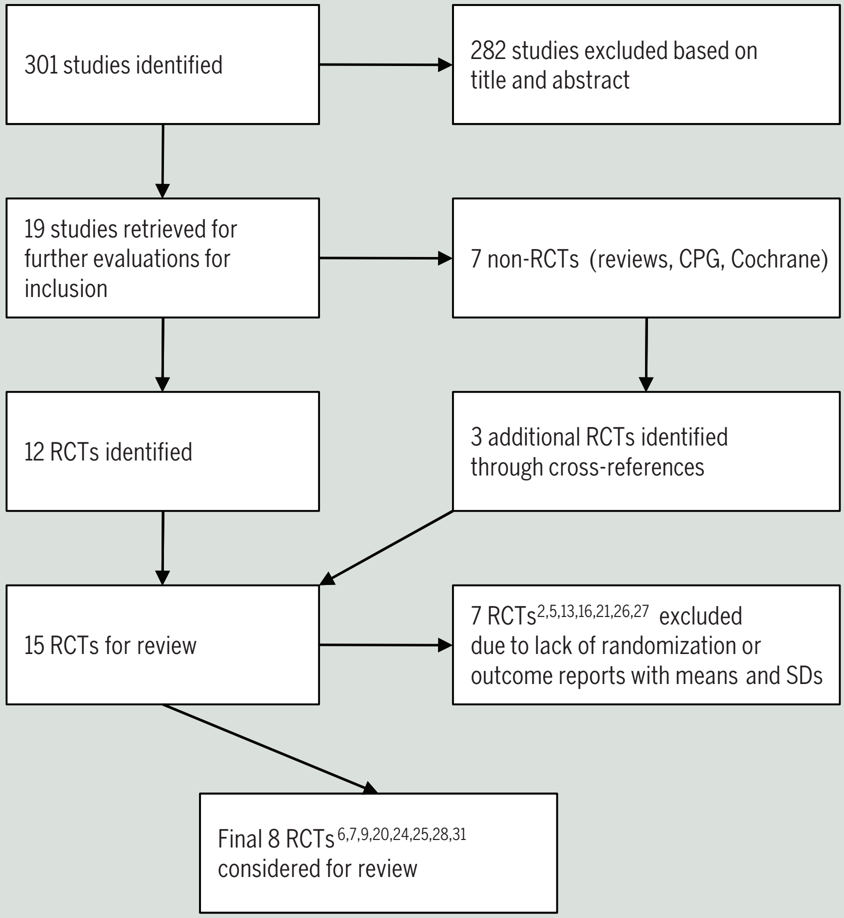

FIGURE 1. Study selection. Abbreviations: CPG, clinical practice guideline; RCT, randomized clinical trial; SD, standard deviation.

TABLE 1 Summary Results

Author	PEDro Scores	Sample Size: NMES	Sample Size: Control	NMES Intervention	Control Intervention	Outcome Measure	NMES (Mean ± SD)	Control (Mean ± SD)
Sisk[25]	4	10	9	NMES + EX	EX	Isometric (Nm)	0.73 ± 0.41*	0.70 ± 0.30*
Delitto[6]	4	10	10	NMES	EX	Isometric (ft-lb)	114.0 ± 41.0*	84.0 ± 20.0*
Wigerstad-Lossing[31]	4	13	10	NMES + EX	EX	Isometric (Nm)	90.0 ± 9.0*	57.0 ± 9.0*
Draper[7]	4	15	15	NMES + EX	EMG Biofeedback + EX	Isometric (ft-lb)	37.9 ± 12.4*	46.4 ± 10.5*
Snyder-Mackler[28]	5	5	5	NMES + EX	EX	Isokinetic (Nm)		
						210°/s (avg torque)	46.8 ± 6.0†	26.6 ± 4.5†
						90°/s (avg torque)	65.8 ± 10.8†	36.8 ± 6.5†
						210°/s (peak torque)	114.8 ± 21.0†	63.6 ± 11.3†
						90°/s (peak torque)	95.2 ± 14.4†	56.4 ± 11.4†
Paternostro[20]	4	16	17	NMES + EX	TENS + EX, EX only	Isometric (Nm)	108.8 ± 55.3†	81.4 ± 32.2†
						Isokinetic (Nm)		
						60°/s (peak torque)	77.6 ± 45.2†	57.7 ± 23.2†
Ross[24]	3	10	10	WB EX + NMES	WB EX	Lateral step-up test	17.65 ± 5.36	14.35 ± 4.9
						Anterior reach	58.75 ± 7.38	58.3 ± 4.78
						Unilateral squat	70.55 ± 18.46	64.48 ± 15.36
Fitzgerald[9]	6	21	22	NMES	EX	Isometric (Quad Index)	75.9 ± 16.8*	67.0 ± 19.9*
						Self-reported function (12 wk)	89.2 ± 8.9‡	82.2 ± 10.4‡
						Self-reported function (16 wk)	91.05 ± 7.3‡	86.4 ± 8.2‡

Abbreviations: Avg, average; EMG, electromyography; EX, therapeutic exercises; ft-lb, foot-pounds; Nm, Newton meter; NMES, neuromuscular electrical stimulation; PEDro, Physiotherapy Evidence Database scale; Quad Index, quadriceps index; TENS, transcutaneous electrical nerve stimulation; WB, weight bearing.
* *Isometric knee extension torque.*
† *Isokinetic knee extension torque at various testing angular velocities.*
‡ *Self-reported measures of knee function at 12 and 16 weeks following ACL reconstruction.*

in the use of NMES in patients following ACL reconstruction.

METHODS

Search Strategy

Searches were performed in electronic databases using PubMed, CINAHL, SportDiscus, Web of Science, and Cochrane Collaboration from 1966 through October 2008, with key search terms *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*. Language limits were set to include only English-language articles. Research design for inclusion was limited only to RCTs with human subjects. Pertinent studies were cross-referenced to identify articles that met inclusion criteria but were not located during the original database search.

The search strategy is depicted in **FIGURE 1**. Searches from the databases identified 301 articles. Twelve RCTs met the inclusion criteria, while 289 studies were excluded based on title, abstract, or content. There were an additional 3 RCTs identified from the cross-referencing of a previous literature review,[3,17,18,22,32] a clinical practice guideline,[1] and a Cochrane-collaboration protocol,[15] for a total of 15 RCTs. Further assessment excluded 6 of the 15 RCTs; 1 did not have true randomization[16] and 5 studies did not present group means and standard deviations.[2,5] One additional RCT did not compare NMES to a comparable treatment.[21] Eight RCTs were ultimately included in our review. The details of these 8 RCTs are found in **TABLE 1** and **TABLE 2**.

Selection Criteria

RCTs were initially included for assessment if they evaluated the effects of rehabilitation programs that utilized NMES in isolation (or in combination with exercise) following ACL reconstruction upon the variables of interest, which were quadriceps strength, self-reported function, or functional performance. Included studies had to report means, standard deviations, and sample sizes to allow for calculation of Cohen's *d* ES and 95% CI. The RCTs included were required to describe a com-

TABLE 2 Summary of Neuromuscular Electrical Stimulation Treatment Parameters

Author	Frequency	Pulse Width	Duty Cycle	Intensity	Treatment Course* (Duration)	Treatment Sessions†	Follow-up Time‡
Sisk[25]	40 Hz	300 μs	10 s on, 30 s off	MTL	1st-6th wk (6 wk)	38	7th wk
Delitto[6]	50 Hz	400 μs	15 s on, 50 s off	MTL	2nd or 3rd-6th wk (3 wk)	15	6th wk
Wigerstad-Lossing[31]	30 Hz	300 μs	6 s on, 10 s off	65-100 mA	1st-6th wk (6 wk)	18	6th wk
Draper[7]	35 Hz	N/A	10 s on, 20 s off	MTL <50 mA	1st-6th wk (6 wk)	105	6th wk
Snyder-Mackler[28]	75 Hz	400 μs	15 s on, 50 s off	MTL	3rd-6th wk (4 wk)	12	6th wk
Paternostro[20]	30 Hz	200 μs	5 s on, 15 s off	MTL	1st -6th wk (6 wk)	38	6th wk
Ross[24]	50 Hz	200 μs	15 s on, 35 s off	MTL	1st-6th wk (6 wk)	26	6th wk
Fitzgerald[9]	75 Hz	400 μs	10 s on, 50 s off	MTL	3rd-14th wk (11 wk)	21	12th-16th wk

Abbreviations: Hz, hertz; MTL, maximally tolerated level; N/A, not available.
** Start and end of treatment in the postoperative weeks.*
† Estimated number of treatment sessions (treatments a week multiplied by the number of weeks).
‡ Time point after anterior cruciate ligament reconstruction when outcome measures were taken.

parison group that did not receive NMES but performed quadriceps strengthening exercises in isolation (or in combination with other treatment, such as biofeedback using electromyography).

Assessment of Methodological Quality

The quality of each study included was independently assessed by 2 reviewers using the Physiotherapy Evidence Database (PEDro)[14] scale, which is based on a 0- to 10-point scale, with the higher scores reflecting higher-quality studies.

Data Extraction

Two reviewers independently performed the data extraction with regard to study design, intervention, and baseline and outcome measures using standardized forms. One reviewer was a physical therapist with 11 years of clinical experience and the other was an athletic trainer with 4 years of clinical experience. Both were equally trained in assessing quality of evidence using PEDro criteria in a postgraduate doctoral program. Outcomes of interest were quadriceps strength, as expressed by isometric or isokinetic torque, functional test performance, as expressed by a score on a clinically reproducible functional test of the lower extremity, and self-reported lower extremity function, as quantified by a questionnaire completed by the patient. Following independent review of RCTs, both reviewers discussed and verified results. Disagreements were openly discussed and resolved, with any remaining disagreements further discussed with 2 other experienced authors involved in the review process. Finally, the parameters of NMES treatment were collected from each RCT and summarized. In addition, NMES treatment volume, duration, and follow-up times were estimated for each study. Treatment volume was estimated by multiplying the number of treatment sessions over the entire course by the number of treatments per week. The treatment duration included the start and end of treatment in the postoperative weeks, and follow-up times for the outcome measurements were identified in the time point following ACL reconstruction at which outcome measures were taken following the treatment course.

Data Analysis

To evaluate the rehabilitative effects of NMES on quadriceps strength, self-reported function, and functional performance, Cohen's *d* ES and 95% CI (based upon pooled standard deviations) were calculated between the outcome measures of the NMES training group and the control group at each reported follow-up period. The strength of ES was interpreted using the guidelines described by Cohen,[4] with values less than 0.2 interpreted as weak, from 0.21 to 0.8 as moderate, and more than 0.8 as strong. No meta-analysis was performed due to the heterogeneity of the quadriceps strength outcomes measurement method (isokinetic versus isometric), variable treatment parameters utilized, and variable treatment durations. Data regarding functional performance and self-reported outcomes were selected from 1 RCT, respectively, and thus could not be pooled.

RESULTS

PEDro Score

The 8 RCTs included in this systematic literature review had a mean PEDro score of 4.3, with a range of 3 to 6 and a mode of 4 (**TABLE 1**). The authors were blinded to the scores posted on the PEDro database prior to scoring of the included RCTs. All RCTs had random allocation to treatment group, whereas none of them concealed the allocation. Only 1 RCT[31] had baseline data from patients prior to their ACL reconstruction included in the study. Two RCTs[8,19] used blinded assessors, while no RCTs blinded subjects and therapists. All RCTs reported outcome measures for between-group comparisons with measures of variability.

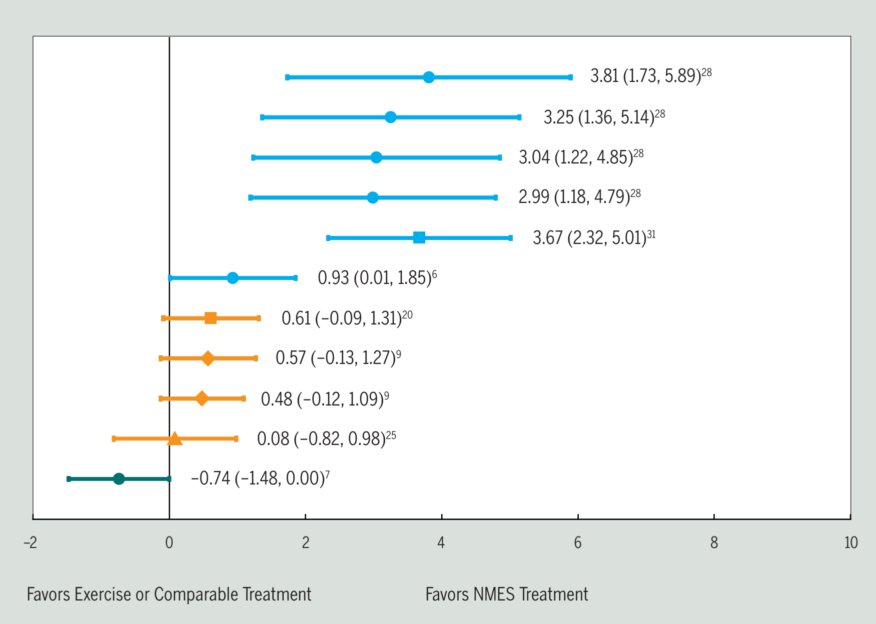

FIGURE 2. Isometric and isokinetic knee extension strength outcomes. Data are effect sizes calculated from group differences, and their 95% confidence intervals in parentheses. The corresponding study reference number is indicated next to the parentheses. Abbreviation: NMES, neuromuscular electrical stimulation.

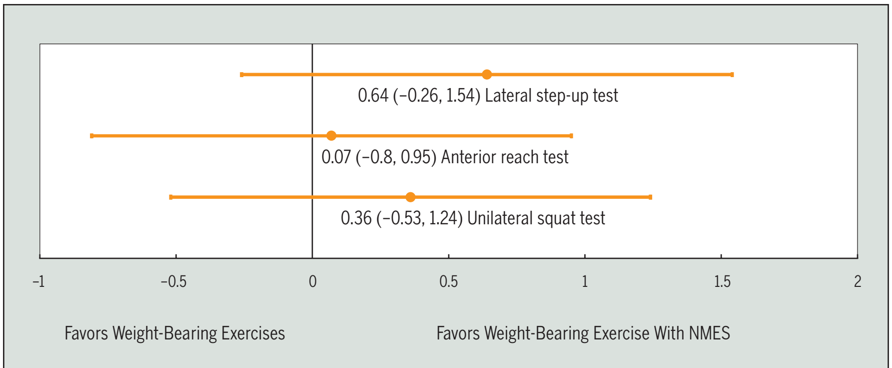

FIGURE 3. Functional performance test outcomes. Data are effect sizes calculated from group differences and corresponding 95% confidence intervals from Ross et al.[24] Abbreviation: NMES, neuromuscular electrical stimulation.

Treatment Parameters

Treatment parameters and follow-up times were collected from 8 RCTs, including NMES parameters and treatment duration and number of sessions (**TABLE 1**). Each RCT presented a variety of variables in terms of NMES parameters. The major parameters associated with NMES, such as frequency, phase duration, duty cycle, and intensity, were consistently reported. Most studies used a similar subjective level of treatment intensity that was set at the patient's maximally tolerated level, whereas 1 study[31] used an objective quantifiable measure of intensity as expressed as a percentage of maximal voluntary isometric contraction of the uninjured limb. Overall, there was no consistent parameter set up for NMES across all RCTs.

The treatment duration for all 8 RCTs ranged from 3 to 11 weeks, with a mean of 6 weeks. One RCT[9] extended the treatment up to the 14th postoperative week. The number of treatment sessions over the entire course ranged from 12 to 105 sessions, with a mean of 34. One RCT[7] had substantially more treatment sessions (105) than the other RCTs (mean, 24 sessions). Most RCTs had 1 follow-up for outcome measures, which occurred immediately after the end of the treatment course.

Strength Outcomes

ESs for quadriceps strength outcomes were obtained from 7 of 8 RCTs[6,7,9,20,24,28,31] and consisted of 11 between-group comparisons (NMES alone or NMES in combination with exercise versus exercise alone or in combination with another treatment) shown in **FIGURE 2**. Six of the 11 comparisons (55%), representing the results from 3 studies,[6,28,31] had mean differences and 95% CIs that favored NMES treatment over comparable treatments. Four of the 11 comparisons (36%), representing the results from 3 studies,[9,20,25] demonstrated equivocal results, with 95% CIs crossing zero; however, the ES point estimates favored NMES therapy in all 4 comparisons. Lastly, 1 comparison[7] (9%) favored the comparable treatment of electromyography biofeedback training over NMES.[7] The ES analysis findings revealed an equal to moderate effect of NMES upon quadriceps muscle strength as compared to exercise alone.

Functional Test Outcomes

ESs for functional test outcomes were calculated from 1 RCT. Ross et al[24] reported outcomes on 3 functional tests between 2 groups (n = 10 subjects each) that performed weight-bearing exercise versus weight-bearing exercise plus NMES. The tests included the lateral step-up, anterior reach, and unilateral squat. Point estimates for the ESs all were measured in favor of the group receiving NMES (**FIGURE 3**) versus the weight-bearing exercise group. The ESs for the lateral step-up, anterior reach, and unilateral squat tests were 0.64 (95% CI: −0.26, 1.54), 0.07 (−0.8, 0.95), and 0.36 (−0.53, 1.24), respectively, indicating inconclusive effects of NMES on these particular test outcomes.

Self-reported Functional Outcomes

Patient self-reported outcomes were presented in 1 RCT. Fitzgerald et al[9] presented data from the Knee Outcome Survey activities of daily living scale at 12 and 16 weeks following ACL reconstruction. This outcomes instrument is a 14-item questionnaire that assesses general daily activities and how a patient's knee condition affects the ability to perform various functional tasks. A significant shift favoring NMES was shown in this study, and ES results are shown in **FIGURE 4**. The effect size was 0.72 (95% CI: 0.10, 1.34) for the 12-week comparison and 0.66 (95% CI: 0.04, 1.27) for the 16-week comparison, indicating a moderate effect favoring a 4-week NMES treatment regimen.

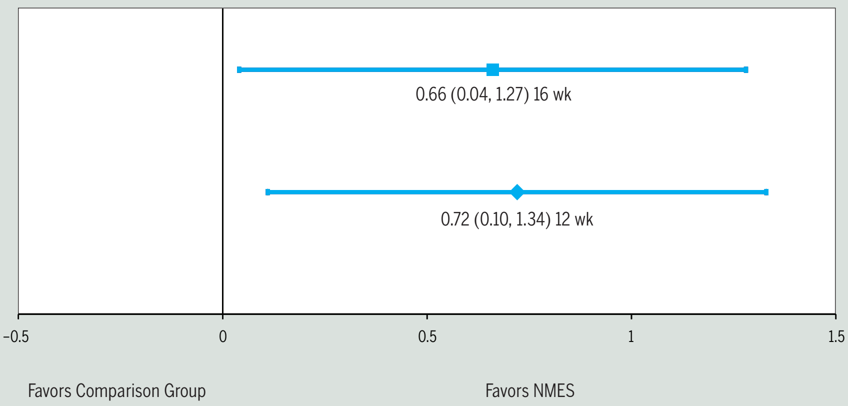

FIGURE 4. Self-reported function outcomes (Knee Outcome Survey activities of daily living scale). Data are effect sizes calculated from group differences and corresponding 95% confidence intervals from Fitzgerald et al.[9] Abbreviation: NMES, neuromuscular electrical stimulation.

DISCUSSION

In patients recovering from ACL reconstruction, NMES in conjunction with exercise may be more effective in improving quadriceps strength than exercise alone, whereas its effects on patient-oriented outcomes and tests of functional performance are inconclusive. Considerable inconsistencies were noted in the NMES parameter and application techniques across trials.

Strength Outcomes

Based on the literature, we determined that NMES in combination with exercise, compared to exercise alone or in combination with electromyographic biofeedback, results in equal to moderately greater quadriceps strength recovery after ACL reconstruction. These conclusions are similar to those of previous literature reviews by Palmieri-Smith et al[19] and Bax et al,[3] who indicated that NMES with exercise is more effective than exercise alone in improving isometric knee extension strength. Wright et al[32] agreed that NMES could be successful in improving quadriceps strength when applied early in the postoperative rehabilitation period; however, it is not completely necessary for a successful recovery from ACL reconstruction. The results of the quadriceps strength ES analysis, combined with the results of previous reviews,[3,19,22,32] suggest that the incorporation of NMES treatment along with exercise is warranted in the treatment of patients recovering from ACL reconstruction and treatment should be initiated within the first week and continued through at least the fourth postoperative week. The 3 RCTs,[6,28,31] which found clear strength increases with NMES, also reported the fewest number of treatment sessions (12-18 sessions) of all the included RCTs in the present review. This consistent recommendation regarding quadriceps strength and NMES across the present systematic review and 3 previous reviews[3,19,32] strongly suggests that future research to develop a clinical guideline for the utilization of NMES following ACL reconstruction is warranted.

Quadriceps strength outcomes were deemed inconclusive in 3 RCTs,[7,20,25] which had ES point estimates favoring NMES but 95% CIs that crossed zero. Interestingly, all of these studies used patient self-treatment and battery-operated portable NMES stimulators that delivered low-levels of electrical stimulation. The Philadelphia Panel[1] concluded that no recommendations could be made on the effectiveness of NMES in the treatment of quadriceps weakness and stated that there is insufficient evidence surrounding this treatment to justify a clinical practice guideline. Draper et al[7] observed that NMES produced inferior strength results compared to electromyographic biofeedback training. The difference between the NMES and electromyographic biofeedback groups was believed to be due to work effort and overall training intensity, which favored electromyographic biofeedback. Sisk et al[25] reported that NMES may not provide any additive benefit to exercise alone when prolonged treatment is utilized during a period of cast immobilization. Paternostro-Sluga et al[20] also found no significant differences between an NMES group and an exercise group. This lack of difference was attributed to high preoperative strength of both groups, a short immobilization period, and an intensive postoperative rehabilitation regimen. Risberg et al[22] believed that the wide variability in results across trials using NMES was likely due to the variety of parameters utilized across those trials, a point which the current review supports. From this evidence, it appears that multiple factors which include a patient self-treatment regimen with a portable NMES stimulator may not provide benefits in quadriceps strength outcomes following ACL reconstruction. The intensity of stimulation with a battery-operated stimulator, as well as patient compliance, raises questions on the effectiveness of home NMES units in the treatment of postoperative quadriceps weakness. Overall, 3 studies[6,28,31] that favored NMES for quadriceps strength outcomes had, relatively, the shortest treatment durations (mean, 4.3 weeks) and number of sessions (mean, 15). However, an increase in treatment volume may not result in improved quadriceps strength. One study[7] favoring electromyographic biofeedback over NMES had substantially more treatment sessions (105) than those of the other 3 studies[9,20,25] (average, 33 sessions), all of which were inconclusive on the effectiveness of NMES.

Functional Test Outcomes

NMES appears to result in no added benefit to weight-bearing exercise for functional performance tests in patients post-ACL reconstruction. Only 1 RCT[24] reported outcomes of functional test scores using the anterior reach, unilateral squat, and lateral step-up tests. Other investigators have used hop and triple-hop tests as measures of functional outcomes following ACL reconstruction and found significant differences attributed to graft selection, with patients receiving semitendinosus grafts performing better than those receiving bone-patellar tendon-bone grafts.[11] All 20 subjects of the study by Ross et al[24] were treated with a bone-patellar tendon-bone graft. Ernst et al[8] reported that patients at a mean of 9.8 months post-ACL reconstruction demonstrated significant lower extremity compensations from persistent quadriceps weakness during the lateral step-up and vertical jump tests. Hence, the results from Ross et al[24] may be attributed to either test selection, graft types, or early onset of compensatory muscle strategies that could reduce group differences (and improve functional performance) between patients who receive either NMES or perform weight-bearing exercises alone. Fitzgerald et al[9] noted that a significantly greater proportion of patients in the NMES group were able to progress to agility training after 16 weeks of rehabilitation, as compared to the comparison group at the same point in time, which suggests that NMES may affect return to high-level activity following ACL reconstruction.[9] The single RCT (PEDro score of 3) included in the present review does not provide sufficient evidence to indicate that NMES treatment has a positive or negative impact upon functional performance tests used in patients post-ACL reconstruction. The lack of high-quality RCTs reporting on functional performance following ACL reconstruction negatively impacts this aspect of the current review by restricting the ability to make definitive claims on the ability of NMES to impact functional performance. Further research is warranted to determine the ability of NMES to affect this outcome variable.

Self-Reported Functional Outcomes

NMES treatment appears to have a moderate effect upon patient self-reported function versus comparable treatment. Fitzgerald et al[9] published the only RCT that reported patient outcomes using a self-report questionnaire like the Knee Outcome Survey activities of daily living scale. These ESs were moderate at both 12 and 16 weeks postsurgery. This study was 1 of 2 included RCTs that had blinded assessors at follow-up and 1 of 5 that utilized an intention-to-treat analysis. A PEDro score of 6 established this study as the most methodologically sound RCT included in our review. Thus patients post-ACL reconstruction who received NMES for 4 weeks reported significantly better Knee Outcome Survey activities of daily living scale scores at 12 and 16 week postsurgery. NMES may be beneficial for improving self-report of function in this population, but further research is needed in this area to draw more definitive conclusions. Patient-oriented outcomes are a key facet of evidence-based practice and clinicians require this information to be included in a larger amount of RCTs to independently judge the efficacy of NMES.[17]

Treatment Parameters

This review revealed inconsistencies in the NMES parameter selection and application of NMES across all RCTs reviewed. Differences in treatment times, duration, frequency of stimulation, type of stimulator used (portable versus clinical stimulator), and duty cycle existed across most of the RCTs. High-intensity electrical stimulation may be the most beneficial,[22] particularly when administered shortly after surgery[32]; however, other reports suggest that stimulation at the 50- to 80-Hz frequency may result in fatigue and patient discomfort and limit the benefits of NMES.[21,29] Gorgey et al[10] also studied the effects of NMES pulse duration and stimulation duration on joint torque output and compared 2 different treatment protocols. He suggested that the protocol with the longer pulse duration (450 microseconds versus 250 microseconds) resulted in 38% higher normalized knee extensor torque. However, this study reported a confounding effect of the frequency of stimulation. Ward et al[29] suggested that stimulation parameters (particularly the popular 2.5-kHz frequency) commonly used for muscle strengthening are suboptimal for achieving their stated goals. He further indicated that current treatment regimens came about in spite of equivocal evidence as to their effectiveness. Ward et al[30] investigated the optimal electrical parameters to yield maximum electrically induced torque and found that 1.0- to 2.5-kHz frequency, with burst duration of 2 milliseconds (10% duty cycle), elicited the highest maximum electrically induced torque in wrist extensors of healthy volunteers. Minimum discomfort was noted at 4-kHz and 4-millisecond burst duration. The clinical recommendation from those results is that a stimulus waveform of 1.0- to 2.5-kHz frequency alternating current, with a 2- to 4-millisecond burst, may yield the best torque output with the least patient discomfort. These findings from Gorgey et al[9] and Ward et al[30] provide information for future clinical trials that investigate the NMES parameters balancing both patient comfort with knee extensor torque output. However, the inconsistencies with NMES parameter selection remain, and the currently available evidence prevents a specific clinical recommendation for use of NMES in patients following ACL reconstruction from being made.

Recommendations

The present review suggests that the use of NMES in patients post-ACL reconstruction is warranted to yield a positive effect upon quadriceps strength based on the level of evidence grade 2b from the Strength of Recommendation Taxonomy criteria. Compared to exercise alone or electromyographic biofeedback, NMES may result in equal to moderately positive effects on quadriceps strength during the first 4 weeks postoperatively; however, variation in NMES application across studies, the low quality of RCTs, and a failure to conceal allocation may blunt the true effect of NMES or overestimate the results. The best evidence suggests that 4 weeks of NMES using a clinical stimulator in conjunction with exercise therapy can result in a moderate effect in self-reported patient outcomes at 12 to 16 weeks postoperatively and is recommended for inclusion into postoperative ACL reconstruction rehabilitation. There is no evidence to conclude that NMES has an effect on functional performance when measured by the anterior reach, lateral step-up, and unilateral squat tests; however, compensatory lower extremity movement strategies have been observed in patients post-ACL reconstruction, which may require further studies using additional or different outcome measures. There is sufficient evidence to show that a wide variability in the clinical application of NMES can limit the interpretation of the available literature to either support or refute the use of NMES.

Future clinical trials using NMES should utilize the PEDro criteria as a method to improve the quality of clinical research. The RCTs included in the present review suffered from poor quality, which makes it difficult to accurately interpret the data and make definitive conclusions. Future trials should obtain baseline preoperative knee extensor torque data, self-reported function, and functional performance test scores. Clinicians assessing outcomes should be blinded to group assignment, and all point estimates and measures of variability should be included in the results. The maximum PEDro possible score for a RCT involving NMES is estimated to be 8 out of 10, as the treating therapist and subjects would be difficult to blind due to the nature of the treatment.

CONCLUSION

The present review supports the use of NMES in conjunction with exercise during the first 4 weeks following ACL reconstruction to improve quadriceps strength. The effectiveness of NMES on quadriceps strength was observed with lower treatment volumes and fewer sessions, an observation that should warrant further study into the cost-effectiveness of NMES treatment. Conclusions regarding self-reported outcomes cannot definitively be made, but the limited existing data suggest that there may be at least a trivial effect to, at best, a clinically meaningful benefit on patient-oriented outcomes on the Knee Outcome Survey. The effect of NMES upon functional performance is unconvincing, and the imprecision in the limited reported results suggest that a clinically meaningful benefit may or may not exist based upon both the ES point estimates and the width of 95% CIs. Moreover, methodological flaws and suboptimal parameter selection is likely to have impacted the results of the RCTs included in this review. Recommendations are given for future clinical trials to improve methodological quality and NMES treatment parameter consistency. Further recommendations are made for development of clinical practice guidelines in the application of NMES following ACL reconstruction. ◉

REFERENCES

1. Albright J, Allman R, Bonfiglio RP, et al. Philadelphia Panel evidence-based clinical practice guidelines on selected rehabilitation interventions for knee pain. *Phys Ther*. 2001;81:1675-1700.
2. Anderson AF, Lipscomb AB. Analysis of rehabilitation techniques after anterior cruciate reconstruction. *Am J Sports Med*. 1989;17:154-160.
3. Bax L, Staes F, Verhagen A. Does neuromuscular electrical stimulation strengthen the quadriceps femoris? A systematic review of randomised controlled trials. *Sports Med*. 2005;35:191-212.
4. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
5. Currier DP, Mann R. Muscular strength development by electrical stimulation in healthy individuals. *Phys Ther*. 1983;63:915-921.
6. Delitto A, Rose SJ, McKowen JM, Lehman RC, Thomas JA, Shively RA. Electrical stimulation versus voluntary exercise in strengthening thigh musculature after anterior cruciate ligament surgery. *Phys Ther*. 1988;68:660-663.
7. Draper V, Ballard L. Electrical stimulation versus electromyographic biofeedback in the recovery of quadriceps femoris muscle function following anterior cruciate ligament surgery. *Phys Ther*. 1991;71:455-461; discussion 461-454.
8. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther*. 2000;80:251-260.
9. Fitzgerald GK, Piva SR, Irrgang JJ. A modified neuromuscular electrical stimulation protocol for quadriceps strength training following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2003;33:492-501.
10. Gorgey AS, Dudley GA. The role of pulse duration and stimulation duration in maximizing the normalized torque during neuromuscular electrical stimulation. *J Orthop Sports Phys Ther*. 2008;38:508-516. http://dx.doi.org/10.2519/jospt.2008.2734
11. Keays SL, Bullock-Saxton JE, Keays AC, Newcombe PA, Bullock MI. A 6-year follow-up of the effect of graft site on strength, stability, range of motion, function, and joint degeneration after anterior cruciate ligament reconstruction: patellar tendon versus semitendinosus and Gracilis tendon graft. *Am J Sports Med*. 2007;35:729-739. http://dx.doi.org/10.1177/0363546506298277
12. Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon)*. 2002;17:56-63.
13. Lieber RL, Silva PD, Daniel DM. Equal effectiveness of electrical and volitional strength training for quadriceps femoris muscles after anterior cruciate ligament surgery. *J Orthop*

Res. 1996;14:131-138. http://dx.doi.org/10.1002/jor.1100140121
14. Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. Reliability of the PEDro scale for rating quality of randomized controlled trials. *Phys Ther*. 2003;83:713-721.
15. Mizusaki IA, Almeida GJM, Atallah AN, Peccin MS, Cohen M, Soares B. Electrical stimulation for rehabilitation after soft-tissue injury of the knee in adults (protocol). *Cochrane Database Syst Rev*. 2005;(4). http://dx.doi.org/10.1002/14651858.CD001826.pub2.
16. Morrissey MC, Brewster CE, Shields CL, Jr., Brown M. The effects of electrical stimulation on the quadriceps during postoperative knee immobilization. *Am J Sports Med*. 1985;13:40-45.
17. Noteboom JT, Allison SC, Cleland JA, Whitman JM. A primer on selected aspects of evidence-based practice to questions of treatment. Part 2: interpreting results, application to clinical practice, and self-evaluation. *J Orthop Sports Phys Ther*. 2008;38:485-501. http://dx.doi.org/10.2519/jospt.2008.2725
18. Paillard T. Combined application of neuromuscular electrical stimulation and voluntary muscular contractions. *Sports Med*. 2008;38:161-177.
19. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. *Clin Sports Med*. 2008;27:405-424, vii-ix. http://dx.doi.org/10.1016/j.csm.2008.02.001
20. Paternostro-Sluga T, Fialka C, Alacamliogliu Y, Saradeth T, Fialka-Moser V. Neuromuscular electrical stimulation after anterior cruciate ligament surgery. *Clin Orthop Relat Res*. 1999;166-175.
21. Rebai H, Barra V, Laborde A, Bonny JM, Poumarat G, Coudert J. Effects of two electrical stimulation frequencies in thigh muscle after knee surgery. *Int J Sports Med*. 2002;23:604-609. http://dx.doi.org/10.1055/s-2002-35525
22. Risberg MA, Lewek M, Snyder-Mackler L. A systematic review of evidence for anterior cruciate ligament rehabilitation: how much and what type? *Phys Ther Sport*. 2004;5:125-145.
23. Rosenberg TD, Franklin JL, Baldwin GN, Nelson KA. Extensor mechanism function after patellar tendon graft harvest for anterior cruciate ligament reconstruction. *Am J Sports Med*. 1992;20:519-525; discussion 525-516.
24. Ross M. The effect of neuromuscular electrical stimulation during closed kinetic chain exercise on lower extremity performance following anterior cruciate ligament reconstruction. *Res Sports Med*. 2000;9:239-251.
25. Sisk TD, Stralka SW, Deering MB, Griffin JW. Effect of electrical stimulation on quadriceps strength after reconstructive surgery of the anterior cruciate ligament. *Am J Sports Med*. 1987;15:215-220.
26. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg Am*. 1995;77:1166-1173.
27. Snyder-Mackler L, Delitto A, Stralka SW, Bailey SL. Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. *Phys Ther*. 1994;74:901-907.
28. Snyder-Mackler L, Ladin Z, Schepsis AA, Young JC. Electrical stimulation of the thigh muscles after reconstruction of the anterior cruciate ligament. Effects of electrically elicited contraction of the quadriceps femoris and hamstring muscles on gait and on strength of the thigh muscles. *J Bone Joint Surg Am*. 1991;73:1025-1036.
29. Ward AR. Electrical stimulation using kilohertz-frequency alternating current. *Phys Ther*. 2009;89:181-190. http://dx.doi.org/10.2522/ptj.20080060
30. Ward AR, Robertson VJ, Ioannou H. The effect of duty cycle and frequency on muscle torque production using kilohertz frequency range alternating current. *Med Eng Phys*. 2004;26:569-579. http://dx.doi.org/10.1016/j.medengphy.2004.04.007
31. Wigerstad-Lossing I, Grimby G, Jonsson T, Morelli B, Peterson L, Renstrom P. Effects of electrical muscle stimulation combined with voluntary contractions after knee ligament surgery. *Med Sci Sports Exerc*. 1988;20:93-98.
32. Wright RW, Preston E, Fleming BC, et al. A systematic review of anterior cruciate ligament reconstruction rehabilitation: part II: open versus closed kinetic chain exercises, neuromuscular electrical stimulation, accelerated rehabilitation, and miscellaneous topics. *J Knee Surg*. 2008;21:225-234.