A Modified Neuromuscular Electrical Stimulation Protocol for Quadriceps Strength Training Following Anterior Cruciate Ligament Reconstruction

G. Kelley Fitzgerald, PT, PhD, OCS[1]
Sara R. Piva, PT, MS, OCS, FAAOMPT[2]
James J. Irrgang, PT, PhD, ATC[1]

Study Design: Randomized clinical trial, single-masked.
Objectives: To determine the effectiveness of using a modified neuromuscular electrical stimulation (NMES) training program as an adjunct treatment for improving quadriceps strength and physical function in rehabilitation following anterior cruciate ligament reconstruction (ACLR).
Background: NMES training for quadriceps strengthening has previously been shown to be an effective adjunct treatment following ACLR when performed against isometric resistance using a dynamometer with the knee positioned in flexion. We developed a modified version of published NMES protocol because some patients have difficulty tolerating the existing protocol and many clinics may not have instrumented dynamometers. There is a need to determine the effectiveness of this modified protocol.
Methods and Measures: Forty-three subjects who had undergone ACLR were randomly assigned to either a group that received (NMES group) or did not receive (comparison group) the NMES treatment in conjunction with their rehabilitation. Group means for quadriceps strength and self-reported measures of knee function were compared after 12 and 16 weeks of rehabilitation. The proportion of subjects in each group achieving clinical criteria to initiate ambulation without crutches, treadmill running, and agility training at selected times during rehabilitation were also compared.
Results: The NMES group demonstrated moderately greater quadriceps strength at 12 weeks (effect size, 0.48), and moderately higher levels of self-reported knee function at both 12 (effect size, 0.72) and 16 (effect size, 0.65) weeks of rehabilitation compared to the comparison group. A greater proportion of subjects in the NMES group achieved clinical criteria for advancing to agility training at 16 weeks.
Conclusions: The modified NMES quadriceps training protocol can be a useful adjunct to ACLR rehabilitation programs, but the treatment effect is smaller than what has been reported in previous studies. *J Orthop Sports Phys Ther* 2003;33:492-501.

Key Words: *ACL, clinical trial, knee, strengthening, training*

Neuromuscular electrical stimulation (NMES) has been recommended as an adjunct treatment for strengthening the quadriceps femoris muscle following anterior cruciate ligament reconstruction (ACLR).[4,8,13,19-21] Studies that have shown NMES to be effective in improving quadriceps strength following ACLR have typically utilized a protocol that included a 2500-Hz alternating current (AC), time-modulated to bursts of pulses applied at intensities that induced at least 50% of maximum voluntary isometric torque. A typical contraction time was 10 seconds followed by 50 seconds relaxation, and each session induced 10 to 15 contractions.[4,19,20] Subjects in these studies were seated in a chair connected to a dynamometer with the knee positioned in approximately 60° to 85° of flexion so that quadriceps torque could be monitored during the NMES treatment. The results of these studies indicated that use of this type of NMES protocol, combined with voluntary exercise, yielded greater gains in quadriceps strength and functional ability than voluntary exercise alone.[4,19,20]

[1] *Assistant Professor, Department of Physical Therapy, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh, PA.*
[2] *Doctoral Candidate, Department of Physical Therapy, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh, PA.*
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Send correspondence to G. Kelley Fitzgerald, Department of Physical Therapy, University of Pittsburgh, 6035 Forbes Tower, Pittsburgh, PA, 15260. E-mail: kfitzger@pitt.edu.

Recently, we developed a modified version of the published NMES protocol because some patients who had undergone patellar tendon autograft ACLR had reported patellar donor site pain during forceful, electrically stimulated quadriceps contractions at high flexion angles. Recent data from cadaveric specimens have shown that strain on the patella, from which the middle one-third of the patellar tendon autograft has been harvested, increases with increased knee flexion angle during isometric loading of the quadriceps.[18] Based on these data, we hypothesized that performing the NMES protocol with the knee in extension might reduce patellar discomfort for these patients by reducing the strain on the patella.

We had considered continued use of the dynamometer to set a stimulus dosage based on quadriceps torque generated during treatment, by simply reducing the amount of knee flexion to 45° or 30°. Although this would have reduced the risk of strain on the patella, it may have increased the risk of strain on the healing ACL graft.[1,2,10,22] Therefore, we elected to position the knee in full extension without isometric resistance being applied to the distal tibia.

Because we no longer were using a dynamometer, we were unable to use a torque-output criterion for setting the amplitude of the electrical stimulus as a percent of maximum voluntary torque. Therefore, our second modification was related to selecting the stimulus amplitude. We increased stimulation amplitude so that at a minimum it would result in a full tetanic contraction of the quadriceps (no fasciculations observed on visual inspection) with evidence of a superior patellar glide, based on visual inspection and palpation. We then continued to increase the stimulus amplitude to the patient's maximum tolerance level.

Some additional benefits to the modifications we have described above are that it would allow for an alternative treatment setup for therapists who practice in facilities that do not have access to a dynamometer, and treatment setup time would be reduced as the patient would not have to be positioned on a dynamometer prior to treatment. Once modified, the efficacy of the protocol needed to be tested. Therefore, the purpose of this study was to determine the effectiveness of using the modified NMES training program as an adjunct to rehabilitation following ACLR. We hypothesized that subjects receiving the modified NMES training program would demonstrate greater quadriceps strength and higher self-reported ratings of knee function compared to subjects who did not receive the NMES training in conjunction with their postoperative rehabilitation following ACLR.

METHODS

Subjects

Individuals 14 years of age or older who were referred by their surgeon to our facility for rehabilitation following ACLR were eligible to participate as subjects in our study. Subjects were excluded from participation if they had undergone surgical repair of the meniscus or other knee ligaments concomitant with the ACLR. Subjects were also excluded if they had initiated rehabilitation at another facility prior to their first physical therapy session at our facility. All subjects signed a written informed consent form that was approved by the University of Pittsburgh Institutional Review Board prior to participation in the study.

Forty-eight subjects were enrolled in the study. Five subjects were eliminated from the final data analysis. Four of these subjects did not return to physical therapy for treatment shortly after enrollment in the study and did not respond to attempts to include them in the testing procedures. Therefore, we did not have data for these subjects. One subject signed the informed consent form, but before being randomly assigned to a treatment group, it was determined that this individual had received a meniscal repair concomitant with the ACLR and the subject was subsequently excluded from participation in the study. A total of 43 subjects completed the study. Table 1 provides a description of subject characteristics.

Treatment Groups

Subjects were randomly assigned to a group that either received NMES (NMES group) or did not receive NMES (comparison group) in conjunction with rehabilitation following ACLR. Subjects in both groups received the same basic rehabilitation program that is described below. Subjects in both groups received 2 treatment sessions per week. The average number (± SD) of weeks of therapy was 10.9 ± 3.6 for the NMES group and 10.6 ± 3.6 for the comparison group.

Rehabilitation Program Following ACLR Because (1) individual patients will vary to some extent with regard to postoperative healing rate and tolerance for rehabilitation activities and (2) the NMES treatment was considered an adjunct to the overall treatment plan, we did not strictly control the basic rehabilitation program. We allowed therapists who treated subjects in the study to progress rehabilitation according to their own judgments. However, prior to initiating the study, we established guidelines for content and progression of the basic rehabilitation program with the treating therapists. Details of the content and progression of the basic rehabilitation program

TABLE 1. Subject characteristics (mean ± SD) for the group receiving neuromuscular electrical stimulation (NMES) and the comparison group.

	NMES Group (n = 21)	Comparison Group (n = 22)	*P* value
Sex			.66
Male	n = 12	n = 14	
Female	n = 9	n = 8	
Age (y)	29.2 ± 10.1	31.9 ± 10.9	.40
Height (cm)	172.8 ± 10.3	170.6 ± 10.3	.49
Weight (kg)	81.4 ± 24.6	76.3 ± 15.7	.42
Type of surgery			.42
Patellar tendon autograft	n = 5	n = 5	
Hamstring autograft	n = 12	n = 9	
Allograft	n = 4	n = 8	
Time from surgery to initial physical therapy treatment (d)	12.2 ± 6.7	11.2 ± 3.7	.54
Presence of 5° or greater knee extensor lag	n = 10	n = 8	.46
Preinjury sports activity level*	2.9 ± 2.5	3.6 ± 2.9	.39
1 = strenuous, 4-7 times/wk	n = 11	n = 6	
2 = strenuous, 1-3 times/wk	n = 3	n = 8	
3 = strenuous, 1-3 times/mo			
4 = strenuous, <1 times/mo			
5 = moderate, 4-7 times/wk	n = 2	n = 1	
6 = moderate, 1-3 times/wk	n = 4	n = 3	
7 = moderate, 1-3 times/mo			
8 = moderate, <1 times/mo		n = 1	
9 = light, 4-7 times/wk	n = 1	n = 1	
10 = light, 1-3 times/wk		n = 1	
11 = light, 1-3 times/mo			
12 = light, <1 times/mo			

* Strenuous: activities such as football, soccer, and basketball; moderate: activities such as tennis and skiing; light: activities such as cycling, swimming, and golf.

are provided in the Appendix. The content areas included joint mobility, muscle performance training, progression of weight bearing and ambulation, balance training, and progression to running activities.

Joint mobility training included active range of motion, lower-extremity muscle flexibility exercises, patellofemoral mobilization techniques, and stationary cycling. Muscle performance training was initiated with isometric exercises for the quadriceps and hamstrings, active knee flexion and extension, and with straight-leg raises. These exercises were progressed to light resistance with cuff weights and then eventually to progressive resistance on exercise machines (see Appendix). Balance training was initiated with single-leg balance on a hard floor with progression to balance activities on a foam surface and mini-trampoline (see Appendix). Perturbation training techniques, as described by Fitzgerald et al,[5] were also incorporated into the balance training program when subjects were progressed to the single-leg balance training on the mini-trampoline.

Progression to running activities was not initiated until at least 12 weeks after surgery. To initiate running activities, subjects had to achieve the criteria for full weight-bearing ambulation (active knee flexion to 100°, no extensor lag on straight-leg raising, no pain on weight bearing) and quadriceps strength of the involved limb had to be at least 70% of the uninvolved limb, as measured during a maximum voluntary isometric torque test. Running activities were initiated on a treadmill. Our clinical experience has been that individuals recovering from ACLR are able to tolerate treadmill running better than track or road running when a running program is initiated. Recent evidence indicates that treadmill running may expose the lower extremity to less strain than track or road running,[14] which might explain our clinical observations. When subjects could tolerate 1 to 2 miles of running on the treadmill without pain, increased swelling, or complaints of giving way, they were progressed to running on a track or road. When subjects could tolerate 1 to 2 miles of running on a track or road without symptoms, and if their quadriceps strength was at least 80% of the uninvolved limb (as measured during a maximum voluntary isometric torque test), agility training techniques were added to the program.

NMES Training Program The subject was positioned in supine with the knee in full extension. Large (6.98×12.7 cm [2.75×5.00 in]) self-adhesive electrodes (Dura-Stick, Chattanooga Group, Inc., Hixson, TN) were placed over the vastus lateralis muscle proximally and the vastus medialis muscle distally. A VersaStim 380 medium-frequency neuromuscular

stimulator (Electro-Med Health Industries, Inc., Miami, FL) was used to provide the electrical stimulus during treatment. The stimulus characteristics used during the treatment were similar to those described by Snyder-Mackler et al,[19] and included a 2500-Hz alternating current (AC), time modulated to deliver 75 bursts per second, with a 2-second ramp-up and ramp-down time, a 10-second stimulation period at the maximum amplitude, followed by a 50-second rest period. The amplitude of the stimulus was set at an intensity that was high enough to produce a full, sustained, tetanic contraction of the quadriceps (no fasciculations observed on visual inspection) with visual and/or palpable evidence of superior glide of the patella. Once this was achieved, the stimulus intensity was increased further to maximum subject tolerance. Maximum tolerance was the maximum amount of discomfort under the electrode sites that the subject could tolerate during NMES. We instructed subjects to inform the therapist if they experienced knee or patellofemoral pain during the NMES, as this would also be a reason to reduce the intensity of the stimulus. However, no subjects complained of knee or patellofemoral pain during NMES. Subjects were not performing active voluntary muscle contractions when the maximum tolerable stimulus intensity was determined nor during application of the stimulus during treatment. Subjects were instructed to relax and allow the electrical stimulus to contract their muscles during treatment. Ten contractions were performed during a treatment session, resulting in a treatment time of approximately 11 to 12 minutes. This NMES treatment was performed twice a week at the time of the regularly scheduled physical therapy visit.

Treatment Outcome Measurements

Quadriceps Strength A maximum voluntary isometric torque test was used to determine quadriceps strength. Testing was performed at 12 weeks and 16 weeks following the initial physical therapy treatment. The examiner was masked to the subject's group assignment. Subjects were seated on an isokinetic dynamometer (Biodex System 3 Pro, Biodex Medical Systems, Inc., Shirley, NY) with the dynamometer force arm secured to the ankle. The knee was positioned in 60° of flexion, with the lateral femoral epicondyle aligned with the dynamometer's axis of rotation. A thigh strap, waist strap, and 2 chest straps were then secured to stabilize the patient in the dynamometer chair. Prior to recording quadriceps strength, subjects were given a series of practice trials to familiarize them with the testing procedure, and to provide a warm-up activity before testing. Subjects practiced producing voluntary isometric quadriceps contractions against the force arm of the dynamometer at 50%, 75%, and 100% of their perceived maximum voluntary effort.

During formal testing, subjects were asked to exert as much force as possible while extending the knee against the fixed force arm of the dynamometer. A torque target line was displayed on the computer monitor to provide subjects with visual feedback in an effort to maximize their ability to produce torque during the test. The torque target was placed at a torque level slightly greater than the peak torque produced during the practice maximum voluntary isometric contraction. If subjects exceeded this torque target during a given trial, the target was reset at a higher level for the next trial. Subjects performed 3 trials with a 2-minute rest between contractions. The maximum torque output of the 3 trials was recorded as the torque output for that limb. If the maximum output occurred on the third trial, additional trials were performed until the torque output decreased. Quadriceps strength was expressed as the quadriceps index, which was calculated as follows:

$$\frac{\text{maximum voluntary isometric torque output by the involved limb}}{\text{maximum voluntary isometric torque output by the uninvolved limb}} \times 100$$

Preliminary reliability testing in our laboratory indicated that this procedure yields reliable quadriceps femoris torque measurements. Intraclass correlation coefficients were 0.97 for test-retest reliability when repeated by the same person over a period of 1 to 3 days, and 0.82 for intertester reliability when repeated the same day.

Knee Outcome Survey—Activities of Daily Living Scale (ADLS) The ADLS was used as a patient self-report measure of function to determine the effect of the patient's knee condition on functional activities, which has been shown to be reliable and responsive to changes in functional status in patients with knee pathologies.[9] The ADLS is a 14-item scale that queries patients about how their knee symptoms affect their ability to perform general daily activities (6 items) as well as how their knee condition affects their ability to perform specific functional tasks (8 items). Each item is scored on a scale of 0 to 5 with 5 indicating ''no difficulty'' and 0 representing ''unable to perform.'' The highest possible score is 70. The scores of all items are summed, divided by 70, then multiplied by 100 to give an overall ADLS score. Higher ADLS scores reflect higher levels of functional ability. The ADLS was administered at the 12-week and 16-week test sessions.

Achievement of Clinical Milestones for Progressing Functional Activity The proportion of subjects in each group who achieved clinical milestones used at our facility for progressing to ambulation without crutches, treadmill running, or agility training at specified periods during rehabilitation was used as a measure of functional recovery. The milestones for progression to ambulation without crutches included full passive knee extension, absence of a knee exten-

TABLE 2. Twelve- and 16-week maximum isometric torque quadriceps (quad) indices, Activities of Daily Living Scale (ADLS) scores, and knee pain ratings. All values are mean ± SD.

	NMES* Group	Comparison Group
12-wk quad index†	75.9 ± 16.8	67.0 ± 19.9
16-wk quad index	83.1 ± 15.6	75.0 ± 17.8
12-wk ADLS†	89.2 ± 8.9	82.2 ± 10.4
16-wk ADLS†	91.5 ± 7.3	86.4 ± 8.2
12-wk knee pain rating	1.5 ± 1.9	1.2 ± 1.4
16-wk knee pain rating	0.9 ± 1.1	1.1 ± 1.2

* Neuromuscular electrical stimulation.
† Significant difference between groups, $P<.05$.

sor lag during a straight-leg raise against gravity, and the ability to ambulate without limping. Progression to running required all milestones for ambulation without assistive devices and a quadriceps index of at least 70%. Progression to agility training required patient tolerance of running for 1 to 2 miles without pain, swelling, or episodes of knee instability, and a quadriceps index of greater than 80%.

Knee Pain Ratings Numeric ratings of knee pain at the 12- and 16-week testing sessions were performed to account for the potential confounding effect of knee pain on treatment outcome. Subjects were asked to rate the greatest amount of knee pain they had experienced in the last 24 hours on a 0 to 10 numeric pain scale, with 0 representing ''no pain'' and 10 representing the ''worst pain imaginable.'' Numeric rating scales have been shown to be reliable and valid measures of pain.[11,12]

Data Management and Analysis

Demographic variables and other variables that may be potential confounders with treatment outcome were recorded. Group means and standard deviations were calculated for age, height, weight, time in days from the day of surgery to the initial physical therapy treatment, preinjury sports activity level, and 12- and 16-week knee pain ratings (see Tables 1 and 2). Group frequency counts were calculated for sex, type of graft used for ACLR, or the presence of a knee extensor lag at the time of enrollment into the study (see Table 1). A subject was considered to have an extensor lag if they demonstrated a 5° or greater limitation in active knee extension during a straight-leg raise maneuver, compared to the subject's range of passive knee extension, measured with a standard goniometer. Independent *t* tests were performed to determine if there were differences between groups on all continuous demographic and potential confounder variables. Chi-square analyses were performed to determine if there were differences between groups on frequency count data.

Group means and standard deviations were calculated for the 12- and 16-week quadriceps indices and ADLS scores. Frequency counts were calculated for the proportion of subjects in each group who met the criteria for progressing to ambulation without crutches at 4 weeks and 8 weeks following the initial physical therapy session (Table 3). Frequency counts were calculated for the proportion of subjects in each group who met the criteria for progressing to treadmill running at 12 weeks and 16 weeks (Table 4), and for progressing to agility training at 16 weeks (Table 5) following the initial physical therapy session.

An analysis of covariance (ANCOVA) was used to determine if there were group differences in the quadriceps indices at 12 and 16 weeks. Because the type of graft used to reconstruct the ACL can affect quadriceps torque output,[19] ACL graft type was used as a covariate in the ANCOVA. One-way analysis of variance (ANOVA) was used to determine if there were group differences in ADLS scores at 12 and 16 weeks. Chi-square analyses were used to determine if there were differences in the proportion of subjects in each group that met the clinical milestones for ambulation, treadmill running, and agility training. The significance level for all statistical tests was $P<.05$.

TABLE 3. Number of subjects achieving milestones for progressing to ambulation without crutches at 4 weeks and 8 weeks of rehabilitation.

	4 wk*		8 wk†	
	No	Yes	No	Yes
NMES‡ group	1	20	0	21
Comparison group	4	18	2	20

* Chi-square, 1.88 ($P>.05$).
† Chi-square, 2.00 ($P>.05$).
‡ Neuromuscular electrical stimulation.

TABLE 4. Number of subjects achieving milestones for progressing to treadmill running at 12 weeks and 16 weeks of rehabilitation.

	12 wk*		16 wk†	
	No	Yes	No	Yes
NMES‡ group	8	13	3	18
Comparison group	12	10	7	15

* Chi-square, 1.17 ($P>.05$).
† Chi-square, 1.85 ($P>.05$).
‡ Neuromuscular electrical stimulation.

We used an ''intention-to-treat'' approach to the data analyses.[6,7] According to this approach, subject data are analyzed according to randomization, meaning that if subjects cross over from the treatment to the control group, or they are not compliant with the experimental treatment, their data are still analyzed in the group to which they were originally randomized.[6,7] In addition, if there are missing data for a subject for a given test session, the missing data set is replaced by moving the last available score from the previous test session forward to the missing data set for that subject.[7] One subject refused to continue NMES treatment after 2 treatment sessions, but agreed to continue in the study and the data from this subject were included in the final analysis in the NMES group. Six subjects (3 subjects from each group) did not return for the 16-week testing session. Accordingly, we carried the scores from the 12-week testing over to the 16-week testing data and included these 6 subjects in the 16-week analysis.

RESULTS

There were no significant differences between groups with respect to age, sex, height, weight, preinjury physical activity level, time from surgery to the time of the first physical therapy treatment, or knee pain ratings at 12 and 16 weeks. There were also no differences between groups in the number of physical therapy treatments received (NMES group, 21.7 ± 7.3; comparison group, 21.3 ± 7.3 [P = .86]).

Means and standard deviations for quadriceps index and ADLS scores at 12 and 16 weeks are presented in Table 2. The NMES group demonstrated a higher 12-week quadriceps index compared to the comparison group ($P<.05$). Although the NMES group mean appeared higher for the 16-week quadriceps index, this difference did not achieve statistical significance (P = .06). The NMES group demonstrated significantly higher ADLS scores at both the 12- and 16-week test sessions ($P<.05$).

Frequency data to determine the proportion of subjects who met our clinical criteria to progress to ambulation without crutches, treadmill running, and agility training activities are provided in Tables 3, 4, and 5, respectively. There were no significant differences in the proportion of subjects in each group who met the clinical milestones for ambulation without crutches at 4 and 8 weeks of rehabilitation, or for treadmill running at 12 and 16 weeks of rehabilitation. A greater proportion of subjects in the NMES group achieved the clinical criteria to progress to agility training activities at 16 weeks compared to the comparison group ($P<.05$).

TABLE 5. Number of subjects achieving milestones for progressing to agility training at 16 weeks of rehabilitation.

	16 wk*	
	No	Yes
NMES‡ group	8	13
Comparison group	15	7

*Chi-square, 3.91 ($P<.05$).
‡ Neuromuscular electrical stimulation.

DISCUSSION

The results of our study indicate that subjects receiving the modified NMES treatment with their rehabilitation demonstrated greater quadriceps strength and higher ADLS scores than the comparison group that did not receive NMES. The estimated treatment effect size for quadriceps strength in our study was 0.48. The effect size was estimated by dividing the mean difference in quadriceps torque between the groups by the average standard deviation for the groups. According to convention, the estimated value of effect sizes are as follows: small, 0.20; medium, 0.50; and large, ≥0.80.[16] Our treatment effect size was modest compared to larger effect sizes that can be estimated from quadriceps knee extensor torque data provided in previous studies using NMES against isometric resistance applied via a dynamometer force arm with the knee in flexion.[4,21] The estimated effect sizes in these studies ranged from 1.9 to 5.5.[4,21] We have 2 possible explanations for this difference. The first is that our modified technique may not produce as much tension in the muscle during treatment when compared to the technique where the knee is in flexion and the torque produced during the NMES is monitored and set above a minimum criteria. We did not measure torque production during treatment in our study, however, it has been demonstrated that increased contraction inten-

sity produced during NMES treatment results in proportionally increased improvements in isometric strength.[3,17,20] Differences in contraction intensity between the 2 types of NMES applications could explain the differences in treatment effect sizes.

A second explanation for the difference in effect sizes between our study and previous studies may be related to the time of testing. Snyder-Mackler et al[21] compared group quadriceps strength after 4 weeks of training that occurred within 6 weeks of surgery. Similarly, Delitto et al[4] compared group quadriceps strength after 3 weeks of training that occurred within 6 weeks of surgery. In contrast, we did not measure group differences in quadriceps strength until after 12 weeks of training. After this duration of recovery time, the voluntary exercise program may have a better chance of making up some of the difference in restoring quadriceps torque output.

The difference in ADLS scores at 12 weeks and 16 weeks in favor of the NMES group can also be considered modest, with estimated treatment effect sizes being 0.72 and 0.65, respectively. The actual group mean differences were 7 points at 12 weeks and 5.1 points at 16 weeks. To put these differences into perspective, a 7-point difference in ADLS score could be represented by having slight difficulty with standing, walking, stair climbing, rising from a chair, and squatting as a result of an individual's knee condition, compared to having no difficulty with any of these activities. A 5-point difference in ADLS score could be represented by having slight difficulty with walking, stair climbing, and squatting, compared to having no difficulty with any of these activities.

Based on our findings of a modest treatment effect on quadriceps strength and self-reported knee function with the modified NMES protocol, if given a choice, we would probably use the original high-intensity NMES protocol, in which the stimulus induced contraction is performed against an isometric resistance provided by a dynamometer and the stimulus intensity is determined based on contraction torque output during training, as a first approach.[4,19-21] However, we believe our data support the use of the modified NMES protocol in cases where therapists may not have a dynamometer accessible to them, or in cases where patients may not tolerate the treatment on a dynamometer.

Our findings are in contrast to a recent study investigating the effects of NMES treatment for quadriceps strength training after ACLR. Paternostro-Sluga et al[15] did not find significant differences in quadriceps strength at 6, 12, or 52 weeks following ACLR between subjects receiving NMES combined with voluntary exercise compared to those not receiving the NMES protocol. The difference in results may be explained by different applications of the NMES training protocol.

Paternostro-Sluga et al[15] used a portable, battery-operated, electrical stimulator to provide the stimulus in their study. In contrast, we used a clinical stimulator, in which the power source is from an in-house plug-in wall socket with a 60-hz, 100-V AC current to provide the stimulus for treatment in our study. It has been demonstrated that portable stimulators produce significantly less torque output during training than clinical models.[20] Snyder-Mackler et al[20] demonstrated that although subjects in postoperative ACLR rehabilitation using portable stimulators utilized significantly greater stimulus current output (83 mA versus 55 mA) and performed 40 to 60 more contractions per day, they had significantly less torque output following 4 weeks of training compared to those who received NMES with a clinical stimulator. The training torque output for the portable stimulator group averaged only 8.3% of the uninvolved limb's maximum voluntary isometric torque output. In contrast, the training torque output for the clinical stimulator group was greater than 50% of the uninvolved limb's maximum voluntary isometric torque output. Because we used a clinical stimulator to provide the stimulus in our study, it is possible that our subjects generated higher training torque than what may have been experienced by subjects receiving NMES in the study reported by Paternostro-Sluga et al,[15] even though both studies utilized patient tolerance as the criteria for setting the stimulus amplitude.

Similar to what has been reported by other investigators,[19] ACL graft type was associated with the quadriceps strength measurements in our study. (Eta squared, 0.46 [$P<.001$] and 0.33 [$P<.001$] for 12-week and 16-week tests, respectively). Subjects who received patellar tendon autografts demonstrated lower quadriceps indices compared to those who either received hamstring autografts or patellar tendon allografts. Results for the 12-week quadriceps index were: patellar tendon autograft, 50.2; hamstring autograft, 81.9; and patellar tendon allograft, 70.5. Results for the 16-week quadriceps index were: patellar tendon autograft, 63.4; hamstring autograft, 87.8; and patellar tendon allograft, 77.3. These findings support the use of ACL graft type as a covariate in the final analysis for comparing quadriceps indices between treatment groups.

We used the achievement of clinical criteria for progressing functional activity levels such as initiating ambulation without crutches, treadmill running, and agility training, as a way to compare functional recovery between groups. We found that a greater proportion of subjects receiving the NMES training met the criteria to progress to agility training at 16 weeks. In contrast, we did not find a significant difference between groups in the proportion of subjects who met the milestones for ambulation without crutches or initiating treadmill running. Low statistical power could explain, in part, why we did

not find significant differences for these analyses. This may be particularly true for the treadmill running milestone data, in which the NMES group seemed to have a higher proportion of subjects achieving these milestones at both 12 weeks (62% versus 45%) and 16 weeks (86% versus 68%). But statistical power was only 0.20 and 0.28, respectively. It should be clarified that these clinical criteria are used specifically at our facility and were developed to promote a safe progression of functional activity, based on our clinical experience with rehabilitation following ACLR. These criteria have not yet been formally validated and further study is needed to determine the validity of these criteria.

Prior to conducting this study, some therapists at our facility had indicated that they only used NMES as an adjunct to voluntary strengthening exercises if their patients exhibited a persistent knee extensor lag after 1 week of rehabilitation. They explained that they believed only these subjects were in need of this adjunct treatment. However, we found no relationship between the presence or absence of a knee extensor lag at the time subjects were enrolled in the study and treatment outcome (point biserial $r = 0.10$ [$P > .49$] for quadriceps strength at 12 and 16 weeks; point biserial $r = 0.07$ [$P = .64$] for ADLS scores at 12 weeks; point biserial $r = 0.10$ [$P = .11$] for ADLS scores at 16 weeks). Our data do not support the presence or absence of a knee extensor lag as a criterion for using or not using NMES as an adjunct treatment in rehabilitation following ACLR. At this time, we believe our data indicate that NMES is a helpful adjunct to treatment, regardless of whether or not a patient exhibits a knee extensor lag.

We did not examine the effects of using NMES in subjects who have other surgical procedures performed concomitantly with ACLR, such as meniscal repair or multiple ligament repair or reconstruction. It is possible that these patients may have even greater difficulty in restoring quadriceps strength postoperatively, as there are typically greater restrictions for weight bearing and progressing functional activity levels following these procedures. It is possible that NMES may have a greater treatment effect in this population of subjects. This is an area for further study.

CONCLUSION

Use of the modified NMES protocol as an adjunct to rehabilitation resulted in modest increases in quadriceps torque output after 12 weeks of rehabilitation and in self-reported knee function at 12 and 16 weeks of rehabilitation, when compared to subjects who underwent rehabilitation without NMES treatment. We believe this modified NMES protocol is an acceptable alternative to an earlier published protocol in instances where therapists do not have access to a dynamometer, or for patients who do not tolerate NMES-induced contractions against isometric resistance with the knee in flexion.

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Appendix

Basic Postoperative Rehabilitation Program

Progression of Weight Bearing (Dependent on Graft Type)	
Patellar tendon autograft	Weight bearing as tolerated (WBAT) with brace locked in extension during ambulation for 1 wk. Unlock brace at 1 wk and progress WBAT to full weight bearing (FWB). Brace removed when patient tolerates FWB.
Hamstring autograft and patellar tendon allograft	WBAT with brace locked in extension during ambulation for 4 wk. May progress to FWB as tolerated but brace remains locked in extension for 4 wk. Brace removed after 4 wk.
Criteria to progress to FWB without crutches	Active knee flexion to 100°, no extensor lag on straight leg raise, no pain on weight bearing.
Joint Mobility	
Techniques	**Progression**
Active-assisted knee flexion and extension	Progress to active range of motion when tolerated. 10-15 repetitions (reps), 3-5 sets per day.
Quadriceps, hamstring, and gastrocnemius flexibility	Hold at end-range for 30-secs each (1 rep per set). Progress to 3-5 sets per day.
Prone hangs for terminal knee extension (knee extended, leg hanging over edge of plinth)	Initiate without weight, 30-sec hold, progress to 5 minutes. Add cuff weights to distal leg for added stretching force as tolerated. Usually 1 time per session. May divide into several reps of 30-sec holds if tolerated better by the patient.
Terminal knee extension stretching in long sitting with heel on towel roll and cuffweights over anterior proximal anterior leg	To do if patient does not tolerate prone hang stretching. Progression is same as prone hang stretching. Usually 1 time per session. May divide into several reps of 30-sec holds if tolerated better by the patient.
Stationary cycling	Initiate when passive knee flexion is at least 85°. Begin with low resistance at 5 min and progress to 20 min at self-selected speed. 1 time per session.
Weight-Bearing Exercises	
Techniques	**Progression**
Partial squats (0°-45°), box step-ups (2-8 in [5.08-20.32 cm]), calf raises	Initiate when patient is FWB without pain. 10-15 reps, 3-5 sets per day.
Progressive-Resistance Exercises	
Techniques	**Progression**
Cuff weights for straight leg raises, sitting knee extensions (90°-60°), and prone hamstring curls (0°-90°)	Initiate when tolerating 3-5 sets of 10-15 reps of active range of motion against gravity resistance.
Progressive-resistance machines (sitting knee extension [90°-60°], prone hamstring curl [0°-90°], leg press [0°-45°], hipabduction/adduction, calf raises)	Initiate when tolerating 3-5 sets of cuff weight exercises with 4.5 kg (10 lbs). Initiate with 1 plate of resistance (4.5 kg), 10 reps, up to 3 sets. When tolerating 3 sets of 10 reps with 1 plate, progress to 1 plate × 10 reps, 2 plates × 6-8 reps, 2 plates × 5 reps. When tolerating above, progress to 1 plate × 10 reps, 2 plates × 6-8 reps, 3 plates × 5 reps. Program is further progressed by adding a plate to each set (eg, 2 plates × 10 reps, 3 plates × 6-8 reps, 4 plates × 5 reps, etc).
Balance Exercises	
Techniques	**Progression**
Single-leg balance on level surface	Initiate when ambulating FWB without crutches. Try to maintain balance for 30 sec.
Single-leg balance on foam surface	Initiate when tolerating 30 sec single-leg balance on level surface.
Add ball catching, throwing, reaching to single-leg balance exercises	Initiate when tolerating 30 sec of single leg balance on foam surface.
Mini-trampoline and perturbation training	Initiate when tolerating all of the above balance activities.